Design for Deconstruction and Materials Reuse

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Edited by

Abdol R. Chini, University of Florida
Frank Schultmann, University of Karlsruhe

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CIB, International Council for Research and
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Task Group 39: Deconstruction
www.cce.ufl.edu/affiliations/cib

Center for Construction and Environment
M.E. Rinker Sr., School of Building Construction
College of Design, Construction and Planning
http://cce.ufl.edu/

French-German Institute for Environmental Research (DFIU)
University of Karlsruhe
Karlsruhe, Germany
http://www-dfiu.wiwi.uni-karlsruhe.de/

CIB General Secretariat
International Council for Research and Innovation in Building Construction
P.O. Box 1837
3000 BV Rotterdam
the Netherlands
http://www.cibworld.nl/
secretariat@cibworld.nl

Contents

Paper 10 **Reconstructing Deconstruction**
John Storey
Victoria University of Wellington, New Zealand

Paper 11 **Understanding the Concept of Flexibility in Design for Deconstruction**
Dennis S. Macozoma
CSIR Building and Construction Technology, Pretoria, South Africa

Paper 12 **An Overview of Demolition, Recovery, Reuse and Recycling practices in Turkey**
Soofia Tahira Elias-Özkan
Middle East Technical University, Ankara, Turkey

Paper 13 **Design for Deconstruction – Tools and Practices**
James Hurley, Chris Goodier, Elizabeth Garrod, Rob Grantham, Tom Lennon, and Anthony Waterman
BRE, Watford, UK

Paper 14 **Anticipating and Responding to Deconstruction through Building Design**
Abdol R. Chini and Shailesh Balachandran
University of Florida, Gainesville, Florida, USA

Paper 15 **Design for Deconstruction and Materials Reuse**
Bradley Guy, University of Florida, Gainesville, Florida, USA and
Scott Shell, Esherick, Homsey, Dodge & Davis Architecture, San Francisco, California, USA

Paper 16 **Designing for Deconstruction Safety**
Jimmie Hinze
University of Florida, Gainesville, Florida, USA

Paper 17 **Deconstruction’s Role in anEcology of Construction**
Charles Kibert
University of Florida, Gainesville, Florida, USA

Paper 18 **Characterization of Aggregates from Recycled C7D Waste: A Proposal for its Use and Commercialisation in Barquisimeto, Venezuela**
C. J. Suárez and R. E. Malavé
Central-Western University “Lisandro Alvarado”, *Barquisimeto, Venezuela*

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Preface

Task Group 39 of International Council for Research and Innovation in Building Construction (**CIB**) was formed on 5 May 1999 in Gainesville, Florida (University of Florida) to produce a comprehensive analysis of, and a report on, worldwide building deconstruction and materials reuse programs that address the key technical, economic, and policy issues needed to make deconstruction and reuse of building materials a viable option to demolition and landfilling. The first meeting of TG 39 was on 19 May 2000 in Watford, England (BRE) and the group's first product is the fully electronic CIB Publication 252, "Overview of Deconstruction in Selected Countries," which addresses the subject of deconstruction in eight countries: Australia, Germany, Israel, Japan, the Netherlands, Norway, the United Kingdom, and the United States.

The second publication of TG 39 is the CIB Publication 266, "Deconstruction and Materials Reuse: Technology, Economic, and Policy." This electronic Proceedings includes ten fully reviewed papers presented at the second annual meeting of TG 39 that took place in conjunction with the CIB World Building Congress in Wellington, New Zealand on 6 April 2001. The papers address the technical, economic, and policy issues related to deconstruction and materials reuse in eight countries: Australia, Germany, Japan, the Netherlands, South Africa, Sweden, the United Kingdom, and the United States.

This electronic Proceedings includes eighteen fully reviewed papers presented at the third annual meeting of TG 39 that took place in Karlsruhe, Germany (DFIU - University of Karlsruhe) on 9 April 2002. The papers discuss design for deconstruction and other collateral issues such as recycling potential and materials reuse in eleven countries: Australia, Germany, Italy, Japan, the Netherlands, New Zealand, South Africa, Turkey, the United Kingdom, the United States, and Venezuela. All three publications can be downloaded at the Center for Construction and Environment website at the University of Florida (www.cce.ufl.edu/affiliations/cib).

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Abdol R. Chini and Frank Schultmann
Editors

DESIGN FOR BUILDABILITY AND THE DECONSTRUCTION CONSEQUENCES

Philip Crowther
(Queensland University of Technology, Brisbane, Australia)

SUMMARY

The disassembly of a building may sound like the opposite of its assembly, but in practice it seldom occurs this way. The slow careful process of construction requires large numbers of people, large quantities of materials, and long periods of time. The reversal of this sequence is usually practiced as demolition and requires very little of the time and effort of the construction sequence. Despite these usual differences, if controlled and sequential disassembly were practiced instead of demolition, the construction and disassembly sequences could essentially be the same, one simply being the reversal of the other.

This paper presents a discussion of buildability and the notion that designing a building for ease of assembly might also lead to ease of disassembly for future reuse and recycling. Principles of design for ease of assembly, or ease of construction, can be adapted to become principles of design for disassembly.

If such reverse sequencing were to be attempted and designed for, both heuristic principles of buildability and broader philosophies or approaches to better assembly, should be valuable sources of knowledge in designing for disassembly.

KEYWORDS: Buildability, Construction, Deconstruction, Design, Disassembly.

INTRODUCTION

The way in which we currently design and construct buildings in the industrialised world, is wasteful and irresponsible. Most buildings are designed with a life expectancy of just a few decades with no consideration of what will happen after their service life. In fact up to one third of all solid waste going to landfill comes from building construction and demolition [1]. The negative environmental impacts of this waste are substantial.

Such waste can be avoided or reduced by increasing the current rates of reuse and recycling of building materials and components. One of the main obstacles to such reuse is that buildings are not designed for such ease of disassembly, and a developed knowledge base for design for disassembly does not yet exist.

There are however a number of related fields of knowledge that might offer information that will be of use in designing for disassembly. These areas include: industrial design, architectural technology, structural engineering, building maintenance, and buildability. Research into this last area of buildability has already established some broad concepts and philosophies of how to achieve ease of assembly, as well as heuristic design principles of design for assembly. Information on how to design for ease of assembly should be transferable to create knowledge of how to design for disassembly.

DEFINING BUILDABILITY

Several researchers and organisations have offered definitions of buildability, but the widely accepted definition [2] is that of the Construction Industry Research and Information Association (CIRIA), which quite explicitly states that 'buildability is the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building' [3].

Further definitions of buildability share the two main points of this definition; that it is about designing for ease of construction, and that it is within a holistic vision of the building project. The CII (Construction Industry Institute) at the University of Texas refers to buildability as the 'optimum integration of construction knowledge and experience…. to achieve overall project objectives'. The CII at the University of South Australia defines buildability as 'a system for achieving optimum integration of construction knowledge in the building process…. to achieve maximisation of project goals'. Other definitions refer to ' building efficiently…. to agreed quality levels' and the extent to which decisions 'facilitate the ease of construction and the quality of the completed project'. [4]

These definitions share an important implication, which CIRIA discusses. Any principles or philosophies of buildability must sit within a set of ‘overall requirements for the completed building’, which may in some cases be in conflict with the principles of buildability. This is to say that the overall project goals may actually restrict the buildability of the project, such that heuristic principles of buildability may not necessarily be appropriate in all cases.

Such a conflict is also evident in previously developed principles of design for disassembly [5] and the overall requirements for the completed building. This way in which the principles of buildability must be qualified reinforces the similarities that such principles might have with principles of design for disassembly. This similarity of application supports the potential for borrowing these principles of buildability for use in developing a knowledge base for design for disassembly.

RESEARCH INTO BUILDABILITY

Research into buildability can be split into two types: that which looks at broad systems of construction and the building process in general, and that which looks at particular heuristic principles of how to design buildings for better assembly or constuctability.

Buildability Systems

Much of the more recent research into buildability has focused on the broader view of what it takes to make a building easier to construct. In particular, research at the University of Newcastle, Australia [6][7], has developed a conceptual model of buildability. This model can be used to identify buildability factors within project specific environments. Development of the model relies on a systems view of the design-construction process. This model seeks to understand the entire construction process as a system of interrelated activities and people, each of which may have an impact on the construction process (refer to Figure 1).

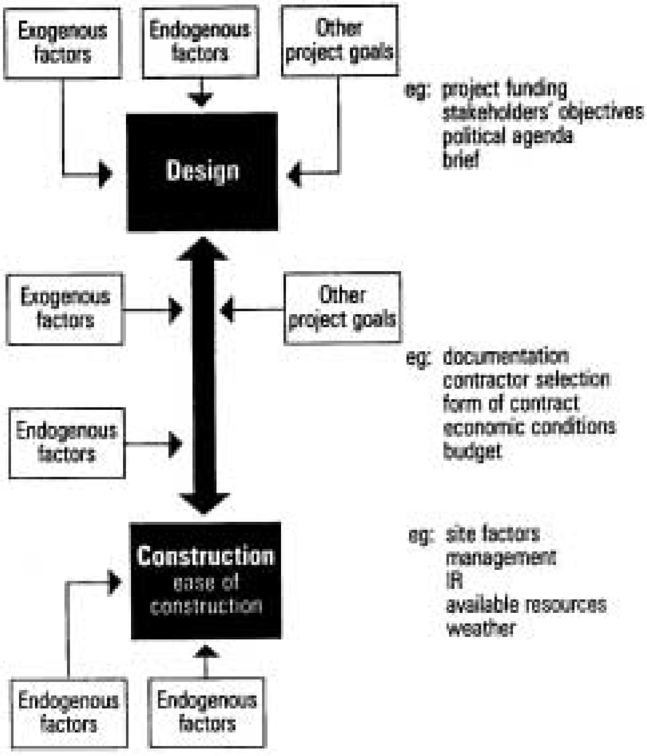

Figure 1 A systems view of the design-construction process [8].

Using such a systems approach the researchers have identified three dimensions to the model of buildability. These are: the participants, the buildability factors, and the stages of the building life cycle. The participants might include: clients, users, financiers, regulatory bodies, contractors, designers, and numerous others. Buildability factors are the cultural and technological activities that might be undertaken to achieve ease of assembly. The stages of the building life cycle will include: feasibility study, design, documentation, construction, commissioning, and demolition or deconstruction. A graphic representation can be made of this model of three dimensions (refer to Figure 2).

This model allows 'the identification and characterisation of the most influential factors impacting on project buildability, to enable the negative effects of these factors to be mitigated, and the positive effects enhanced, in terms of the overall project objectives' [9]. The importance of this model, with respect to informing design for disassembly knowledge, is in identifying the complexity of the system that allows or disallows good buildability. Since demolition, deconstruction, or disassembly is at the end of the project life cycle in this model, a similarly complex system must be understood to effectively design for disassembly. This is to say that while a set of design principles can be developed for design for disassembly, they must be understood within a broader context of the overall project and its systems environment.

This type of modelling of the construction process and context to understand buildability has also been investigated by other researchers who have used a systems approach [10]. The assembly process can be seen as a system in which the building gains mass through the conversion of materials into components, components into sub-assemblies, and sub-assemblies into buildings. Buildability then allows for ease of progress from materials to building. Design for disassembly then should consider the ease of the reversal of this process, loosing mass, from building through sub-assemblies and components to materials.

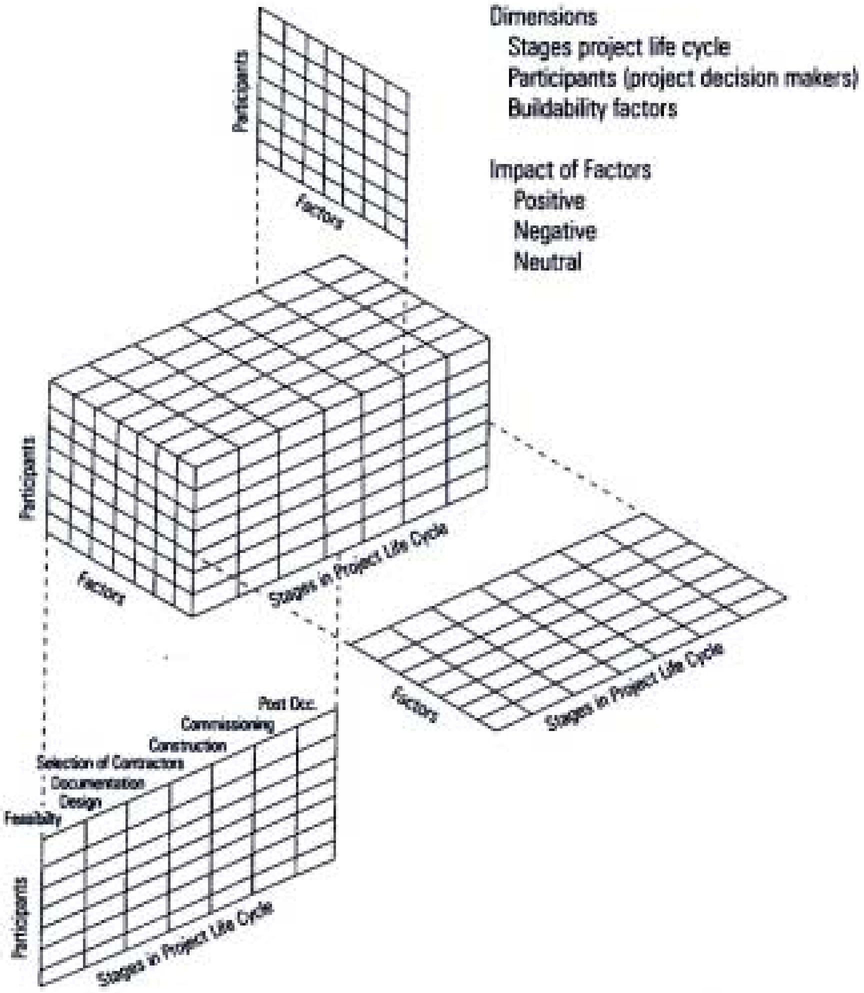

Figure 2 Three dimensional conceptual model of buildability [11].

Another important systems consideration of buildability that may inform the knowledge base of design for disassembly is the concept of trade packages. It is common practice to consider the construction process in terms of the type of work being done, each type usually being performed by a specialist sub-contractor. The boundaries of these packages are usually related to a particular type of building component or sub-assembly, such as electrical systems, plumbing, air conditioning, structure, cladding, glazing, concrete, etc. It is usual to schedule the construction process in terms of these trade packages such that they will occur in a particular sequence to allow for the optimum assembly procedure, good buildability. [12]

As already noted the disassembly process may be a direct reversal of the assembly process and it should ideally be so if total component reuse is desired. However if the goal of disassembly is the recycling of materials (rather than reuse of components) the process of disassembly may be other than a direct reversal of the assembly process, and the notion of trade packages will be obsolete. Trade packages concern themselves with particular component types, not necessarily with material types. If the goal of disassembly is recycled materials, the order in which things are disassembled need not relate to trade packages.

It can be seen then that there are a number of systems issues about how buildability is achieved that may be valuable in developing an understanding of how disassembly might be achieved, and in particular how it might be designed for.

Buildability Principles

The second major aspect of research into buildability is that of heuristic design principles. These are rules of thumb about the design of the building that an architect or building designer might employ in order to ensure the good buildability of a project. Several researchers have produced sets of such principles, usually from analysis of case studies of buildings that achieved good buildability in comparison with case studies of buildings with poor buildability.

Different researchers have developed their principles in different ways but there is much common ground in these proposed strategies. These strategies cover issues such as access, timing, skill levels, repetition, tolerances and sequences. CIRIA [13], in their study of the construction industry, identified seven general principles of buildability:

- Carry out thorough investigation and design
- Plan for essential site production requirements
- Plan for a practical sequence of building operations and early enclosure
- Plan for simplicity of assembly and logical trade sequences
- Detail for maximum repetition and standardisation
- Detail for achievable tolerances
- Specify robust and suitable materials

For each of these seven principles a number of recommendations are made, resulting in a total of twenty-four recommendations. Some of these recommendations will not have any relevance to the issues of disassembly. For example, ‘the design and shape of reinforced concrete elements should encourage the re-use of formwork’ [14]. While the re-use of formwork is good practice in construction, it will have no relevance in disassembly since the curing of wet concrete is one of the few assembly actions that is not reversed in the disassembly process. From the twenty-four recommendations, eleven are relevant to the issues of design for disassembly.

Adams [15], in his later discussion of CIRIA research, simplifies the analysis by proposing only three principal criteria for good buildability:

- Simplicity
- Standardisation
- Clear communication

These three criteria are then developed into sixteen design principles for good buildability [16]. Similar to the earlier CIRIA study, only some of these principles are relevant to issue of design for disassembly. Nine of the sixteen can be seen to have general relevance to disassembly, the remainder being either too specific in the form of prescriptive guidelines, or being related to assembly procedures that have no equivalent in a disassembly sequence.

Several other research efforts have also produced strategies or criteria for good buildability, though not in as much detail as the CIRIA work. In a report prepared for The Construction

Industry Institute (CII) Constructability Task Force, by O'Connor, Rusch and Schultz [17], seven key buildability concepts or strategies are identified:

- Construction-driven planning and programming
- Design simplification
- Standardisation and repetition of design elements
- Specification development for construction efficiency
- Modular and pre-assembly designs should be developed to facilitate prefabrication and installation
- Designs should allow for accessibility of labour, materials and plant
- Designs should facilitate construction under adverse weather conditions

Research in Australia includes that of the Construction Industry Institute, Australia (CII, Australia). This research has resulted in several publications [18] which have presented explicit constructability, or buildability, principles. Within these publications are twelve principles from the CII, Australia, which represent broad criteria for consideration of buildability issues. As such they provide a framework for considering the problems. The principles are:

- Integration
- Construction knowledge
- Team skills
- Corporate objectives
- Available resources
- External factors
- Program
- Construction methodology
- Accessibility
- Specifications
- Construction innovation
- Feedback

DESIGN FOR DISASSEMBLY PRINCIPLES

These strategies, or principles, and others from related buildability research [19][20] have been studied for possible application in designing for disassembly. Those principles that may have relevance to the process of design for disassembly are shown in Table 1. While not all principles of buildability will be relevant to design for disassembly, it is also true that not all principles of design for disassembly will come from buildability. This table shows only those principles that have been informed by buildability sources.

Table 1 Design for Disassembly principles from Buildability Research

No.	Principle	Reference
1	Minimise the number of different types of components - this will simplify the process of sorting on site and make the potential for reprocess more attractive due to the larger quantities of same or similar items	Adams 1989, Chen 1994, Hon 1988

2	Use an open building system where parts of the building are more freely interchangeable and less unique to one application - this will allow alterations in the building layout through relocation of component without significant modification	CIRIA 1983, Hon 1988
3	Use modular design - use components and pre-assembled subassemblies that are compatible with other systems both dimensionally and functionally	Adams 1989, Chen 1994, CIRIA 1983, Hon 1988, Illingworth 1993
4	Use assembly technologies that are compatible with standard building practice - specialist technologies will make disassembly difficult to perform and may require specialist labour and equipment that makes the option of reuse more difficult	Adams 1989, CIRIA 1983, Miller 1990
5	Provide access to all parts of the building and all components – ease of access will allow ease of disassembly, if possible allow for components to be recovered from within the building without the use of specialist plant equipment	Adams 1989, Hon 1988
6	Use components that are sized to suit the intended means of handling – allow for various possible handling options at all stages of assembly, disassembly, transport, reprocessing, and re-assembly	Adams 1989
7	Provide a means of handling components during disassembly – handling during disassembly may require points of connection for lifting equipment or temporary supporting devices	Adams 1989, Illingworth 1993
8	Provide realistic tolerances to allow for movement during disassembly – the disassembly process may require greater tolerances than the manufacture process or the initial assembly process	Adams 1989, CIRIA 1983, Hon 1988, Illingworth 1993, Miller 1990
9	Design joints and connectors to withstand repeated use - to minimise damage and deformation of components and materials during repeated assembly and disassembly procedures	CIRIA 1983
10	Allow for parallel disassembly rather than sequential disassembly - so that components or materials can be removed without disrupting other components or materials, where this is not possible make the most reusable or ‘valuable’ parts of the building most accessible, to allow for maximum recovery of those components and materials that are most likely to be reused	CIRIA 1983, Miller 1990
11	Use prefabricated subassemblies and a system of mass production - to reduce site work and allow greater control over component quality and conformity	CIRIA 1983, Hon 1988
12	Provide spare parts and on-site storage for them - particularly for custom designed parts, both to replace broken or damaged components and to facilitate minor alterations to the building design	CIRIA 1983
13	Sustain all information on the building manufacture and assembly process – measures should be taken to ensure the preservation of information such as ‘as built drawing’, information about disassembly process, material and component life expectancy, and maintenance requirements	Adams 1989, CIRIA 1983

CONCLUSIONS

Research into buildability is still relatively new and not especially well developed, but there have already been major developments in identifying strategies, systems, and principles that will help to achieve better assembly. Such strategies and principles can be adopted by, and adapted for, design for disassembly by simple extending responsibility for the building beyond its service life and using the same design techniques that promote good assembly to promote good disassembly. In essence design for disassembly is just a logical, and environmentally preferable, extension of design for assembly. The knowledge base already partially exists.

Design for disassembly needs to concern itself with a holistic view of the project goals. These might be the reduction of waste through materials recycling, or through component reuse, or even total building relocation. A thorough understanding is however needed of these goals in order to understand the dimensions of the problem: the participants, the disassembly factors, and the project life cycle. Only with an understanding of these dimensions can heuristic design principles be appropriately employed, to achieve the project goals.

Design for disassembly may in the short term have added economic and possibly environmental costs, but on the much larger scale of the life cycle of resources, the long term benefits are potentially much greater. Design for disassembly may not always be appropriate, as design for ease of assembly may not be. But in the construction industry, which is responsible for such a large portion of our resource use and waste production, it is a strategy worthy of exploration.

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COST -EFFECTIVE DECONSTRUCTION BY A COMBINATION OF DISMANTLING, SORTING AND RECYCLING PROCESSES

A. Seemann, F. Schultmann and O. Rentz
French-German Institute for Environmental Research, Hertzstrasse 16,
University of Karlsruhe, Germany

SUMMARY

In this paper an approach for the combination of dismantling, sorting and recycling processes will be presented. By the deconstruction of buildings, significant improvements in the quality of waste arising can be achieved by the application of selective dismantling techniques. As the dismantling of buildings generally requires more manpower than traditional demolition, the costs also tend to be higher. In order to reduce the overall costs of the dismantling and recycling procedure the building materials and building elements to be dismantled have to correspond with the requirements of the intended recycling options. In some cases the dismantling of certain building elements can be substituted by subsequent sorting processes or the building materials can be separated by recycling and preparation devices.

KEYWORDS: Dismantling, Sorting, Recycling, Planning Tool, Mass Flow Management

INTRODUCTION

In recent years the sustainability of construction and demolition work has attracted more and more attention mainly because of the volume and the heterogeneity of the building materials used. The demolition of buildings leads to large amounts of construction and demolition waste. In order to reduce the environmental impact of this waste, new approaches have to be developed and efforts have to be made to maintain building materials in closed loop concepts.

In several research projects it could be shown that by the selective dismantling instead of the destruction of buildings the environmental burden of recycled construction materials could be decreased [1], [2], [3]. Furthermore, these projects showed, that environment-friendly dismantling and recycling strategies can even sometimes prove to be advantageous from an economic point of view [4], [5]. Nevertheless selective dismantling requires extensive manpower, for the necessary deconstruction work. As a consequence required manpower represents a significant expense factor in the recycling loop of building materials arising from selective dismantled buildings. On the other hand, the possibilities of downstream sorting of building waste as well as the material separation by recycling and preparation devices are not completely taken into account in the present procedure of selective dismantling. In order to reduce the costs of dismantling and to encourage the cost efficient production of mineral recycling products, deconstruction, sorting of building waste and the potentialities of recycling plants should be combined in an integrated approach.

In a current research project possibilities of subsequently separating building materials by sorting processes or recycling and preparation devices are being investigated by the French-German Institute for Environmental Research. The project aims to decrease the costs of selective dismantling by combining the mentioned processes. Therefore detailed mass flows during dismantling, sorting and preparation are being explored. Based on these results a computer supported planning system will be developed, which makes it possible to plan the dismantling of buildings taking sorting and preparation into consideration. This approach starts with the requirements of the different recycling options, adapting the amount of material separation to avoid expensive dismantling processes if possible. Thus the costs for the dismantling of buildings can be decreased while the quality of the recycling materials to be produced maintained or can be increased. The fact that the composition of the building waste is known in advance helps to produce recycling materials with defined qualities.

In the following, selected topics from the project will be explained ranging from the high sophisticated recycling options for recycling building waste to the basic heuristics of the developed approach combining the deconstruction, sorting and recycling of building waste.

REQUIREMENTS FOR THE CLOSED LOOP RECYCLING OF BUILDING WASTE

Originally in the recycling of building waste in Germany recycling materials were used for backfilling, for the erection of noise protection systems as well as for road construction. These classical recycling options for mineral wastes can be mostly characterised as downcycling recycling options. Stimulated by the idea of the establishment of a closed loop recycling, making it possible to use the recycling materials for the same purpose as the original building materials, avoiding a downcycling of building materials, new recycling options have been approved in recent years. Especially in the field of mineral waste arising from the demolition of buildings, new ways have been developed such as the use of recycled aggregates for the production of concrete. The use of recycled building materials in such highly sophisticated recycling options requires defined information about material characteristics of the recycling materials as well as strict standards for the composition and production of the recycling materials.

Table 1: Selection of guidelines for the use of recycled mineral materials in Germany.

Area of Application	**Regulation**	**Application**
General use of mineral recycling materials	• Technische Regeln der LAGA [6]	⇒ Requirements for the recycling of mineral wastes
Road construction with recycling materials	• RAL-RG 501/1 [7] • TL Min-StB 2000 [8] • TL RC ToB-StB 1995 [9]	⇒ Quality assessment for recycled materials in road construction ⇒ Technical delivery conditions for mineral materials in road construction ⇒ Supplementary technical delivery conditions for recycled mineral materials in road construction
Concrete with recycled aggregates	• Richtlinie des Deutscher Aus-schuss für Stahlbeton "Beton mit rezykliertem Zuschlag" [10]	⇒ Guideline for concrete with recycled aggregates 1998 (revised edition will be published in spring 2002)

	• DIN 4226-100 [11]	⇒ Recycled aggregates for concrete and mortar
	• DIN 4226 [12]	⇒ Aggregates for concrete
	• DIN 1045 [13]	⇒ Concrete and reinforced concrete: dimensioning

To ensure, that the use of recycled building materials is as good as the use of new materials, regarding the material characteristics as well as environmental and chemical aspects, different guidelines have been issued. These guidelines differentiate the area of application of the recycled materials. Based on detailed specifications for the application of recycled building materials, corresponding to their area of use, a high level of recycling of building waste, as e.g. the use as aggregates in concrete, can be encouraged (see table 2).

In table 1 a selection of guidelines issued to secure a high standard of production and application of recycled mineral wastes in Germany is presented. The application of recycling materials can be subdivided into general use, use for road construction and at the highest level the use as aggregates in concrete. In most categories the table shows guidelines for new materials and for recycled materials. This is due to the fact, that the use of recycled materials has to fulfil the same quality standards for the end product as the use of new materials. Generally when using recycled materials both guidelines are in force, one for recycled materials and the "normal" guideline.

For the general use of mineral recycling materials the Technische Regeln der LAGA (technical guidelines of LAGA) must be applied. The guidelines contain values limiting the content of different chemical substances either in the material or in the eluate and apply to all applications except for the use as aggregates in concrete. In the field of road construction different regulations exist, where the application area ranges from the characterisation of the materials to chemical, load capacity and frost resistant aspects.

Table 2: Composition of categories for recycled aggregates in concrete and mortar [11]

Properties		**Composition [Mass %]**			
		Type 1	**Type 2**	**Type 3**	**Type 4**
Concrete, aggregate according to DIN 4226-1		≥ 90	≥ 70	≤ 20	
Clinker, non aerated bricks		≤ 10	≤ 30	≥ 80	≥ 80
Sand lime block				≤ 5	
Other mineral properties are		≤ 2	≤ 3	≤ 5	
Foreign matter	asphalt	≤ 1	≤ 1	≤ 1	≤ 20
	mineral	≤ 2	≤ 2	≤ 2	
	Non mineral	≤ 0,5	≤ 0,5	≤ 0,5	≤ 1

Other mineral properties are e.g.:
Aerated bricks, light concrete, aerated concrete, plaster, mortar Aerated slag, pumice
Mineral foreign matters are e.g.:
Glass, ceramics, non iron metal slag, plaster of Paris
Non mineral foreign matters are e.g.:
Rubber, plastics, metal, wood, organics, other materials

The use of recycled aggregates in concrete is regulated by two different guidelines concerning only recycling materials (DIN 4226-100 and "guideline for concrete with recycled aggregates"), which correspond to the guidelines for the use of new materials. In fact the guideline for concrete with recycled aggregates allows only the use of aggregates from category 1 form DIN 4226-100 (see table 2). Category 1 limits the content of clinker to less than 10 mass-%, while broken concrete has to be more than 90 mass-%, non minerals are allowed up to 0,5 mass-%, so that the use as aggregates is only possible for broken concrete at the moment. In general categories 2 to 4 can also be used as aggregates for concrete but the respective regulations have not been enacted up to now [14]. In spring 2002 a revised edition of the guideline of the Deutscher Ausschuss für Stahlbeton will be published, which is expected to allow the use of aggregates from category 2 for the production of light concrete.

Mineral waste arising from the demolition of buildings can hardly comply with the different regulations concerning the requested composition of the materials [15], [16]. Therefore approaches to separate the different building materials and to achieve the necessary purity have been developed as e.g. the selective dismantling of buildings.

SEPARATION OF BUILDING WASTE

The requested separation of building materials can be achieved by different techniques. The most efficient among them is the selective dismantling of buildings. Due to the fact, that every single building element can be separated from the others, the achievable separation of the building materials is extremely high. But on the other hand an extensive dismantling leads to high personnel costs. Depending on the prices for disposal and recycling in the region the building is situated in these personnel costs can be higher than the savings caused by less expansive disposal.

More frequently than with selective dismantling, the different building materials are separated by manual sorting after the demolition of the building. The material separation achieved by manual sorting is not as exact as if the building were dismantled. In many cases sorting takes less time which makes it cheaper compared to dismantling. That means, that if the requirements regarding the purity of the recycling material are not very strict, sorting is probably preferred. Some building elements such as water pipes and cables, located under the plaster or iron radiators can even be better sorted afterwards rather than being dismantled, at least from an economic point of view.

A further possibility to separate the foreign matter from the mineral building waste is the use of separating devices in recycling plants. The main principles and techniques of separation devices will be explained more closely in the following.

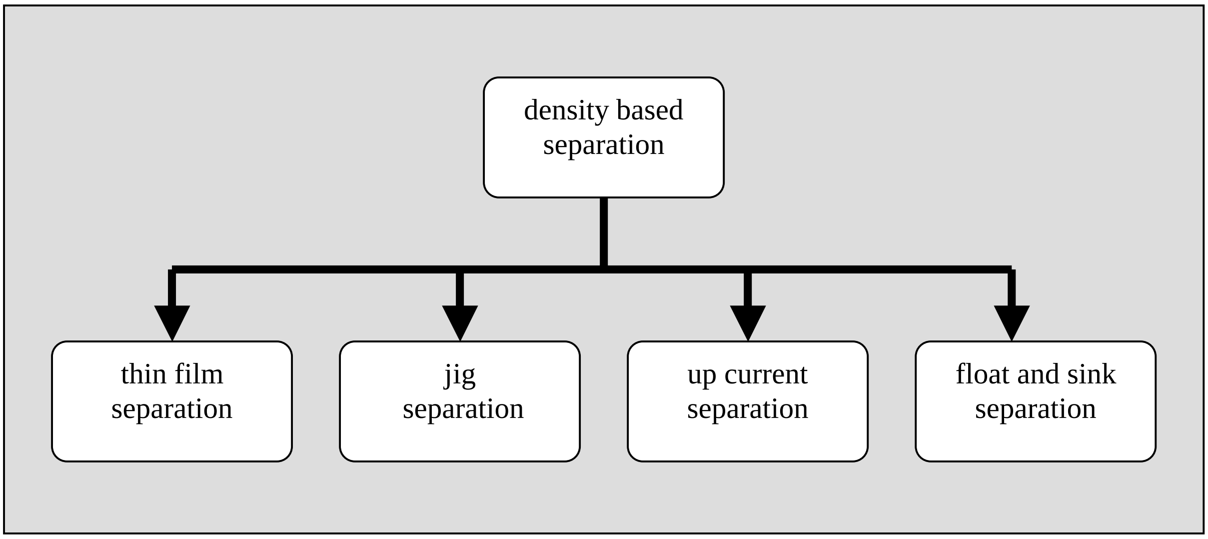
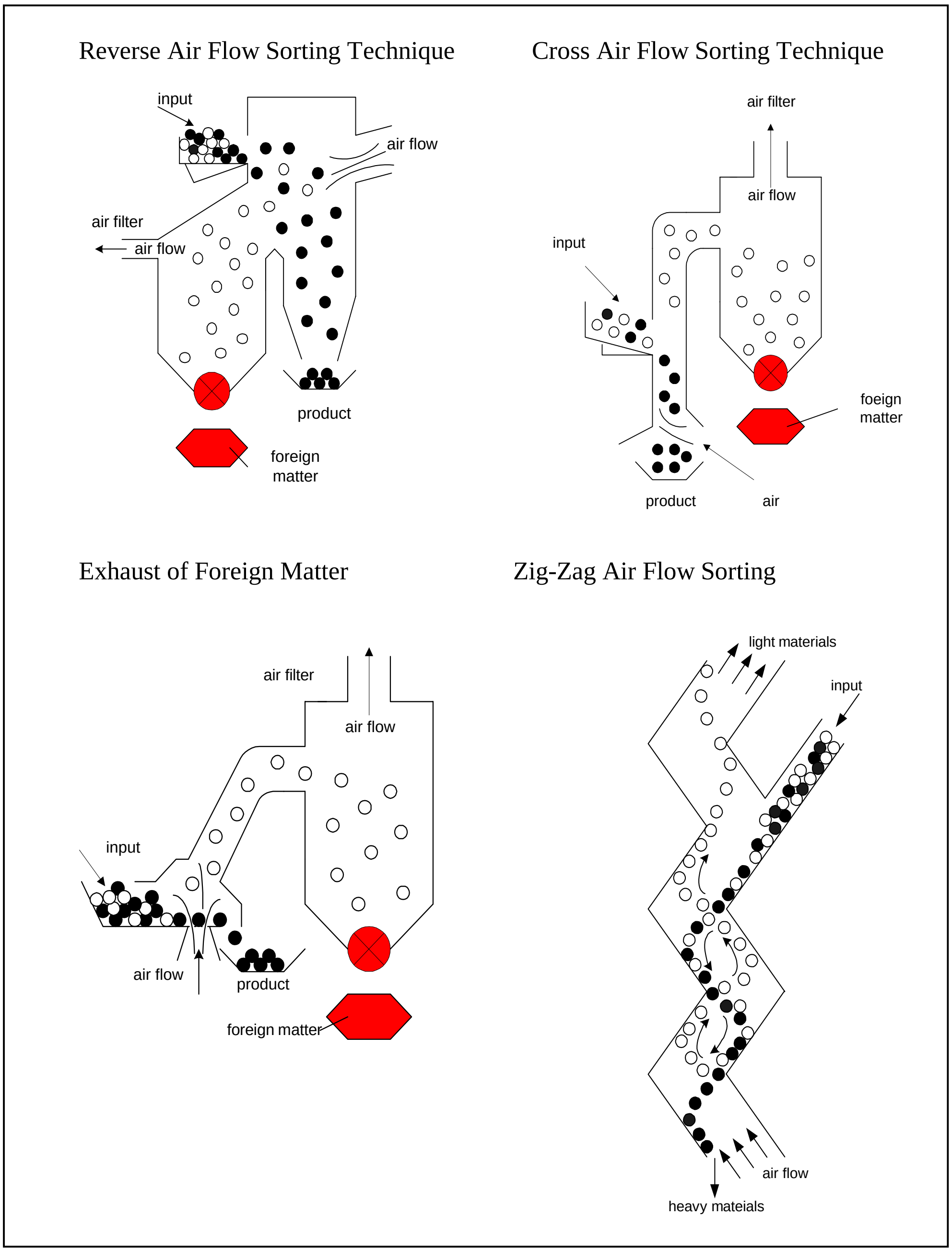


Figure 1: General overview of water based separating techniques

Most stationary recycling plants in Germany possess either an air flow based or a water based separation device, but the majority of German recycling plants use air flow based separation devices, although the water based technique provides the better quality [17], [18].Wet separation techniques use water to separate lighter and heavier materials. In some cases other substances are added to the water to increase the specific weight of the water and to change the point light materials flow up. Some water based separating devices use supplementary water jets or air to support the separation by density differences. Figure 1 gives a general overview of the different kinds of water based separating techniques, which can be differentiated by the four categories: thin film separation, jig separation, up current separation, float and sink separation. Within these four categories several different devices are available based on the same technique which each vary in detail.



Reverse Air Flow Sorting Technique

Cross Air Flow Sorting Technique

Exhaust of Foreign Matter

Zig-Zag Air Flow Sorting

Figure 2: Main principles of flow based separating techniques [19], [20]

Air flow based separating devices use the air flow to "blow away" light materials and to isolate the lighter non mineral materials from the heavier material materials. In general the air flow based techniques are characterised by lower running costs. But, on the other hand, the resulting material separation is not as exact as with the wet techniques.

Figure 2 shows the functionality of frequently applied air flow based separating devices. The "reverse air flow sorting technique" and the "cross air flow sorting technique" are the fundamental systems in the field of air flow based separating devices. Cross air flow sorting has the advantage, that the materials remain in the device for a much shorter time, which increases performance. In addition the geometric form of materials to be separated is much more important than with reverse air flow sorting. As a consequence, modern cross air flow sorting devices use the correlation of geometric form and the quality of material separation to achieve a better sorting [21]. The "exhaust of foreign matter" is a modification of the cross air flow sorting technique. Instead of using a free fall system, the materials to be sorted lie on a vibrating conveyor belt, that preseparates the light materials from the mineral fraction. Zig-Zag separation devices use the reverse air flow sorting technique, which is modified by the zig-zag form of the mechanism. Thus the effectiveness of sorting can be increased, because the zig-zag form has the same effect as a succession of several single cross air flow sorting devices [22].

AN APPROACH TO INTERLINKING OF DECONSTRUCTION, SORTING AND RECYCLING

In the previous section the basics of three different techniques for the separation of different fractions of building waste were explained. At present mostly the building materials are either dismantled or sorted. The application of separating devices depends on the recycling plant, available for the preparation of the recycling materials. As a result on the one hand it cannot be ensured that too many materials are not separated by expensive separating techniques, which thus avoiding unnecessary expenses. On the other hand, which is even worse, it is possible that not enough foreign matters are separated from the mineral waste, so that the quality of the recycling materials cannot fulfil the standards of the scheduled recycling options.

Due to the fact, that the costs for the dismantling of a building at the end of its lifecycle as well as the disposal costs for the demolition waste generally represent an amount, which is not negligible it is essential to decrease these costs. Therefore it is becoming more and more necessary to co-ordinate the separation of foreign materials from mineral waste by dismantling, sorting and separation devices to optimise these processes.

The French-German Institute for Environmental Research is developing an approach for the interlinking of dismantling, sorting and recycling. In this framework essential material flows have been investigated with the cooperation of a major deconstruction company. Based on these results the developed approach will be implemented as a computer aided planning tool (see figure 3).

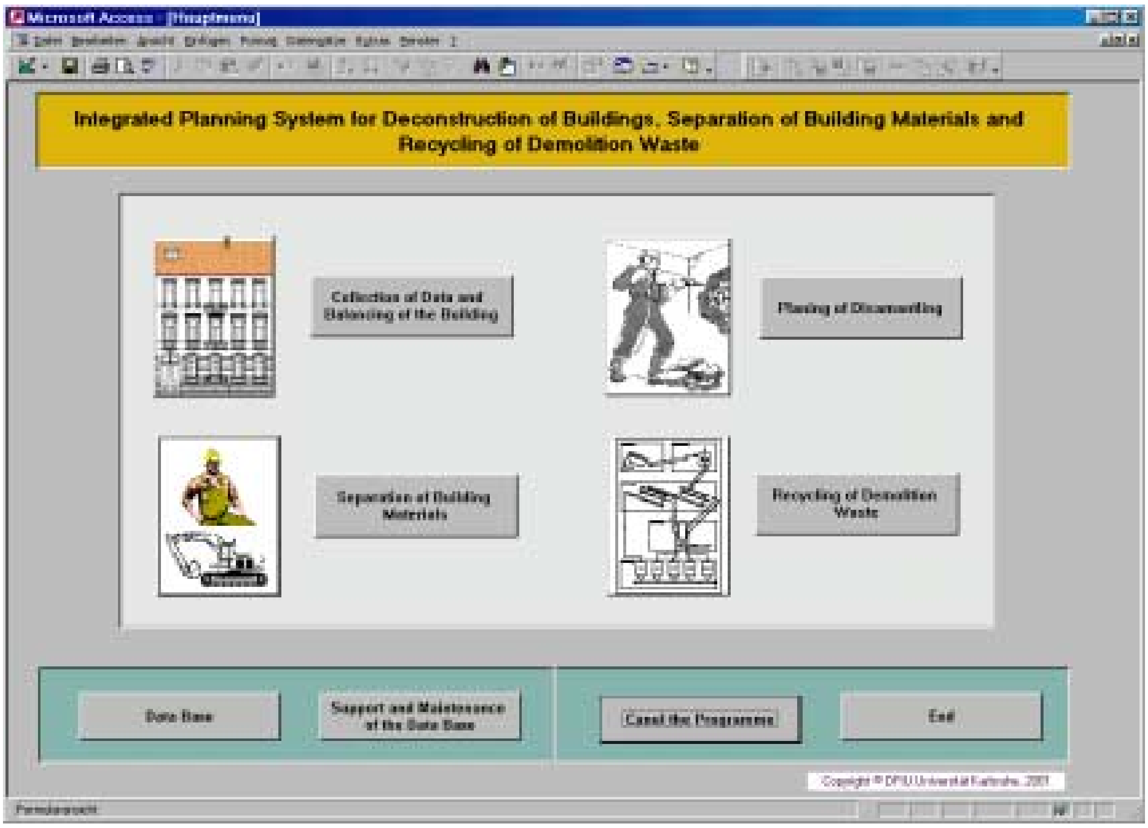


Figure 3: Screenshot of the integrated planning system (translated into English)

Figure 4 shows the structure of the developed approach. The planning process starts with the predetermination of the area of application for the recycling materials to be produced. Depending on the scheduled application, the requirements for the quality of the recycling materials is defined. In a next step the effectiveness of the applied recycling plant with its separating devices has to be chosen. This information, the requested quality of the recycling materials and the effectiveness of the applied recycling plant, represent the basis for further planning steps.

Further planning is based on the ascertainment of the material composition of the investigated building. For that purpose the building has to be audited [4], supported by the developed integrated planning instrument. Then it must be verified if the material composition already fulfils the requirement of the predetermined recycling option taking into account the effectiveness in separating foreign matter by the applied recycling plant. If the requirements are fulfilled no further separation techniques have to be applied. Otherwise some building elements have to be dismantled or sorted before the generated demolition waste can be recycled. The decision as to which building elements should be dismantled and which can be sorted is supported by a heuristic algorithm taking into account material and cost aspects. Therefore the algorithm calculates for each building element different specific values concerning the deconstruction and the sorting of the respective building element. Relevant specific values are e.g. deconstruction costs per kg building material and sorting costs per kg building material as well as the rate of sortable building materials per building element. Based on this values, building elements, containing materials not fitting to the intended recycling option, are either deconstructed or sorted to remove them form the main material flow. Building materials containing harmful substances and building elements which can be reused definitely have to be dismantled. For the rest of the building elements of the investigated building three possibilities are considered, dismantling, downstream sorting or remaining in the demolition waste. The developed algorithm defines by means of dismantling costs, sorting costs and sorting quotes if a building element has to be dismantled, sorted or can be left in the mineral fraction.

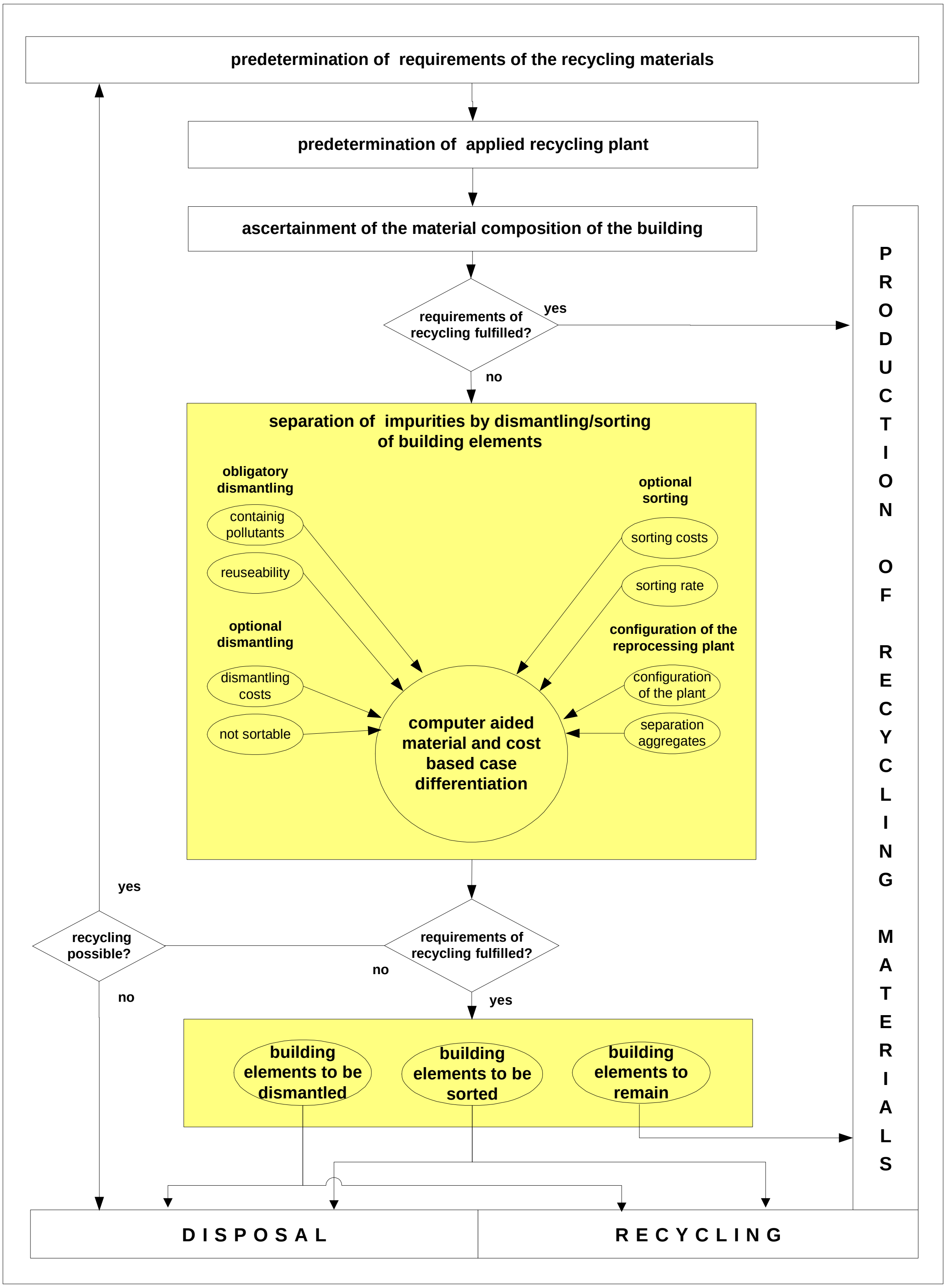


Figure 4: Flow chart of the approach interlinking deconstruction, sorting and recycling

The building materials of the dismantled or sorted building materials can either be recycled separately according to their material composition or they have to be disposed of, if there is no recycling option available. Afterwards the remaining mineral building waste can be recycled in the chosen recycling plant, so that the predetermined quality of recycling materials can be produced.

CONCLUSIONS

The necessity of the creation of closed loop concepts for building wastes has led to the development of new sophisticated recycling options, such as the use of mineral waste as aggregates in concrete and mortar. To secure the quality of products made by the use of recycling materials, several guidelines have been released in recent years. Although the quality of demolition waste can be greatly increased by the application of selective dismantling, the dismantling costs are a significant cost factor. On the other hand the possibilities of sorting and material separation by separation devices in recycling plants are not constantly considered.

The developed approach interlinks dismantling, sorting and the application of separation devices for the production of recycling materials, Whereby the costs for dismantling of a building can be decreased. Furthermore the predetermination of the quality and area of application of the recycling materials to be produced ensures, that the recycling materials fulfil the quality requirements of their intended application. That means, that with this approach the interaction of dismantling and sorting is coordinated so that at the same time the separation of foreign maters from the mineral waste is adapted to the required quality of the recycling materials. Public authorities, architects and especially demolition firms can profit by the results of the research project and the application of the developed approach, contributing to perform demolition and deconstruction work in an economical way without neglecting ecological issues.

ACKNOWLEDGEMENT

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LIGHTWEIGHT AGGREGATE PRODUCED FROM FINE FRACTIONS OF CONSTRUCTION AND DEMOLITION WASTE

Dipl.-Ing. M. Reinhold, Prof. Dr.-Ing. habil. A. Müller
Bauhaus-University Weimar, Faculty of Civil Engineering,
Chair of Processing of Building Materials and Reuse
Coudraystr. 7, 99423 Weimar, Germany
Phone: +49 (0) 3643. 584606 / 584699

SUMMARY

The paper describes a new technology for the production of lightweight aggregates based on by-products like sand and dust that result from the processing of Construction and Demolition Waste. Technology has developed enabling the targeting of aerated concrete and crushed sand from masonry for reuse. Since the proportions of these materials found in the waste stream will rise in the future, targeting these materials for reuse becomes increasingly important.

From aerated concrete waste first granules are formed by the addition of fine material like sand or dust from brick waste. Treatment by a burning process results in a consolidation of the pellets. The resulting bulk density of the material can be controlled by the addition of expanding agents before burning.

In the described research project three versions of the production of high-quality lightweight aggregates from recycled aerated concrete and brick waste were examined. In each case the material properties were improved by the granulation of the different basic materials and the following burning in the rotary kiln. The best results were obtained by the procedure, in which the finely ground basic materials are mixed and granulated before burning in a rotary kiln. Proportioned additions of SiC as an expanding agent and the variation of the furnace parameters allowed the control of a wide range of resulting granulate characteristics. The characteristics of the resulting granulates are equal those of other mineral lightweight aggregates.

INTRODUCTION

During the processing of Construction and Demolition Waste (CDW), particularly of masonry waste, substantial quantities of crushed sand are generated. For example 13 - 32 m.-% of sand < 4 mm was formed during the treatment of brick material by a single-stage crushing process depending on the type of crusher [1]. While for the coarse fractions of the several materials in CDW different ways of utilization exist already, the sand fractions represent a problem and therefore these fractions are often deposited. The same applies to special constituents of building debris like aerated concrete. Due to its special material properties this material must be sorted out and reused separately. Otherwise the quality of the whole material declines. As a consequence it is possible that the whole quantity of material must be deposited.

If a high grade recycling for a high percentage of waste shall be realized new ways of utilization must be developed for the high quantities of crushed sands already available in surplus today as well as for the aerated concrete or other recyclable constituents of CDW.

In the research project which is described here the common utilization of aerated concrete and brick sands is examined. This research tries to capture and to combine the advantages of both reclaimed materials. The goal is the development of lightweight aggregates or constructional light bulk materials with favorable properties. Material characteristics like density, water absorption, grain size that can be controlled and thus adjusted to non-standard situations in construction shall guarantee a high level of added value.

GENERATION AND COMPOSITION OF MASONRY CDW IN GERMANY

In Germany about 85 million Tons of CDW are generated per year. Thirty million Tons of this material result from the demolition of buildings [2]. The quantity of aerated concrete waste amounts to about 50,000 Tons or 100,000 m³ [3], while the manufactured quantity of aerated concrete is approximately 2.23 million Tons or 4.45 million m³ annually [4]. That means, the quantity of aerated concrete waste amounts to 2.25 % of the produced quantity. The remaining 97.75 % are cumulated at present in existing buildings. This material will be a part of the building debris in the future. 55 million t or 110 million m³ aerated concrete elements are produced in Germany since 1956, which are predominantly still in the stock of buildings [4].

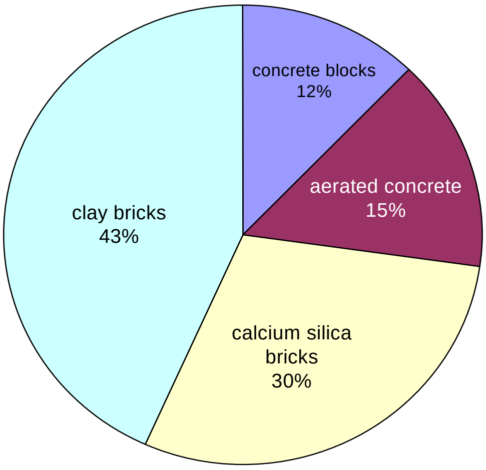

Figure 1 Proportions of types of brick in masonry material produced in 1997 [6]

Considering these facts and assuming an average service life of a building of 30 to 100 years a clear increase of the aerated concrete proportion in the building debris must be expected in the future. The aerated concrete industry itself offers the free take backs and utilization of waste of aerated concrete. An appropriate network of places for the return and the processing is just installed. Today the quantities of aerated concrete which come from the demolition of buildings are so low that they are deposited at local landfill sites [5]. Waste which results directly from the production is crushed, ground to a fine powder and fed back as raw material in the production of aerated concrete. The coarse fraction that is generated by this treatment is processed into cat litter or material for oil-absorption as products with a high added value.

The proportion of masonry waste of the CDW from the demolition of buildings amounts - depending on type of building – to 50 – 65 m.-% [7]. Considering of the total amount according to [2] about 15 – 19.5 million Tons of masonry waste is generated per year.

According to the historical development of the masonry materials the proportion of clay bricks in masonry waste is very high in structures built before 1945. In recent times the proportion is lower and approaches to the proportion of production at present shown in figure 1. The annual production of clay brick amounted to approx. 16.4 million Tons or 12.6 million m³ in 1997. At present about 420 million Tons or 323 million m³ clay bricks are in the stock.

For the coarse fractions of masonry debris with a content of clay bricks > 90 % different ways of utilization are currently well established. They can be processed to substrate for roof gardens as well as to material for tennis courts and sports grounds. Further there are efforts to use finely ground brick powders as admixture in mortar or concrete because most of them have pozzolanic properties. The predominant portion of the masonry waste is fed to a clear downcycling today. The material is used in embankments, as fill material in side walks and by roads, for subgrade improvements or it is landfilled [4]. The situation of crushed sand is particularly critical because there are only a small number of applications compared with the high portion of sand generated by the crushing process.

EXPERIMENTAL INVESTIGATIONS FOR PRODUCTION OF LIGHTWEIGHT AGGREGATES

Characterization of raw materials

For the investigations clay bricks separated from masonry waste by a recycling facility and production waste from the aerated concrete industry were used. Thus variations in the composition and properties of the material can be limited. The properties determined at the raw materials are summarized in the table 1. Table 2 shows the results of the chemical analysis.

Table 1 Properties of the raw materials

Material	**Aerated concrete**	**Clay brick**
Shape	angular, coarse-pores	angular-interlocking
Available fractions	coarse bulk material, powder 0/1 mm	sand 0/4 mm
Used fractions	4/8 mm, 0/2 mm, 0/0.1 mm	0/0.1 mm
Bulk density (fraction 4/8 mm)	0.64 g/cm³	1.85 g/cm³
Water adsorption (fraction 4/8 mm)	99.3 M.-%	12.1 M.-%
Grain strength (fraction 4/8 mm)	low	high
Temperature range for the formation of melt	1200 – 1280 °C	1190 – 1300 °C

Table 2 Chemical composition of the used materials

[m.-%]	**LOI**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**K_2O**	**Na_2O**	**SO_3**	**Cl**
Aerated concrete	15.1	43.6	3.6	1.7	30.1	0.8	1.9	0.5	0.0	0.022
Clay brick	2.6	56.1	15.7	5.8	5.0	2.8	3.5	0.9	0.6	0.017

During an investigation of aerated concrete from 24 German factories [5] values for leachable sulfate of 1.05 m.-% on average were determined. This chemical component is caused by the Anhydrite that is often added to the raw mix to improve the green strength during the production [8]. This high content of sulfate makes the material recycling of aerated concrete more difficult [9]. In the material used in these investigations no sulfate was detectable.

Examined versions of the production of granulates

The goal of the investigations was to manufacture new building materials shaped as granulates. In the new products the positive characteristics of the recycled basic materials shall survive if possible. Three versions were examined, in order to achieve this goal. An overview of the procedure during the investigations is shown in figure 2. The processing of the aerated concrete and the brick material takes place in separate steps. Then the two main components were brought together and converted by addition of water into green granulates. After the drying process these granulates were burned in a rotary kiln. In the experiments the proportions of the main components aerated concrete and clay brick varied between 33 and 67 m.-%.

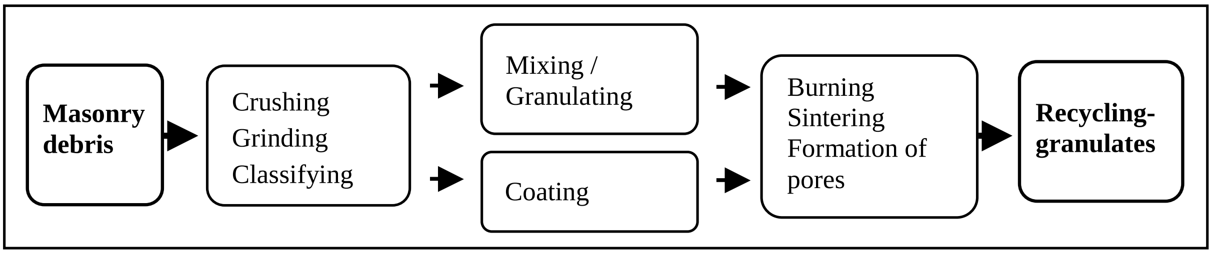

Figure 2 Pattern of the granulates production

In **version 1** the goal of the maintaining of the good properties was achieved consistently. Aerated concrete grains of the fraction 4/8 mm from the crushing process of aerated concrete waste were coated with a layer of masonry powder, thus the porous grains were stabilized and sealed against water. Then the coated grains were burned. The bulk density of the so manufactured granulates amounts to approx. 1.1 g/cm³, the water absorption achieves values of approximately 26 m.-%.

With consideration of the high sand proportion, which results from the crushing process of aerated concrete, **version 2** was developed. By an agglomeration process [10], for which a pan pelletizer was used, grains of the fraction 4/8 mm were formed from fine material 0/2 mm. The aerated concrete agglomerates produced in this way were coated with masonry powder and burned afterwards.

The particle size distribution and the porosity of the aerated concrete sand is unfavorable for granulation. Therefore the application of different bonding agents and high water contents is necessary. These facts result in a complicated production process. The granulates of the version 2 achieved bulk densities of 1.6 g/cm³ and a water absorption of about 10 m.-%. The strength of the grains was clearly increased compared with version 1.

The procedure examined with **version 3** essentially corresponds to the procedure that is used for manufacture of expanded clay or expanded glass products. The basic materials aerated concrete and masonry chippings are ground and mixed before granulation. This process step leads to a clear improvement of the granulation ability and to well controllable characteristics of granulates. These can be controlled in a wide range. The obtained bulk density has values between 0.8 and 1.8 g/cm³. The water absorption is appropriate below 7 m.-%.

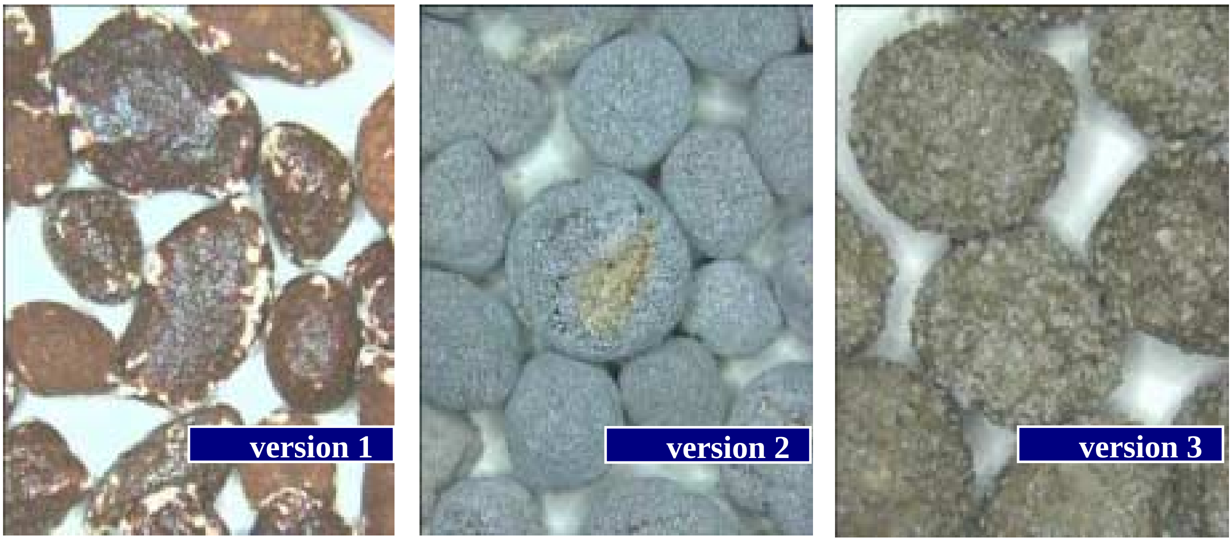

Figure 3 Different types of granulates

During the tests it became clear that the solidification of coarse aerated concrete fractions or the applying stabilizing layers in connection with the thermal treatment in a rotary kiln corresponding to version 1 and 2 is made more difficult by a basic problem. Heating the aerated concrete on temperatures > 1200 °C leads to thermal decomposition of the Calcite and the CSH - phases and thus to shrinkage and to the loss of strength of the aerated concrete grains. The thermogravimetric investigation of the aerated concrete, figure 4, shows mass losses in the range up to 712 °C and at 1171 °C. By the grinding of the raw materials acc. to version 3 the aerated concrete grains are dispersed well in the melting phases formed by the masonry powder. Due to the good granulation ability of the material and the obtained granulates characteristics method 3 is favored at present.

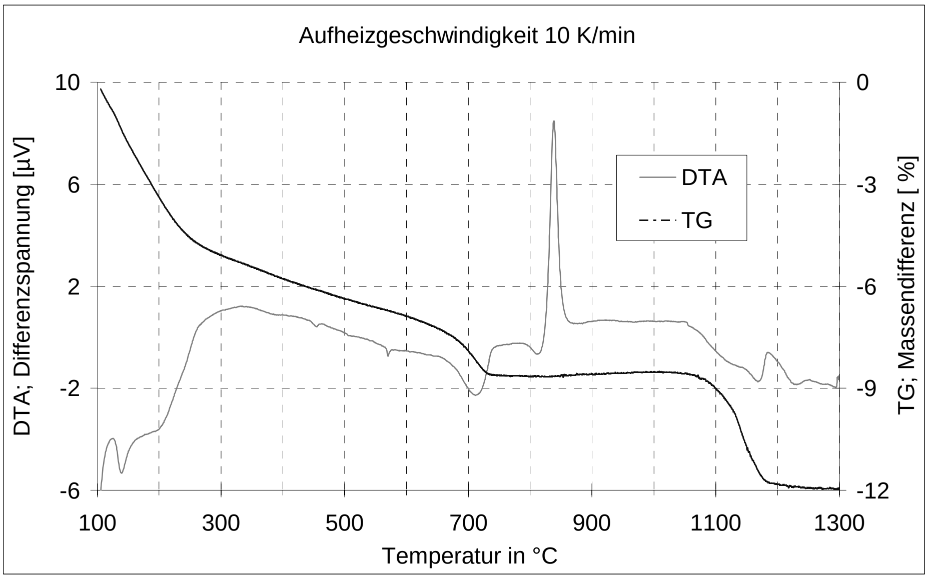

Figure 4 DTA and TG curve of the aerated concrete

INFLUENCES ON PROPERTIES OF GRANULATES FROM FINE GROUND RAW MATERIALS (VERSION 3)

The characteristics of the granulates from the fine ground raw materials depend on the parameters of the burning process (fig. 5) and on the content and the kind of the expanding agent in the mixture (fig. 6).

The required burning temperature is determined by the melting temperatures of the raw components (1190 to 1300 °C for the brick and 1200 to 1280 °C for the aerated concrete) in first approximation. On the one hand the temperature must be high enough for the formation of a sufficient amount of melting phase that connect the particles and enable the expanding agent SiC to act effectively. On the other hand the quantity of melting phase may not be to large in order to receive the stability of the granulates. The plots in figure 5 show the influence of the temperature on the density and the water absorption of the granulates. To low heating temperatures (< 1265 °C) prevent the complete decomposition of the SiC and the formation of a sufficient quantity of melting phase in the mixture, while furnace temperatures above 1290 °C cause a shrinkage of the granules that results in an increasing density. The granulates with the lowest density of about 0.6 g/cm^3 can be obtained in the range between 1260 and 1290 °C. The water absorption behaves in reverse to the density.

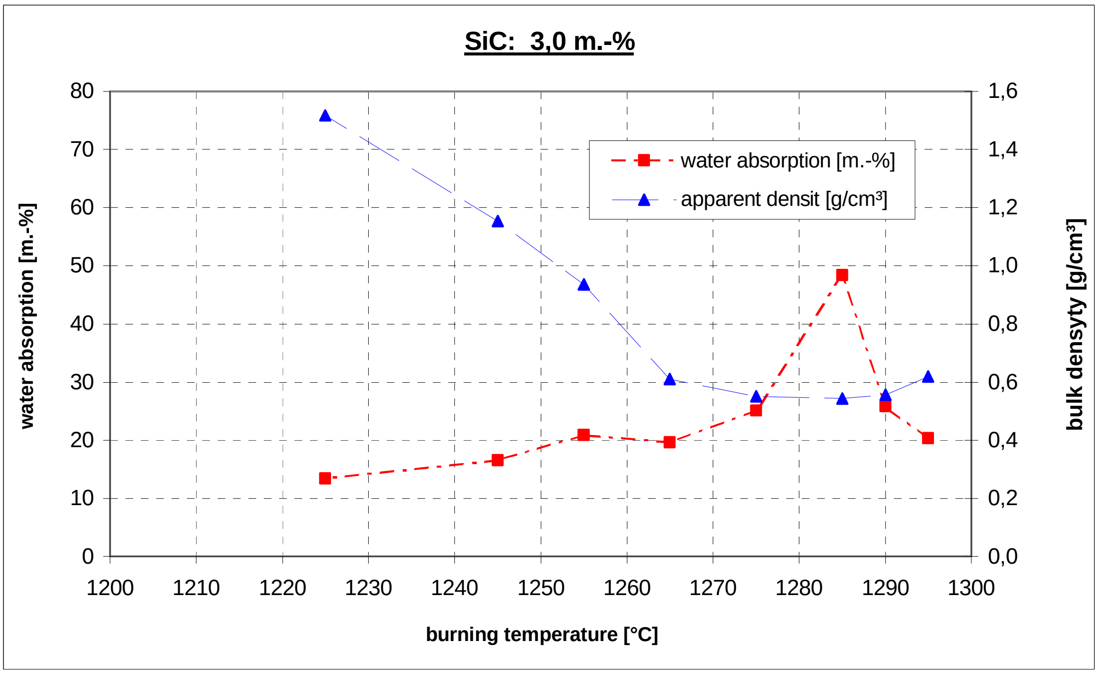

Figure 5 Influence of the temperature on the bulk density and the water absorption

The content of the expanding agent is the second important factor of influence on the properties of the lightweight granulates. For the generation of pores in the material mixture described here silicon carbide (SiC) is suitable, because it releases gas in a wide temperature range (800 to 1150 °C) [11]. By the variation of the content and the particle size of the expanding agent the size of the pores and the aerated structure of the burned granulates can be influenced. For the examined mixtures the maximum expanding effect was obtained with a SiC-content of 3 to 6 m.-% (fig. 6). Within this range the granulates indicate the smallest bulk density. If the SiC -content is to small the available expansion potential is not used completely whereas a to high concentration results in the collapsing of the granules. The values of the water absorption develop in reverse proportionally to those of the bulk density.

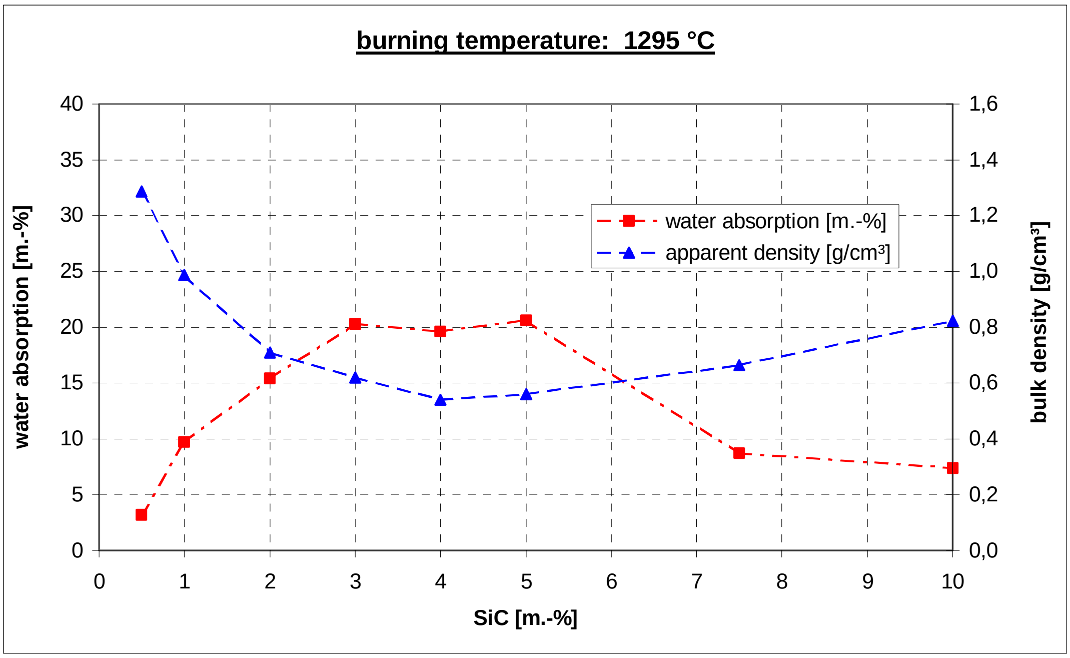

Figure 6 Influence of the SiC-content on the bulk density and the water absorption

The figure 7 shows the fractured surfaces of granules 4/8 mm produced from aerated concrete and masonry powder in the mass proportion of 66.6 % to 33.3 %. The SiC-contents of the granules shown in the pictures are 0.0 m.-%; 1.0 m.-% and 3.0 m.-%. The burning temperature in the rotary kiln amounted to 1295 °C.

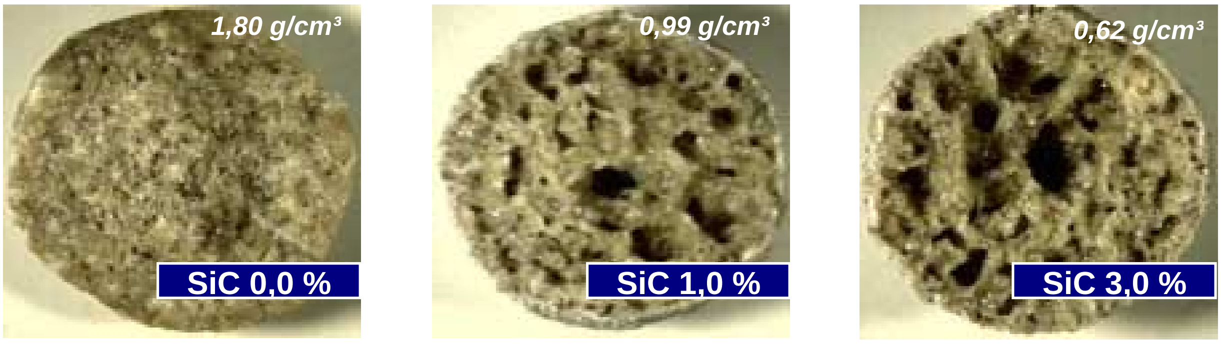

Figure 7 Formation of polyedric pores

With increasing SiC-content the proportion of polyedric formed pores increases, which can appear both as finely distributed, separate pores and as larger, connected voids.

The effect of the expanding agent depends also on its grain size. The plots in figure 6 base on a SiC-powder with a mean particle size of 55 µm. If the powder is ground to smaller grain sizes, the expanding effect is improved. Thus the burning temperature and the added amount of SiC can be reduced.

From the summary of all laboratory results and experiences the parameters for the manufacture of lightweight aggregates can be formulated. The content of SiC in the raw mixture must be between 1 and 3 % m.-%. The required temperatures in the rotary kiln are between 1250 and 1295 °C. The quantity and the fineness of the added SiC influence the portion of pores in the burnt granulates and their shape.

CONCLUSIONS

In experimental investigations new possibilities for the utilization of waste from aerated concrete and masonry powder were tested. The goal was to figure out the fundamentals of a suitable procedure and to determine the characteristics of the products. The following results were obtained:

- The manufacturing process that results in the "best" product consists of three steps:
    → mixing of the finely ground raw materials, i.e. aerated concrete, clay brick, expanding agent → granulation → burning.
- As expanding agent SiC is suitable. The required amount is ≤ 3 m.-%.
- The required burning temperatures are in the range from 1250 to 1295 °C.
- The produced material is a lightweight granulate with a bulk density of 600 to 800 kg/m^3 and a water absorption of 10 to 20 m.-%.
- Characteristics of the produced granulate can be controlled in a wide range by the portion of added SiC, the fineness of SiC and the variation of the furnace temperature.

Further research must be aimed at

- the exact conditions of the creation of pores with regard to the pore size distribution and the formation of pore nucleation
- the examinations of other constituents of CDW as raw materials
- the examinations of other methods of consolidation and
- the energy demand of the process.

The properties of the lightweight aggregates based on CDW are equal those of other mineral lightweight aggregates. First tests in a pre-cast concrete plant show that the material can be used for the production of lightweight concrete blocks.

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RECYCLING OF CLAY BRICK DEBRIS

Prof. Dr.-Ing. habil. Anette Mueller, Dr.-Ing. U. Stark
Bauhaus-University Weimar, Faculty of Civil Engineering,
Chair of Processing of Building Materials and Reuse
Coudraystr. 7, 99423 Weimar, Germany
Phone: +49 (0) 3643. 584606 / 584610

SUMMARY

The paper describes the development of new products and technologies for the high level recycling of all fractions of crushed masonry CDW or clay bricks. The coarse fraction can be used as material for roof gardens or as aggregate for lightweight concrete. These fields of application are already technically used today. A new product from the coarse fraction, in which the pleasant color and the remarkable structure of old bricks is of advantage, is ornamental gravel. By investigations in a semitechnical scale a method that is suitable to create rounded grains was figured out. The produced gravel shows a good frost resistance.

The sand fraction can be used as aggregate for mortar. A comparison of the mortars containing recycled material (RC) with the reference mortars shows nearly no differences of the properties. The RC-mortars were generated by the complete or partial substitution of the fraction > 0.2 mm of technically manufactured reference mortars by recycling sand.

The fine fraction < 200 µm can be used as mineral admixture in concrete. This admixture affects the workability and the strength development in dependence on the fineness. It was experimentally proved that the filler has pozzolanic properties if it is additionally ground to higher fineness. At present research work is done to prove its effect on workability and to apply it to Self-Compacting Concrete.

CHARACTERISTICS OF MASONRY CDW AND BRICK CDW

In Germany 80 to 90 millions tons of Construction and Demolition Waste are generated annually. The largest proportion of CDW results from the re-construction of highways and traffic areas followed by masonry and concrete CDW from structural engineering. The construction method of the demolished buildings - those are at present predominantly buildings from the 19th and the beginning of the 20th Century - determines the material composition of the CDW. Since the selective demolition for cost reasons is still rather rare today, the quality of the RC materials and thus the ratio and the level of utilization depends mainly on the processing technique.

Construction and Demolition Waste is a mixture of different building materials. Its composition depends on the type of building, the age, the region, in which the building is located, the technique of demolition etc. The main components of CDW in Germany are concrete, masonry and wood. Especially in buildings from the former century masonry of clay bricks is the predominant material. In younger buildings further materials like calcium silica bricks, blocks of aerated concrete, plaster boards and different types of materials for thermal insulation are used in an increasing extent.

Today masonry CDW is often recycled at a very low level as embankment or fill material. If masonry CDW shall be reused at higher levels two steps are necessary at least. At first the material must be divided into material groups by a selective demolition and/or a separation during the processing in the recycling plant. Then the separated materials must be prepared for the intended utilization. Either they can be led back as raw material into the original products or they form the basic material for new products making use of the special characteristics of the separated materials directly.

In the course of the processing of CDW the first step is the separate storage of masonry and concrete debris after delivery. Thus a first separation is realized as prerequisite to produce „red“ recycling materials that base on masonry debris and „gray“ aggregates that base on concrete debris. While the gray recycling material has a little varying composition the red material contains a larger number of building materials. Besides the range in which the composition varies is much broader. In table 1 the composition of altogether 26 samples of 7 recycling plants are shown [10]. The content of brick varies between 31 and 79 % by mass. Higher portions of brick are possible by a careful pre-sorting at the site. A nearly pure material consisting only of tiles can be obtained if re-constructions of roofs are carried out.

Table 1: Constituents of masonry CDW

Constituent	Portion [% by mass]
Clay brick	31...79
Concrete	1...27
Mortar	14...49
Natural rock	2...24
Wood/Paper	0...0.3
Glass	0...0.5
Gypsum	0...5.2
Ceramic	0.2...2.4
Other constituents	0...2.6

From the results of the chemical analysis (table 2) follows that the main oxides SiO_2, Al_2O_3, Fe_2O_3 and CaO are predominant with together 89 % by mass in average. Minor components that influence both the structural properties and the environmental properties are chloride and sulfate. Their mean values are equal or below the threshold values if the limits of concrete aggregates are used for comparison. But 25 % of the individual measurements are higher than these threshold values.

Table 2: Chemical composition of masonry CDW

	Content [% by mass]		Threshold value [% by mass]
LOI	2.9...	12.3	
SiO_2	52.0...	74.5	
Al_2O_3	7.2...	13.4	
Fe_2O_3	2.5...	5.3	
CaO	3.7...	15.0	
SO_3	0.2…	3.3	1.0
Cl^-	0.018...	0.058	0.04

The physical properties of the masonry recycling material vary in dependence on the composition (table 3) and the particle size (figure 1). The effect that the bulk density decreases with decreasing particle size is typical for recycling building materials. The reason is the enrichment of particles with a low density and therefore a low strength in the fine fractions.

Table 3: Physical properties of masonry recycling material
(26 samples of 7 recycling plants)

Absolute density [kg/dm³]	2.65...	2.75
Bulk density [kg/dm³]	1.53...	2.10
Unit weight [kg/dm³]	0.9...	1.35
Water absorption [% by mass]	7.5...	19.4
Shape	shippings of brick partly flat, long; other constituents cubic	

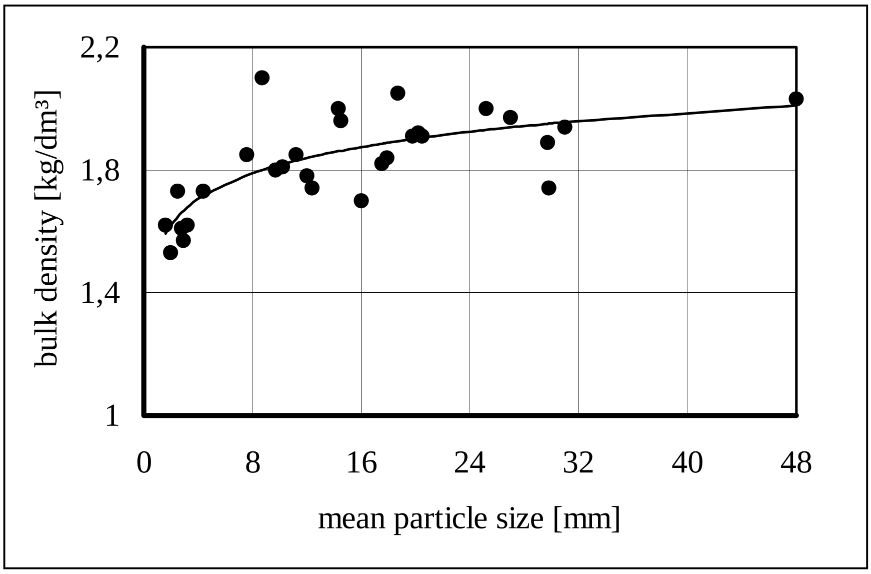

Figure 1: Bulk density of masonry recycling material as function of the mean particle size

The range of variation of the particle size distribution of two recycling building materials produced from masonry debris is shown in figure 2. From that one may conclude that the comminution especially by an impact crusher results in a high portion of sand. Nearly one third of the recycling material 0-56 mm is finer than 4 mm.

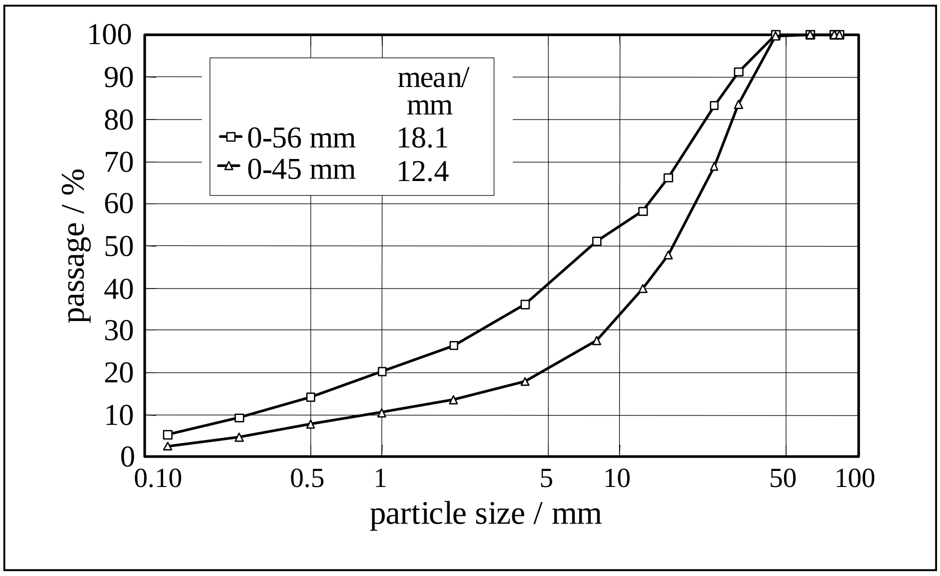

Figure 2: Particle size distribution of two masonry recycling materials from different recycling plants

REUSE OF MASONRY RECYCLING MATERIAL – STATE-OF-THE-ART

The application of masonry recycling material occurs at present predominantly in unbound systems like embankments, fills, subgrade improvements (figure 3). High-grade fields of application arise only if the material has a content of clay brick higher than 80 % by mass and if it is screened in fractions. The required high brick content can be realized only by a selective demolition, a pre-separation or if the material comes from the re-constructions of roofs.

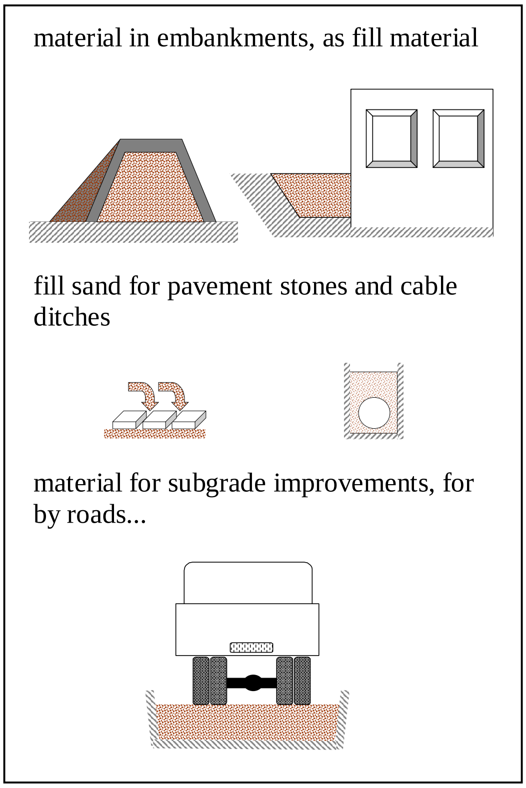

Figure 3: Examples for the application of masonry CDW in unbound systems

Two often described fields of application of brick recycling material are sand for tennis courts and chippings for roof gardens.

Sand < 5 mm that is produced either of pure clay brick debris of brick plants or of mixtures of unused and used debris can be used for construction of tennis courts or sport grounds (figure 4). The layers at the bottom of such a construction act as drain layer and as load-bearing layer respectively. The top layer acts as wearing layer. It consists of brick sand 0-1, 0-2 and 0-4 mm.

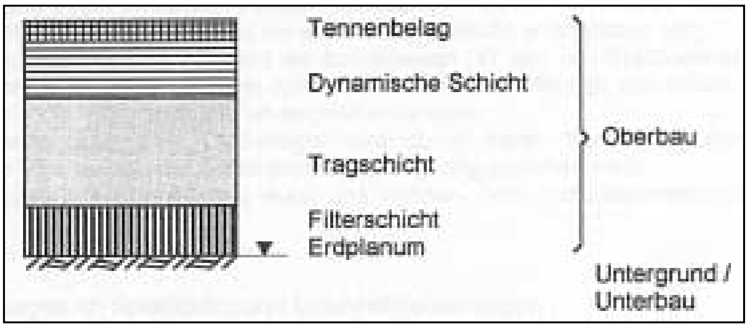

Figure 4: Schematic view of the layers of a tennis court [1]

Coarse aggregates with portions of clay brick and tile > 80 % by mass can be used as component in substrate of roof gardens [2,3,4]. Minor components like pumice, residues of concrete and mortar, rock and aerated concrete do not affect the quality. Iron and other metals shall not be in the material. Properties like the very splintery grain size or the high water absorption which are undesirable in most fields of application are wanted in the material of roof gardens because these properties improve the shearing strength and the storage of nutrients.

In dependence on the planned kind of plants and the roof pitch designs with one or more layers can be realized. With regard to the height of the plants two types of roof gardens can be distinguished (figure 5):

- extensive roof gardens with a carpet of plants of small growth (height < 50 cm) and a low effort for maintenance
- intensive roof gardens with plants up to 10 m height (herbaceous plants, bushes and trees) that need a multilayer structure and a periodical maintenance.

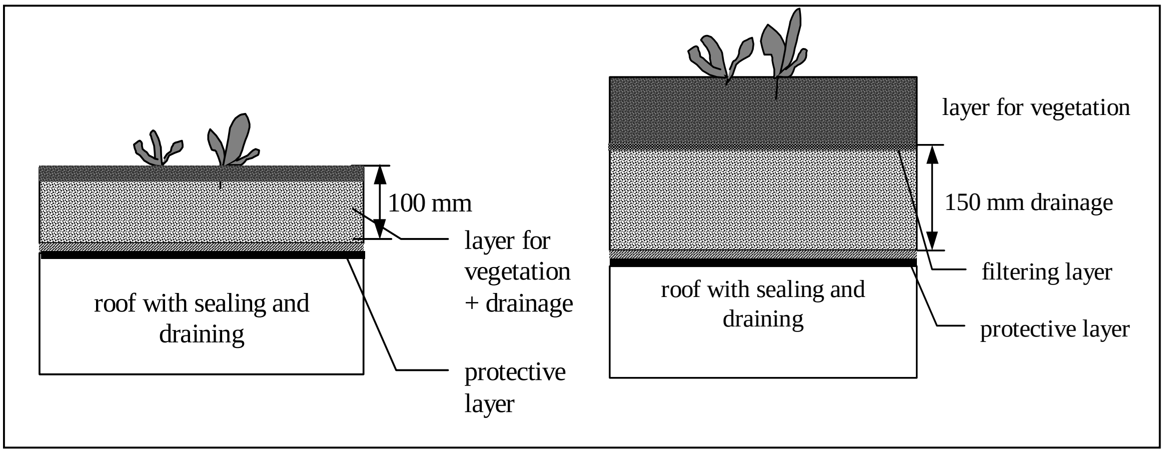

Figure 5: Schematic view of different constructions suitable for an extensive planting

Brick chippings can be used both as drain layer or as constituent of the vegetation layer In the drain layer material without fine particles is required for instance the fraction 4-16 mm to ensure the needed high water permeability. In the vegetation layer material with a broad particle size distribution can be used (figure 6). Besides this material is mixed with compost as nutrient source.

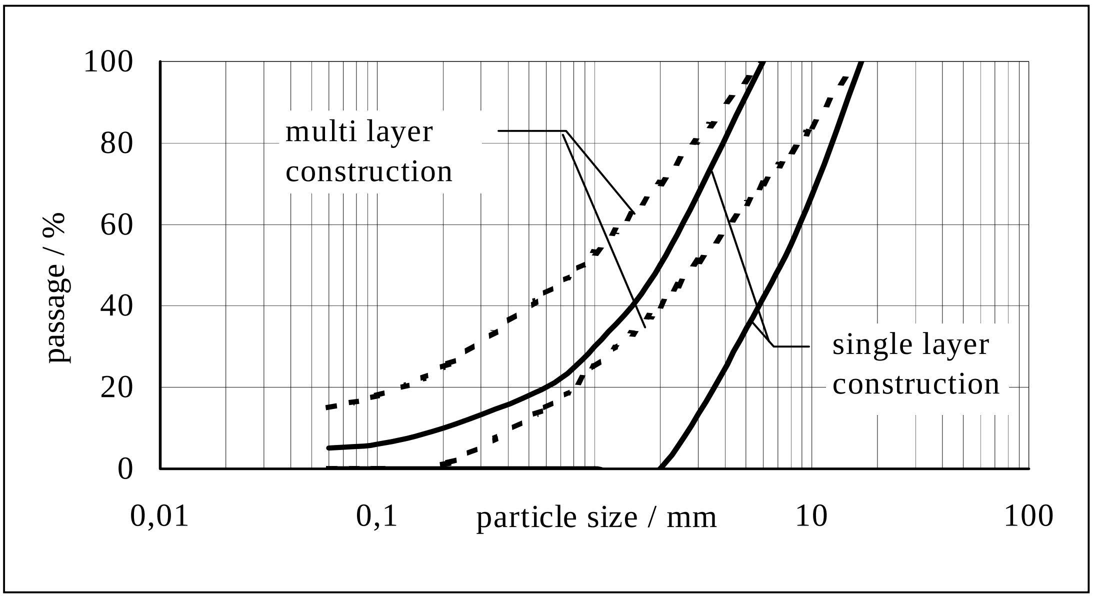

Figure 6: Ranges of particle size distribution of material in the vegetation layer [3]

The application of masonry recycling material in cement bound systems is subject of several patents and papers in the literature [5]. It is proposed to use brick chippings as lightweight aggregate or as aggregate for slabs used for sidewalks and terraces. Another source describes the use of the fractions 0.35-2 mm, 2-8 mm and 3-16 mm or 8-16 mm of crushed brick as aggregate for molded bodies or coverings with polished surfaces. This new material shall be a further development of Roman Concrete. It shall show the constructional advantages of bricks with regard to the shape, the density and the strength. The material is multi-purpose for instance as slab for floors, as masonry block, as hollow block filled with thermal insulation or sound insulation.

In practice there are only a few examples for the production of concrete from aggregates that contain a high amount of brick. One of them is the so called „Storage block“. It consists of brick chippings with a portion of brick > 80 % by mass, expanded clay, cement and water [6].

A comprehensive overview about the possibilities of reuse of the different fractions of masonry or brick material is shown in table 4. In the light gray fields applications are summarized that are already used in practice or described in the literature. In the white fields research projects are listed. These projects deal with the design of products from the fine fraction as well as from the coarse fraction. For both fractions there are not enough possibilities of high-grade application at present. Therefore the material is often used for landfilling or it is dumped.

Table 4: Fields of application of masonry CDW in dependence of the particles size

<table>
<tr><th></th><th colspan="4">Kinds of material with regard to the particle size</th></tr>
<tr><th>Variants of reuse</th><th>Meal</th><th>Sand</th><th>Coarse aggregates 4-16 mm</th><th>Coarse aggregates >16 mm</th></tr>
<tr><td rowspan="3">Technically applied or from literature</td><td colspan="2">– Material for tennis courts, sport grounds
– Sand for pavement works</td><td></td><td></td></tr>
<tr><td></td><td colspan="2">– Material for roof gardens</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">– Aggregate for concrete
– Polished slabs and blocks</td></tr>
<tr><td>Research projects in Weimar</td><td>– Raw material for lightweight aggregates
– Raw material for mineral fibers
– Mineral admixture for concrete</td><td>– Admixture for mortars</td><td colspan="2">– Ornamental gravel</td></tr>
</table>

NEW PRODUCTS FROM MASONRY RECYCLING MATERIAL

With regard to the meal and the sand of masonry CDW promising variants for utilization arise from the four research projects:

- Manufacture of lightweight aggregates from meals of masonry CDW and aerated concrete [7].
  The sand fractions of masonry CDW and aerated concrete are separately ground to particle sizes < 100 µm, mixed and then granulated by adding an expanding agent. The green granules are stabilized by burning in a rotary kiln at temperatures of about 1200 °C. The properties of the burnt granules are comparable with the properties of well-established lightweight aggregates like expanded clay.
- Utilization of masonry CDW as raw material component for the production of mineral insulation material [8].
  Mixtures of pure brick and concrete show a melting behavior similar to that of the raw materials of rock wool. Masonry CDW presents a mixture of both materials and could be therefore used as raw material component of rock wool or other insulation materials.
- Utilization of ground masonry sand with particle sizes < 100 µm as mineral admixture in concrete [9].
  Tests in a BOND mill and in a semitechnical scale show that the grindability of masonry CDW is in the same order like the grindability of lime stone and clear better than the grindability of granulated blast furnace slag. Mortars manufactured of blended binders of 20 % masonry meal and 80 % Portland cement have the same or an improved workability

like mortars of pure PC. The strength development of the mortars from the blended cements do not achieve that of PC mortars. But it exceed the strength development of mortars produced of cement with 20 % inert material.

- Utilization of masonry sand as aggregate in mortars [10].
  The substitution of the aggregates in commercial mortars by sand from masonry CDW results in a loss of strength, if more than 50 % is replaced. A replacement up to 30 % shows no effect. If only the fraction 2-4 mm is substituted then a higher strength after 28 days is obtained.

With regard to the coarse fraction of masonry CDW a new idea for application might be the production of ornamental gravel. This gravel might be used not only as drain and fill material but also as eyecatcher in gardens or landscape gardens because of its nice aesthetic appearance.

The idea can be realized by a mechanical processing of crushed masonry CDW that results in a wear of the grains preferably at the edges. In a first series of laboratory tests the following methods for processing were checked [11]:

- Treatment in a vibration mill – dry with sand as abrasive and wet without abrasive
- Treatment in Los Angeles drum

The best results with regard to the modification of particle shape were obtained when the grains were treated in the Los Angeles drum. Therefore the experiments were continued in a semitechnical scale. For this the material that came from a recycling plant was stressed in a ball mill with a diameter of 1 m and a length of 0.7 m. The mill was operated without balls. The filling level of the material was 30, 40 and 50 %. The time of treatment was 15, 31 und 47 minutes. That is equivalent to 500, 1000 and 1500 revolutions.

Figure 7 shows the scheme of the experiments. The material was crushed and fed into the mill. At a sample of crushed material the portion < 8 mm and the shape of the grains was determined as starting point.

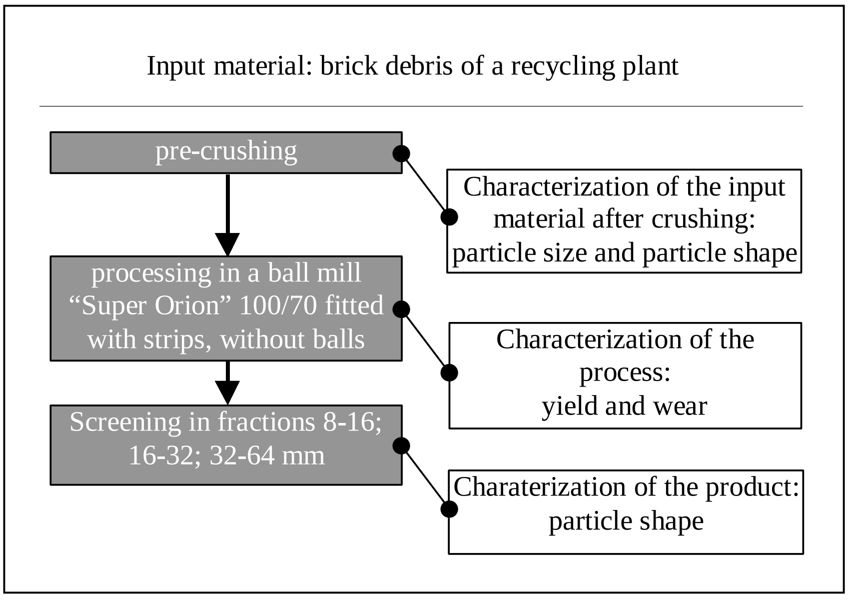

Figure 7: Scheme of the experiments on the improvement of particle shape of brick debris

After the processing the abraded material was determined as increase of the portion < 8 mm compared with the amount at the beginning. From the wear the yield of product can be calculated.

The shape of the grains was measured with the particle shape caliper gauge. A more detailed description of this feature is possible by the parameter "sphericity" measured with a particle analyzer supplied with a line camera that scans the particles. With the help of an image analyzing program informations about the particle size distribution and the particle size can be calculated. The sphericity follows from the area A and the circumference U of the particle projection (equation 1)

$$SPHT = \frac{2 \cdot \sqrt{\pi \cdot A}}{U} \qquad (1)$$

A circle has a sphericity of 1. All other shapes have values below 1. For example the sphericity for an ellipsis with D:d = 2:1 is 0.916. It decreases to 0.851 if the diameter ratio is changed to D:d = 2.5:1.

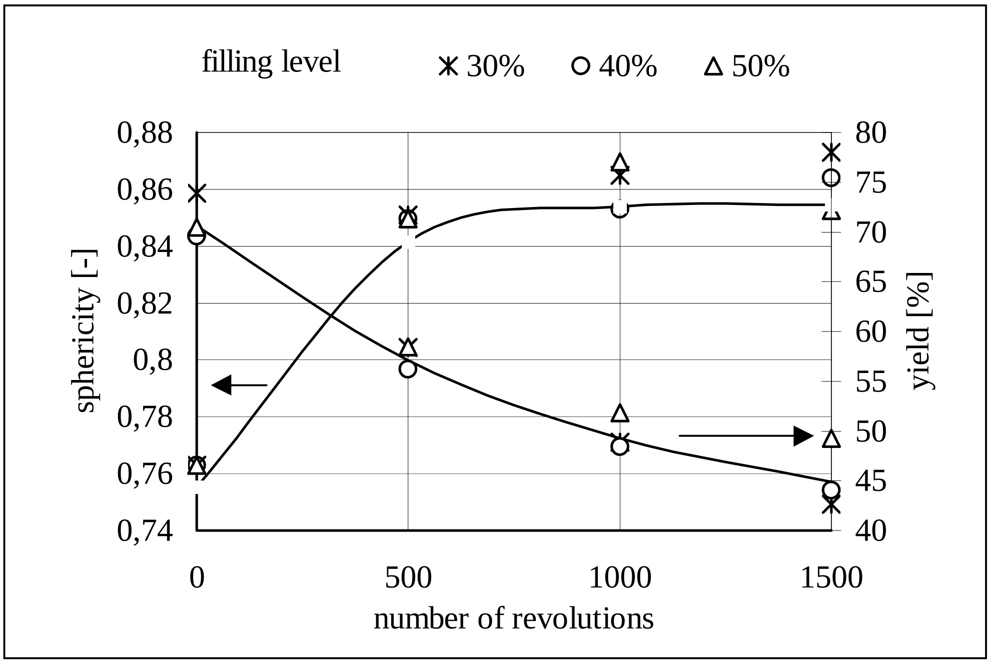

Figure 8: Sphericity of the fraction 16-32 mm and yield as function of the number of revolutions of the mill

In figure 8 the results of the test on the shape modification are summarized. It shows that the sphericity of the particles is improved by the treatment. The clearest effects occur within the first 30 minutes of the treatment. The achieved values of sphericity are higher than 0.85. Compared with the values for defined geometrical bodies the treated brick particles have shapes in order of ellipses with D:d = 2.5:1. The improvement of the shape is clear visible also at the images of the grains (figure 9).

From figure 8 follows additionally that the portion of fine material caused by the abrasion is proportional to the obtained changes in the sphericity of the grains. After 500 revolutions (31 Min) the portion of fine material amounts 40 % by mass. Further treatment in the mill results in an increase to more than 50 % by mass after 1500 revolutions. The yield amounts therefore only 45 %.

The tests show furthermore that the influence of the filling level is negligible in the tested range between 30 and 50 %. The results of the tests with coarser and finer fractions show the same tendencies with regard to the sphercity and the portion of abraded material. With regard to the appearance the coarser fractions seem to show certain advantages (figure 9).

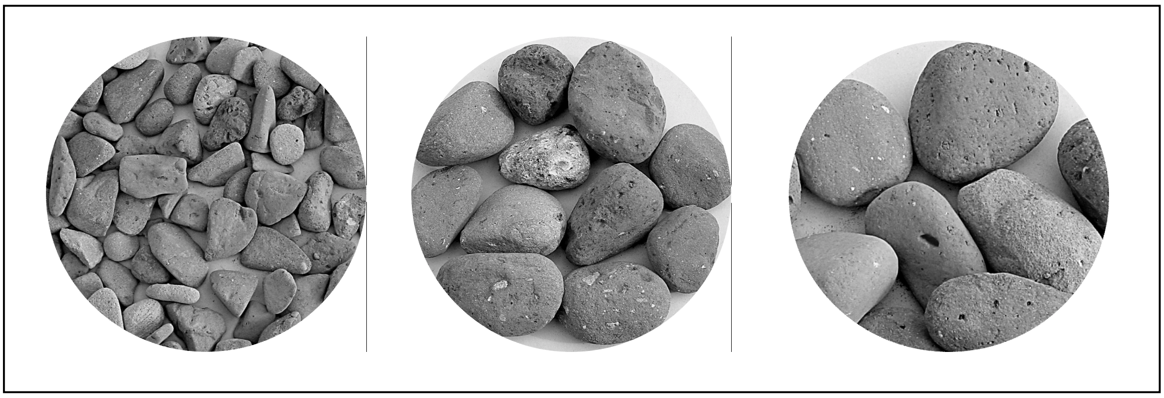

Figure 9: Appearance of ornamental gravel of the fractions 8-16, 16-32 and 32-63 mm

The treatment of the grains in the mill results in additional positive effects. All residues of mortars and plasters are removed as a result of the shear stress acting during the autogenous grinding. The ornamental gravel consists only of clean, homogeneous brick material. The differences in color result merely from the different kinds of brick in the debris. Besides by the selective comminution all weak, high-porous constituents are concentrated in the abraded material. This may be the reason of good frost resistance of the material (table 5).

Table 5 : Physical properties of ornamental gravel

Bulk density [g/cm³]	1.77		
Water absorption [%]	14.2		
Portion of fine particles after 10 freezing and thawing cycle [% by mass]	8-16 mm	16-32 mm	32-63 mm
	2.62	2.20	1.02

Target of further research projects is the design of a technology for the manufacture of ornamental gravel. Two variants are possible:

- Common treatment of all fractions of masonry debris with exception of the fraction 0/8 mm followed by a screening in the wanted fractions. At the same time the separation of the abraded material can take place.

- Separate treatment of the fractions. Only the abraded material must be screened after the treatment.

Besides in further works the properties of the ornamental gravel must be determined both in greater detail and in larger scale. With regard to the utilization of the abraded material falling back on the described proposals is possible considering the specific properties of this material.

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RESOURCE-CONSTRAINT PROJECT SCHEDULING FOR DECONSTRUCTION PROJECTS

Frank Schultmann and Otto Rentz
French-German Institute for Environmental Research (DFIU), University of Karlsruhe, Germany

SUMMARY

In recent years there have been various attempts to set up advanced recycling technologies for demolition waste. As further improvements in processing are technically limited, future efforts will have to concentrate on improving the methods of deconstruction. The conventional demolition of buildings, carried out for instance by pulling-down a building with a backhoe, often leads to the mixing of various materials and contamination of non-hazardous components. Hence, advanced approaches aim at deconstruction or selective dismantling of buildings, where a building is disassembled into various parts. Although the idea of dismantling buildings evolved fast in the construction industry, only very few approaches for planning and optimizing dismantling projects have been available until now. A promising methodology to improve the management of dismantling and recycling is the use of resource-constrained project scheduling, which has gained particular attraction in make-to-order production.

The purpose of this paper is to investigate how sophisticated methods of project scheduling can be applied to plan and optimize the environment-friendly dismantling and recycling of buildings. The concept is based on material-flow management, which ensures that certain environmental requirements are met. Using the results of material-flow management resource-constrained project scheduling models can be derived in order to optimize deconstrucion processes on the site. The approach is applied to the deconstruction of domestic buildings and the results show that tremendous improvements in the management of deconstruction projects can be realised.

KEYWORDS: Deconstruction; Optimization; Project planning models; Scheduling

INTRODUCTION

The extraction of raw materials as well as the emissions of waste exert heavy pressure on the environment. Due to stricter environmental regulations, environment-friendly production and recycling management are becoming an increasingly important goal in order to reduce adverse environmental impacts from industrial production systems. The minimization and recycling of residues and waste have attracted growing attention in industry in the last decade. The construction industry plays a major role in this context. In recent years there have been various attempts to set up advanced recycling technologies for demolition waste. As further improvements in processing are technically limited, future efforts will have to concentrate on improving the methods of demolition. The conventional demolition of buildings, carried out for instance by pulling-down a building with a backhoe, often leads to the mixing of various materials and contamination of non hazardous components. Hence, advanced approaches aim at deconstruction or selective dismantling of buildings, where a building is disassembled into various parts. Dismantling instead of demolition helps the separation of different building materials and the reuse of recycled materials in superior utilization options. Although the idea of dismantling buildings evolved fast in the construction industry, only very few approaches for planning and optimizing dismantling projects have been available until now. A promising methodology to improve the management of dismantling and recycling is the use of resource-constrained project scheduling, which has especially gained particular attraction in make-to-order production. Resource-constrained project scheduling problems take into account that resources are limited. Jobs, also known as activities, can be carried out in different ways, that is, using different techniques and different resources, respectively.

The purpose of this paper is to present an approach on how sophisticated methods of project scheduling can be applied to plan the environment-friendly dismantling and recycling of buildings. The concept consists both of material-flow management, which ensures that certain environmental requirements are met, and of resource-constrained project scheduling, which aims at optimizing processes on the construction site. The approach is applied to the dismantling of domestic buildings and the results are compared with figures gained in research projects carried out in practice.

The paper is structured as follows. In section 2 we introduce the problem of planning the deconstruction of buildings according to manufacturing system typology. Section 3 is devoted to a material-flow analysis which serves as a framework for project scheduling that is later covered in section 4. In Section 5 we outline some results. Finally, in section 6 conclusions are drawn.

A TYPOLOGY FOR THE PLANNING OF DISASSEMBLING ON DECONSTRUCTION SITES

According to the common manufacturing typology the dismantling and recycling of buildings (as well as the construction of buildings) represents a make-to-order production. A production is classified as make-to-order if all products are manufactured only in response to customer orders. That means no inventories are built up for future sales. Make-to-order production can be found for instance in single-item production, in the construction industry, in shipbuilding or the construction of prototypes. Considering the internal structure of the manufacturing system, the dismantling and recycling of buildings is regarded as on-site manufacturing due to the fact that all resources needed for dismantling have to be transferred to the production site, i.e. the construction site, instead of vice versa. Usually, on-site manufacturing requires more planning than other types, like job shop or flow shop manufacturing [1]. While the erection of buildings often works more or less like a hybrid structure using certain prefabricated components (produced in flow shop or job shop structures) that are finally assembled on the construction site (on-site manufacture), the demolition or dismantling of buildings at the end of their life time can only take place on the deconstruction site.

Concepts for production planning in manufacturing are often based on the well-known Materials Requirements Planning (MRP). MRP consists mainly of the four steps:

(1) determination of gross requirements of final products, subassemblies and components, usually carried out by bill of materials explosion,
(2) determination of net requirements, based on the gross requirements, scheduled receipts and inventory,
(3) lot sizing and
(4) time phasing.

MRP analysis provides order releases for final products as well as for subassemblies and components which have to be processed on a given set of machines. In contrast to assemble-to-order-systems, in make-to-order systems even subassemblies and components are manufactured only if they are required for the production of a customer-ordered final product. Therefore steps 2 and 3 are skipped in make-to-order-production. One disadvantage of this approach is that resource capacities are not explicitly considered in MRP. An implicit assumption of the temporal analysis in MRP (done in step 4) is the availability of unlimited capacity of resources needed for the execution of the activities. However, in reality resources are normally scarce. As a consequence of the limitation of resource availability, usually revisions in the scheduled delivery times are often necessary, often resulting in large delays in the delivery of the ordered products. Recently, new capacity-oriented MRP concepts have been suggested to overcome this drawback [2].

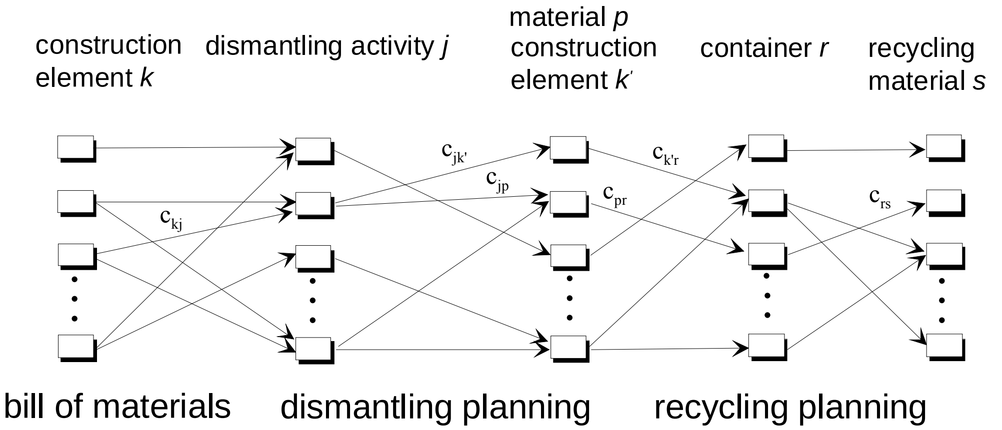
Apart from manufacturing system typology, production at the beginning of a products life time, as well as disassembling at its end is determined by the characteristics of the product. Like consumer products, such as cars, buildings have finite lifetimes, however the lifetime of a building usually ranges between 50 and 150 years. Furthermore, buildings can be characterized as meta-products, in other words as a collection of multiple products all with their own characteristics, combined in unique and complex manners [3]. Both the attribute meta-product with unique characteristics and the long lifetime impose severe problems both for construction and for dismantling planning. The unique combination of products, also called construction elements of a building, requires an approach that considers each building separately when dismantling and recycling are planned. This uniqueness is one of the motivations for the approaches considered in section 4. A consequence of the long lifetime of buildings is that due to several modifications or renovation measures often very few reliable data on the composition of the building are available. The material-flow analysis proposed in the next section will take this fact into account.

For make-to-order production the planning of the entire production can be modeled using project scheduling models. Following this approach the separation of material and capacity requirements planning can be avoided by an integrated time and capacity planning which is done in algorithms for resource-constrained scheduling and will be discussed in section 4. If environmental requirements have to be considered, the planning of dismantling and recycling has to include material-flow management. Thus, before detailed planning takes place, an analysis of mass and flows has to be made. In the next section we present a material-flow analysis for dismantling and recycling buildings that also serves as a prerequisite for the project scheduling presented in section 4.

MATERIAL FLOW MANAGEMENT ON DECONSTRUCTION SITES

As material flow analysis is an arduous but necessary task when environmental tasks are of concerned, several studies have been carried out covering various industrial sectors. A complete review of the studies in this field is far beyond the scope of this work. In this chapter, an approach is presented that helps to reveal, to control and to navigate the material flows on construction sites and in recycling facilities.

Problems with material flow management in the construction industry mainly arise because of the large time-lag between construction and end-of-life of buildings. Due to the mostly unknown composition of buildings at the end of their life cycle, the first step for dismantling and recycling planning is a proper pre-demolition survey, also called a building audit. The building audit mainly aims at identifying and quantifying materials in order to give decision support as to how the dismantling has to be carried out. Based on the documents of the building (e.g. construction plans, descriptions, history) detailed data on the composition of the building have to be collected and analyzed. During this audit indications of substances contained in the building, which may influence the quality of the materials must be determined. The audit results in a bill of materials which contains details of the construction elements and the corresponding building materials [4]. In order to model the relevant material flows on deconstruction sites, material flow graphs as shown in Figure 1 can be derived. The sources of this graph represent the construction materials *k*. By the application of a set of dismantling activities *j*, the corresponding building is dismantled into various parts. Depending on the stage of dismantling, the dismantled components can be either a single construction element *k'* or a mix of various building materials *p*. In order to avoid a mix of toxic materials and non toxic materials the environmental compatibility of various components has to be determined [5].



legend:

c_{kj}: number of construction element *k* concerning dismantling activity *j*
c_{jp}: mass of material *p*, resulting from carrying out dismantling activity *j*
$c_{jk'}$: number of construction elements *k'* dismantled as whole elements by dismantling activity *j*
c_{pr}: number of container type *r*, used for material *p*
$c_{k'r}$: number of container type *r*, used for construction element *k'*
c_{rs}: coordination of container type *r* to recycling material *s*, ($c_{rs}=1\ \forall$ r,s, if (r,s)$\in$ set of arcs)

Figure 1 Material flow graph for dismantling and recycling of buildings

It should be observed that both, plain and mixed grades of building waste, could contain pollutants, which could harm the environment, especially by leaching, during storage or re-use. Since generally only a very small part of the building materials contains pollutants, it is essential to identify these before dismantling starts, in order to avoid mixing a small amount of toxic materials with a large amount of non toxic materials. Relevant shares of pollutants are contained both in building materials and surfaces. Pollutants are contained in construction materials due to their natural material composition, or were artificially added during manufacture, for example in the form of additives. Furthermore, a great share of pollutants is caused by surface area treatment. Based on the bill of materials the content of pollutants can be represented by a so-called pollutant vector for each material *p*: $\upsilon_p^T = (\upsilon_{1p},...,\upsilon_{ip},...,\upsilon_{np})$ and for each surface *l*: $\upsilon_l^T = (\upsilon_{1l},...,\upsilon_{il},...,\upsilon_{nl})$. Let $SP = \{ \upsilon_p \mid p = 1,...,P \}$ denote the set of pollutant vectors for materials and $\mathrm{SL} = \{\upsilon_l \mid l = 1,...,L\}$ the set of pollutant vectors for surfaces. The content of pollutants in building materials can then be described by the matrix $SM = (\upsilon_{ip'})_{\substack{i=1,...,n \\ p'=1,...,P+L}}$ [6]. Based on the bill of materials and the information about pollutants, material and pollutant balances for different dismantling steps can be established. For details on the allocation procedure we refer to [6]. Figure 2 illustrates a simplified structure as to how the composition of demolition waste can be influenced by performing seven alternative ways of dismantling a domestic building (alternative I represents a demolition of the building without any dismantling, alternative II reflects decommissioning followed by demolition etc.).

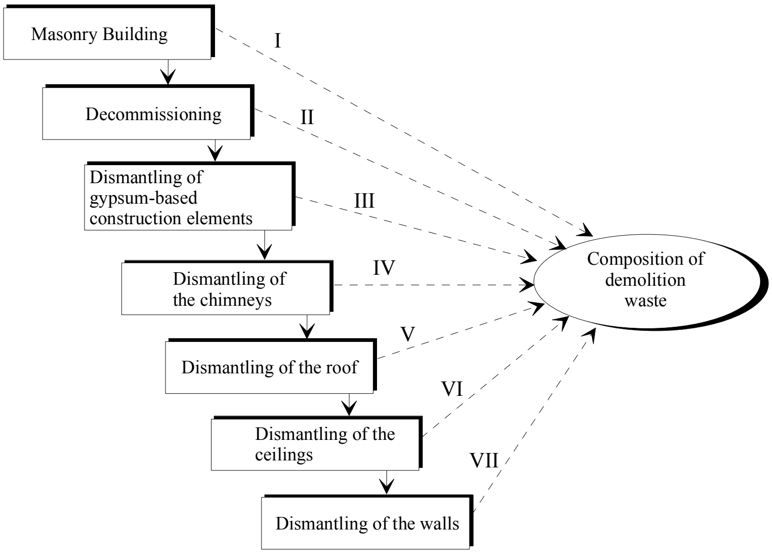


Figure 2 Dismantling alternatives for a domestic building (simplified)

Table 1 displays the building materials and pollutants, remaining after each alternative [7].

Table 1 Composition of demolition waste resulting from the dismantling of a masonry building

					Alternative			
		I	II	III	IV	V	VI	VII
No.	Building material				Amount [kg]			
	Granite	550	0	0	0	0	0	0
1140	Sandstone	957525	957525	957525	957525	957525	957525	0
1210	Sand	16959	16959	16959	16959	16959	0	0
1610	Slag	16959	16959	16959	16959	16959	0	0
2110	Lime mortar	207799	207799	207799	205023	205023	205023	0
2130	Cememt mortar	523	523	523	523	523	523	0
2210	Gypsum	55041	55041	0	0	0	0	0
2710	Bond-beam-block	8843	8843	8843	8843	8843	8843	0
3300	Solid brick	206339	206339	206339	185761	185761	185761	0
3600	Roofing tile	21893	21893	21893	21893	0	0	0
3800	Ceramics	2296	2020	2020	2020	2020	310	0
4100	Sheet glas	504	0	0	0	0	0	0
5100	Cast iron	1423	0	0	0	0	0	0
5200	Steel	1032	0	0	0	0	0	0
5600	Zinc	261	0	0	0	0	0	0
6300	Spruce	78328	77587	75585	75585	60953	2808	0
6310	Spruce treated	9531	2238	2238	2238	2238	2238	0
6730	Cardboard	1021	648	648	648	0	0	0
7460	Polivinyl chloride	1222	0	0	0	0	0	0
7730	Wallpaper	642	642	32	32	0	0	0
8200	Roofing felt	400	400	400	400	400	0	0
10000	Electrical installations	121	0	0	0	0	0	0
10100	Cable	77	0	0	0	0	0	0
	Total	1589288	1575416	1517763	1494409	1457203	1363030	0

	Pollutant				Amount [kg]			
	Chromium (Cr)	52.85	52.57	51.27	50.16	49.06	48.68	0
	Copper (Cu)	107.61	35.39	35.05	34.96	34.92	33.54	0
	Nickel (Ni)	18.11	17.92	17.68	17.04	16.38	15.94	0
	Lead (Pb)	33.48	29.57	27.61	25.13	23.89	22.29	0
	Zinc (Zn)	120.00	88.15	87.30	82.13	77.66	76.34	0
	Cadmium (Cd)	1.45	0.33	0.29	0.26	0.24	0.20	0
	Polycyclic aromatic hydrocarbons (PAH)	1.65	1.65	1.65	0.79	0.79	0.01	0
	Hydrocarbons (CH_x)	286.52	286.52	286.52	217.93	217.93	0	0

Considering the example above, it can for instance be seen that with demolition of the building without any dismantling (alternative I) significant contents of heavy metals and organic compounds are found in the building waste which will cause severe problems in recycling. The reduction of the amount of heavy metals (e.g. cadmium or zinc) in the remaining building waste requires at least decommissioning (alternative II), whereas the content of polycyclic aromatic hydrocarbons (mainly found in the chimneys) can only be significantly reduced after a dismantling of the chimneys (alternative IV).

Material and pollutant balances may serve as a framework for the necessary dismantling work to be carried out in order to guarantee a certain quality level of recycled materials. Using these results, detailed planning of dismantling can start. However, detailed planning has to include not only material-flow aspects but also the necessary technology and resources for the dismantling work. The next section will concentrate on how this can be done using project scheduling.

A SCHEDULING MODEL FOR DECONSTRUCTION SITE MANAGEMENT

Taking into account the basic ideas of material-flow management as discussed in the section above, the detailed planning of dismantling can be supported by resource-constrained project scheduling methods which have gained attention in make-to-order production. Several researchers have concentrated on modeling and algorithms for resource-constrained project scheduling. For a survey on modeling concepts as well as scheduling algorithms for resource-constrained project scheduling we refer to [8], [9], [19], or [11]. In this section we outline the ideas on how to apply resource-constrained project scheduling for our dismantling problem. First we explain the structure of our project networks and the modeling of different dismantling techniques. After outlining the critical path analysis, we finally formulate the well-known multi-mode resource-constrained project scheduling problem and conclude this section with a short outlook on the solution procedure.

Construction of project networks

Bearing in mind the results of the material-flow analysis, dismantling planning aims first at setting up a technological and environmental oriented order of the dismantling activities to be carried out. The technological precedence relations and in certain cases also certain environmental precedence relations of the dismantling process can be illustrated by a topologically ordered activity-on-node network (AON), where the nodes represent the dismantling activities j $(j=1,...,J)$ and the arcs the precedence relations between these activities. Regarding the model that will be formulated later, the network contains one unique source ($j=1$) and one unique sink ($j=J$). This can always be guaranteed by introducing a dummy source and a dummy sink, respectively. Figure 3 gives an example of a topologically ordered dismantling-network for a three storied residential building with 28 dismantling activities. This network was the basis for a pilot project on selective dismantling carried out in practice [12].

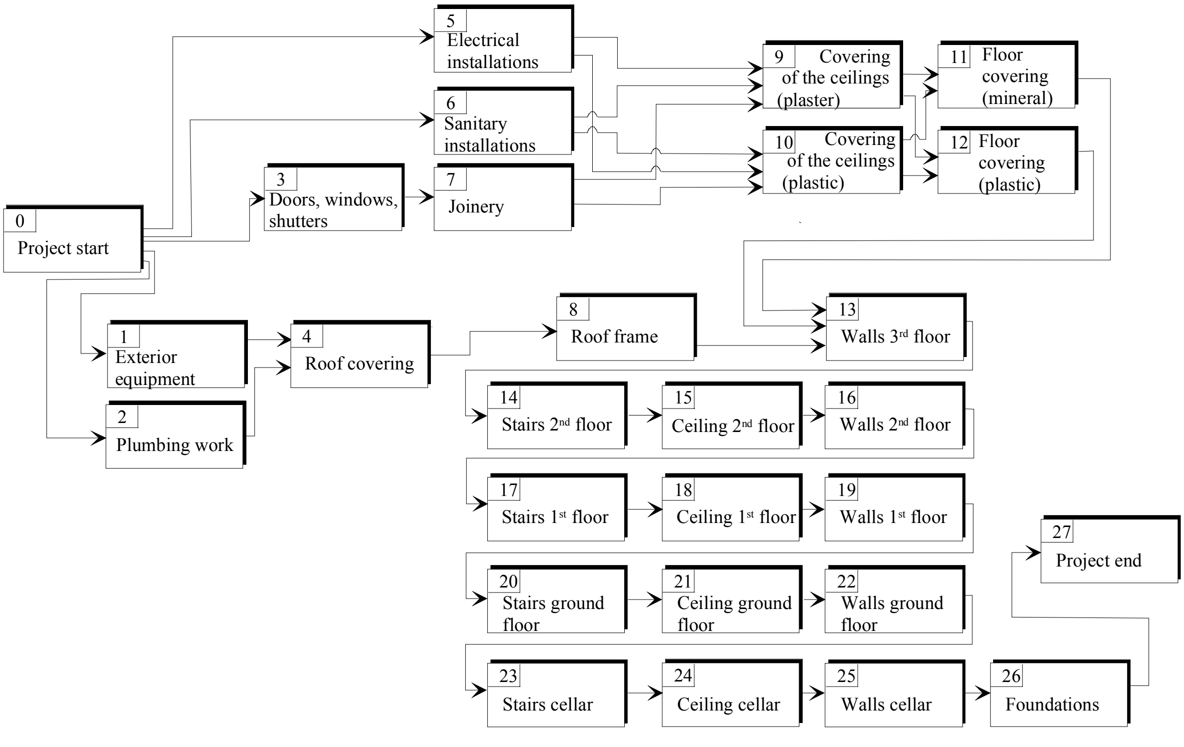
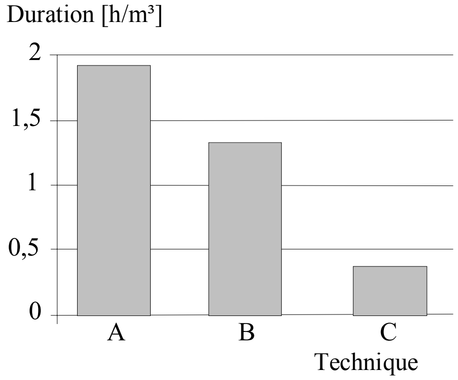


Figure 3 Dismantling-network for a residential building

Topological ordering guarantees that every activity in the set of all immediate predecessor-activities P_j is labeled lower than *j*. Different networks may have to be defined accordingly, including the type of the building under consideration (for instance industrial building or residential building), the dismantling techniques available, or the objective of the dismantling effort. Also, different environmental constraints, like obligatory levels of separation (i.e. materials containing asbestos) can lead to different networks. It is possible to distinguish different networks according to the number of activities and the precedence relations. Considering these criteria, it is essential that networks with different numbers of dismantling activities and/or different precedence relations between (some) of the activities cannot be incorporated in the model we use later.

Modeling of different techniques

After determining the precedence relations, the dismantling activities have to be specified in detail. This comprises the determination of the resources necessary as well as the duration of the activities. Usually each activity can be processed in different ways e.g. using different dismantling techniques that can be expressed by different resources. For instance, as shown in Figure 4, the disassembling of outer walls can be carried out by dismantling, using pneumatic hammers, by a grabbing bucket, or by demolishing the wall with a hydraulic excavator, each resulting in different processing times. Several alternatives, in which a job can be carried out, can be modeled by introducing different modes m $(m = 1,...,M_j)$. Performing activity *j* in mode *m* has a nonpreemtable duration of d_{jm} periods.



	Technique	Resource	Mode
A	Dismantling	Pneumatic hammer	1
B	Grabbing	Grabbing bucket	2
C	Demolition	Hydraulic excavator	3

Figure 4 Dismantling times for walls resulting from different dismantling techniques

Changing the number of dismantling activities in a project or altering the precedence relations leads to different networks, which can not be incorporated in a single model. In contrast to this, altering modes, as considering the activity duration as a (discrete) function of the resources and/or amounts of the resources allocated, and keeping precedence relations and the number of activities constant, could be modeled in an integrated model.

Resource Categories

In order to formulate the scheduling model, the resources needed have to be classified. Associated with activity *j* in mode *m* is the usage of renewable resources and a consumption of nonrenewable resources [13], [14]. While renewable resources (e.g. machines, workers) are only constrained on a period basis (possibly varying from period to period), i.e. after an activity *j* is accomplished, the renewable resources used by *j* are available to process another activity. Nonrenewable resources (e.g. financial budget) are limited on the basis of the entire duration of the project. Consequently, the consumption of a nonrenewable resource by activity *j* reduces its availability for the rest of the project.

Model Formulation

In order to reduce the number of variables in the programming formulation, time windows with earliest (EF_j) and latest (LF_j) finishing times (or earliest and latest starting times ES_j, LS_j) for each dismantling activity *j* can be derived (neglecting resource constraints). This can be done by using the well known critical path analysis [14]. Critical path analysis requires an upper bound *T* for the makespan of the project. It should also be noted that the unique source $(j = 1)$ and the unique sink $(j = J)$ have only zero duration, zero resource usage and consumption, respectively.

Variables for resource usage and consumption as well as for constraints have to be introduced as follows:

q_{jmn}: capacity of nonrenewable resource *n*, consumed by dismantling activity *j* in mode *m* and

q_{jmr}: capacity of renewable resource *r*, used by dismantling activity *j* being performed in mode *m* for each period the activity is in process.

Q_{rt}: capacity of renewable resource *r*, $r \in R$, available in period *t* and

Q_n: total capacity of nonrenewable resource *n*, $n \in N$.

With reference to the resource-constrained project scheduling problem introduced by Pritsker *et al.* [15], scheduling on deconstruction sites can be formulated as a binary linear program with the decision variables x_{jmt} (dismantling activity *j* is performed in mode *m* and completed in period *t*).

Environmental constraints, such as different levels of sorting materials or certain recycling paths, are reflected by the project network, in the precedence relations as well as the configuration of activities. The planning model can then be outlined as follows:

Minimize

$$\Psi(x)=\sum_{m=1}^{M_J}\sum_{t=EF_J}^{LF_J} t\cdot x_{Jmt} \tag{1}$$

Subject to

$$\sum_{m=1}^{M_j}\sum_{t=EF_j}^{LF_j} x_{jmt}=1 \qquad j=1,\dots,J \tag{2}$$

$$\sum_{m=1}^{M_i}\sum_{t=EF_i}^{LF_i} t\cdot x_{imt} \le \sum_{m=1}^{M_j}\sum_{t=EF_j}^{LF_j}(t-d_{jm})\cdot x_{jmt} \qquad j=2,\dots,J,\ i\in P_j \tag{3}$$

$$\sum_{j=1}^{J}\sum_{m=1}^{M_j} q_{jmr}\sum_{\tau=t}^{t+d_{jm}-1} x_{jm\tau} \le Q_{rt} \qquad r\in R,\ t=1,\dots,T \tag{4}$$

$$\sum_{j=1}^{J}\sum_{m=1}^{M_j} q_{jmn}\sum_{\tau=EF_j}^{LF_j} x_{jm\tau} \le Q_n \qquad n\in N \tag{5}$$

$$x_{jmt}\in\{0,1\} \qquad j=1,\dots,J,\ m=1,\dots,M_j,\ t=EF_j,\dots,LF_j \tag{6}$$

The objective function (1) minimizes the completion time of the unique sink and therefore the makespan of the dismantling work. Several further criteria, like minimizing the average completion time, the average weighted tardiness of the activities, as well as minimizing the net present value or leveling of resources, might also be considered [16], [14] [8], [6]. But, since in this case study, minimizing the makespan is by far the most important objective of scheduling dismantling activities, we will omit the discussion of other objective functions. With constraints (2) it is ensured that each activity j is processed exactly in one mode and that one completion time is assigned. Constraints (3) ensure that dismantling precedence relations are respected. Constraints (4) takes into account that per period the capacity restrictions are met. Constraints (5) ensure a feasible schedule with respect to nonrenewable resources.

APPLICATION OF THE MODEL

Comparison of different deconstruction strategies

The purpose of the application of the model is to evaluate the improvement that could be achieved by project scheduling according to the model presented. In the following we will compare computational results for a domestic building with the results in practice (data in [12]). Considering both, the techniques of dismantling as well as the scope of the dismantling and recycling, we define three basically different dismantling scenarios which have been designed in cooperation with demolition companies. *Scenario 1* covers a dismantling approach that is similar to the one chosen in practice. In scenario 1, conventional, mainly manual dismantling techniques are used. This scenario represents more or less the state of the art. In *scenario 2* dismantling is carried out using partly automated devices like pneumatic hammers, mini excavators or high-pressure water jets. This scenario reflects the possibilities of improving the dismantling procedure by the use of sophisticated machines. Finally, *scenario 3* is strictly focused on separating and recycling as many materials as technically feasible according to the material-flow analysis.

First we compare scenario 1, 2 and 3 with the results obtained in practice, as shown in Figure 5 also called “present situation”. The detailed parameter settings can be found in [6]. Figure 6 displays the results when each of the three scenarios is scheduled separately together with a comparison of the dismantling in practice.

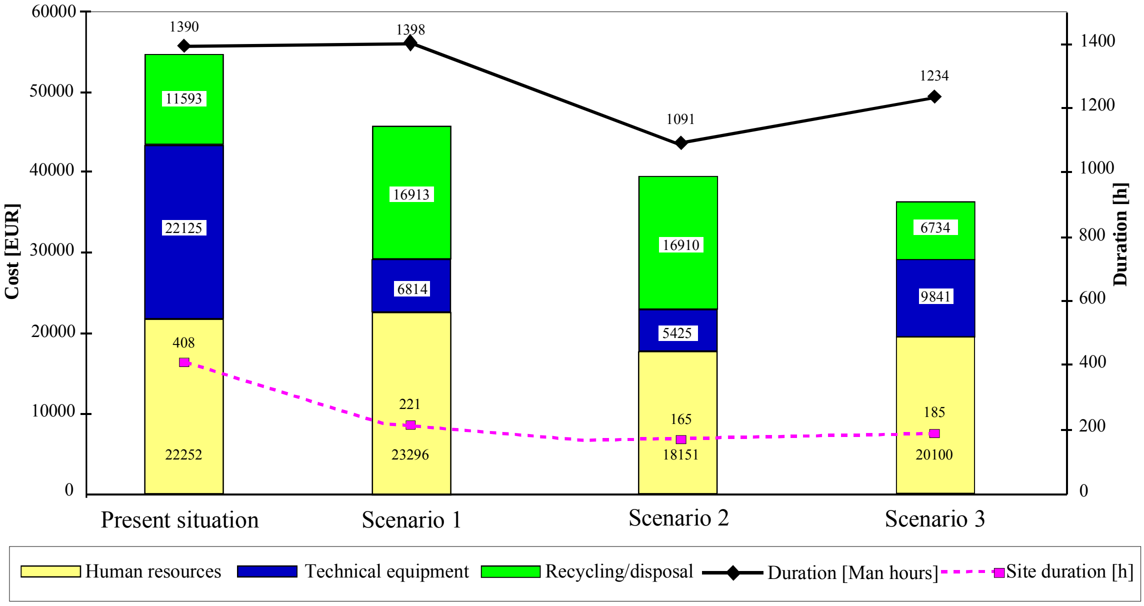


Figure 5 Cost and duration of different dismantling strategies for a residential building

As can be seen, computational results indicate that the site duration, i.e. the projects makespan, can be drastically reduced for all scenarios. Scenario 1, which considers nearly the same resource usage and constraints as in practice, shows an accelerated deconstruction speed. When performing scenario 1, the total dismantling time can be reduced from 408 to 221 hours if work is carried out simultaneously, wherever possible, i.e. according to the precedence relations given in the dismantling-network and respecting resource constraints. In coherence with the reduction of the duration, the cost for technical equipment decrease due to the fact that cost-intensive devices remain on the construction site only for very short periods. The selection of scenario 2 leads to a further reduction of the duration due to the possibilities of accelerating certain activities by the use of sophisticated machines. Compared with scenario 2, scenario 3 leads to a prolongation of the duration because additional activities are needed. Nevertheless, due to the higher quality of the materials resulting from dismantling, scenario 3 has the lowest total costs. Associated with the present situation as well as with scenarios 1 and 2 is a recycling rate of more than 95 %, i.e., a large proportion of the materials are not sent to the landfill. Scenario 3 guarantees a recycling rate of 98 %. Although an increased recycling rate of only 3 % is not very much, it should be noted, that this figure only counts for the portion of the materials recycled, whereas it does not say anything about the quality of the recycling. In fact, taking the material-flow approach, it can be shown that scenario 3 leads to a much higher portion of materials that can be reused for high grade applications [5].

Detailed Scheduling

One major advantage of the scheduling model presented is that the solution allows for detailed planning. In the following we present certain results in more detail.

Figure 6 gives an overview of the results of minimizing the project duration covering the complete time horizon. Here, scenarios 1 and 2 are combined, that is, scheduled simultaneously, and compared with the schedule for scenario 3 (note again that for simplification purposes we omit topologically ordering of the activities in scenario 3). Additionally, the corresponding costs for dismantling and recycling are listed. Again, it can be seen that an environmental oriented dismantling strategy, according to scenario 3, imposes a higher effort for the dismantling work. That is to say, two more activities (*j=28,29*) have to be carried out in order to guarantee prerequisites for the use of recycled building materials in high grade applications. Nevertheless, Figure 6 shows that an environmental oriented dismantling strategy, such as scenario 3, is not necessarily disadvantageous from an economic point of view, if disposal fees are significantly graded according to the degree of mixed materials. Although the removal of the gypsum-based plaster ($j = 28$) and the dismantling of the chimneys ($j = 29$) impose higher costs on the construction site, the remaining materials, covered by activities $j = 13,14,...,26$, show a lower content of pollutants, which finally results in lower recycling costs.

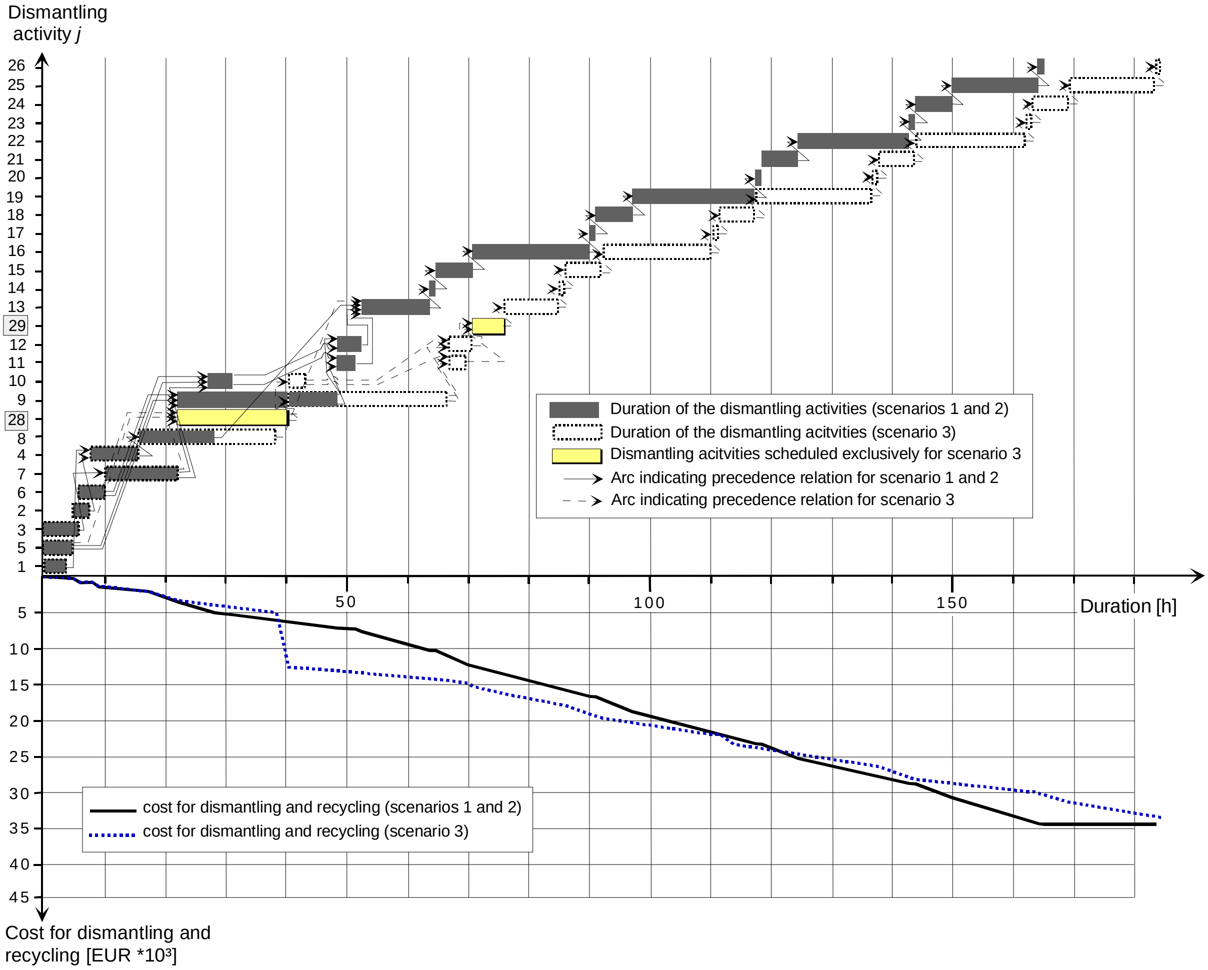


Figure 6 Schedule and project costs for the dismantling of a residential building

Logistic management

Other examples of scheduling concern logistics management on deconstruction sites. Detailed scheduling using our model presented above can help to find solutions for deconstruction in adverse circumstances such as limited net site area for machines or containers. This is often the case when construction sites in urban areas are affected. In our model this can be expressed by constraints (4). We will shortly give an example for container management:

Figure 7 illustrates an example for two schedules that were derived supposing that only a certain number of containers could be placed on the construction site. It can be seen that relaxing the constraints from six to eight containers per period leads to a different ordering of the activities as well as to a different allocation of materials to containers.

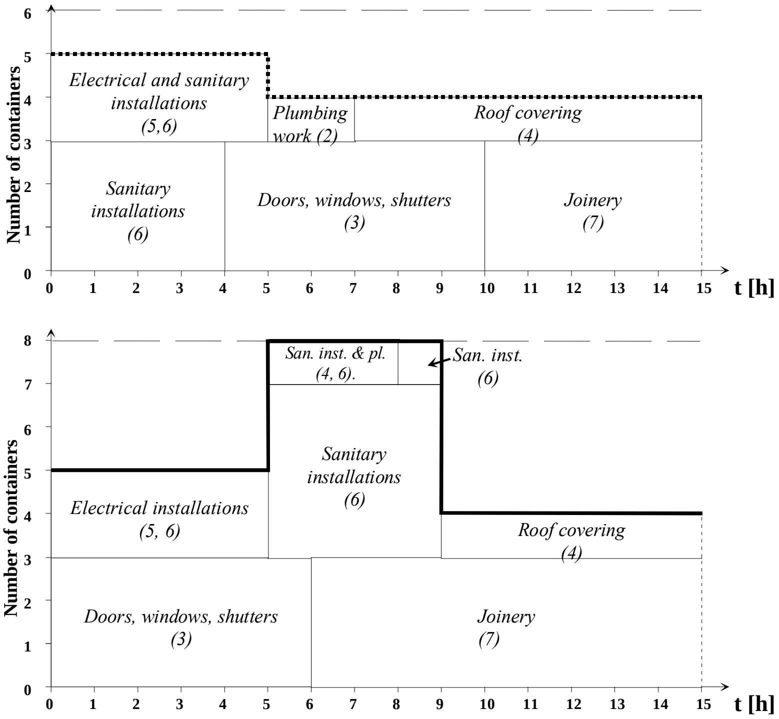


Figure 7 Schedules for the first 15 periods

CONCLUSION

In this paper, we have presented models for deconstruction site management using material-flow management as well as project scheduling. Concerning our examples it has been shown that efficient planning helps to support environment-friendly deconstruction and recycling strategies which are not necessarily disadvantageous from an economic point of view. Compared with results in practice, impressive reductions in dismantling times and costs can be achieved by project scheduling. Besides environmental aspects, the results presented here can also help to develop and assess future concepts for cost efficient construction site management. Nevertheless, our model only covers a selection of some of the resources used in practice. For instance, our results here are based only on the resources that are needed for the deconstruction on the site, i.e. workers and technical equipment. Moreover, nonrenewable resources like the financial budget have to be considered and incorporated in the model using constraints (5). Future work will concentrate on methods covering uncertainities and weak data with methods like stochastic or fuzzy scheduling.

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CONTROLLING ENVIRONMENTAL IMPACTS IN THE DISMANTLING PHASE

Francesca Giglio (Faculty of Architecture, Reggio Calabria, Italy)

SUMMARY

The exploitation of construction waste offers the opportunity to remedy the environmental damages caused by the consumption of natural resources. In the industry sector, the depletion of resources and the increase of waste, as already said, led to experimenting alternative strategies: one of these is the assessment of products in relation to their lifecycle. Waste is reused by being re-routed into a production cycle as secondary raw materials. In order to reduce the quantity of waste, both in general terms and in the sense of materials destined for landfilling, a key role is therefore played by the design phase. This must be conceived by the building entity with a view to a prospective disassembling of the product (and/or of its components) and to its demolition. Although design and demolition phases are distant activities, at the start and at the end of the life cycle of the building, they are tightly interconnected. A careful design could give a suitable solution to the technical-economic problems concerning the phase of dismantling. Therefore, according to the debate on sustainable building, the research generally aims at getting the designers to take into account, when defining the projects, the assessment of environmental compatibility of their technical choices, analyzing and forecasting their environmental impact at the end of the lifecycle. The aim of this research is defining a control instrument that allows the designer to evaluate the impacts of alternative designs on the performance of the building during the use and dismantling phase with a view to sustainable construction. This paper reports the progress of the research that will be ended within the next year with the objective of reporting the state of C&D waste generation in Italy and strategies for minimization and prevention of such waste.

KEYWORDS: Sustainable Development**,** Design for Recycling, Life Cycle, Global Recycling

INTRODUCTION

In general terms, the research refers to the national and international debate concerning the reduction and exploitation of construction and demolition waste (CDW) with a view to sustainable development.

A constantly growing awareness of the limited resources, strongly highlighted worldwide, required the adoption of new initiatives aiming both at promoting the concept of sustainability in local contexts, and at routing the building sector into sustainable design. The goal of sustainable development is supported by several instruments, such as the local Agenda 21. Making reference to a concept already worked out in 1991 by the International Council for Local Environment Initiatives (ICLEI), the Agenda 21 introduces the idea of the local dimension as the driving force towards sustainability. The local Agenda 21 is meant for local authorities, which are encouraged to launch a consultative process between administration, citizens and associations, aiming at a sustainable management of development[i]. In comparison to the problem of the refusals, the chapter 4 of Agenda21, entitled" the change of models of consumption", proposes, for attainment of the objectives of sustainability, the realization, between varied actions of:

- Reuse and recycle, with the application to promote incentives for the reuse and the recycle together with the removal of standard or specific that can determine a discrimination of the recycled materials and inclusion of such tool in the national designs.

Among the strategies which can contribute to channel economy into sustainability, a key role is played by an integrated consumption policy covering at the same time products and waste. The exploitation of construction waste offers the opportunity to remedy the environmental damages caused by consumption of natural resources. Construction and demolition waste is one of the major waste flows produced in Europe: according to a EU assessment, CDW accounts for about 25% of the waste flow in Europe [1]. According to the data elaborated by ANPA (Association National Protection Environment) in Italy out of 20.6 million tons of construction and demolition wastes produced, around 53% come from the sector of micro-demolitions of the residential building estate, 39% from the sector of the micro-demolitions of the non-residential building estate , and 8% of the demolition of whole buildings[2] .

As to the building industry, the availability of raw materials, the possibility of reusing inert materials as filling or road foundations, the relatively low cost of direct landfilling and the availability of dump sites have led to a lack of interest in the problem.

The quantitative data concerning demolition materials in Italy are scarce and often not easily comparable with each other due to several factors, among which the influence of the various building practices adopted in the different countries. It is however possible to assess that CDW accounts for a very high percentage, namely almost twice as much of the solid waste, in terms of weight. According to a valuation respect elaborated by ANPAR (Association National Recycled United Producers), in collaboration with ONR (Osservatorio Nazionale dei Rifiuti) the amount of the Construction and Demolition waste is estimated as 700, 510, and 410 Kg/inhabitants per year in the Northern, Central, and Southern parts of Italy[3], respectively (See Figure 1).

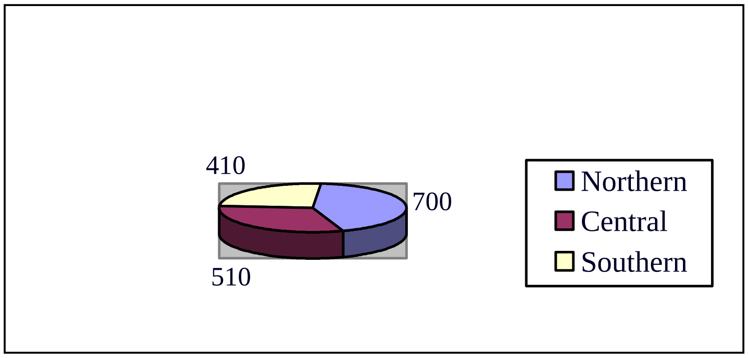

Figure 1. Construction and Demolition waste quantities in Italy (Kg/inhabitants)

The production of CDW not only concerns the final phase of the lifecycle of a building, but also involves every stage of its life: the construction; the use period, which often requires maintenance and restructuring interventions; and the demolition, which is the main cause for the production of the bulk of CDW. See Table 1

Table 1. Waste Production (Source: European Demolition Association)

Wastes production during the lifecycle of a building (Kg/m^2)			
Lifecycle Phase	Italy	Denmark	United Kingdom
Construction phase	25-50	15	1.8
Maintenance phase	50-100	10	-
Demolition phase	1000-2000	900	31

The building sector cannot neglect compelling problems, such as the need for products and energy, the use of portions of land as dumpsites, and the exploitation of natural resources. It’s only during the last few years that attention has been drawn to a strategy envisaging the assessment of resources, linked to the dismantling of products at the end of their lifecycle. Some of the most interesting studies are those concerning the final stage of the lifecycle of the products, namely researches concerning the possibility of adequately reusing, recycling or disposing of the building materials which have served their purpose, and of supporting the introduction of building materials produced by using waste from the building sector or from other industrial fields.

The possibility of recycling CDW is subject to the national legislation. Attention is drawn to the fact that in the last few years these opportunities have been taken into account more strongly compared to the past. In this context, in particular, UNI (Ente Nazionale Italiano di Unificazione,) is actually working along three different lines:

- by activating a working group on “Construction and demolition waste”, which is working on some framework actions, aiming both at defining general references, and at encouraging the building sector to use recycled materials;
- by defining new regulations concerning the requirements for the use of recycling materials;
- by modifying some product standards in order to allow for the possibility of using recycling materials in the production cycle.

The working group “Construction and demolition waste”, operating within the Sub-committee “guidelines for the building process” of the Building Committee, worked on the following initiatives [4]:

- Definition of the specific terminology, with reference to the terms proposed by the existing legislation, and integrated by the present law provisions. The document was prepared in cooperation with QUASCO (Qualità e Sviluppo del Costruire), Bologna, Italy.
- Development of a recommendation concerning selective demolition, presented to the EU. The document is destined to enterprises, and, by identifying construction and demolition

techniques allowing to reduce waste and to produce homogeneous reusable portions of material, proposes to encourage recycling (Guidelines for architectural design[ii]: indications concerning materials, technologies and design criteria which encourage the use of secondary raw materials and a limited waste production [5].

Furthermore, a national team is being set up for the application of the Canadian system called Green Building Challenge, which aims at defining a common language concerning a “green” building industry. Twenty countries have already joined.

In the last few years Italy, even though later than other European and non-European countries, is trying to identify strategies aiming at preventing and minimizing building waste, also with the help of research bodies which benefit from EU financing.
Several public bodies have already launched concrete strategies concerning CDW, on the basis of the guidelines defined during the world conference which took place in Rio de Janeiro in 1992. They can be summarized as follows:

- Preventing and minimizing waste quantity
- Promoting the ability to manage both reuse and recycling practices (rules and incentives)
- Treating and managing waste by applying sustainable techniques
- Expanding additional services, areas and designs destined to waste management.

PROBLEM STATEMENT

Even though later than other sectors, the building industry is increasingly being confronted with the restrictions imposed by the growth, and must face a scenario characterized by radical changes and by the consequent loss of some reassuring reference points: this new scenario is currently defined as sustainable development.

In the industry sector, the depletion of resources and the increase of waste, as already said, led to experimenting alternative strategies: one of these is the assessment of products in relation to their lifecycle. Waste is reused by being re-routed into a production cycle as secondary raw materials.
In order to achieve an acceptable level of sustainability, the building sector must therefore find answers which are environmentally compatible with at least three critical aspects, which stand for the negative sides of the building industry in relation to natural resources:

- the first point concerns the existing buildings and envisages selective demolition of the components;
- the second point concerns the organization of building sites and enterprises;
- the third point concerns recently constructed buildings and involves the approach to the project [6].

In the light of these considerations, the various actors (producers, designers, enterprises, users, dismantlers, dischargers, recyclers, training centers and monitoring authorities) now need to develop instruments to analyze the environmental qualification of the buildings. At present, instruments which take into account the impact of the lifecycle as a whole do not exist, and parameters for adequately assessing the possibility of recycling and disposal of products have not yet been defined or integrated into the building legislation.

This necessitates new requirements, in particular from enterprises and designers, oriented towards assessing the impacts of the adopted technological solutions during the use phase and the final phase of the lifecycle: maintenance, repairs, replacement of the components, recycling and disposal. The analysis instruments required by designers cover therefore the construction phase, the lifecycle, the recycling process and the prospective disposal, and aim at forecasting the performance [7].

SCOPE OF THE STUDY

In order to reduce the quantity of waste, both in general terms and in the sense of materials destined for landfilling, a key role is therefore played by the design phase: this must be conceived by the building entity with a view to a prospective disassembling of the product (and/or of its components) and to its demolition (See Figure 2). The importance of an environmentally minded management of CDW involves the legislative, economic and technical aspects (design).
In the future, therefore, the designer will be increasingly required to conceive solutions which take into account the subsequent destination of the materials concerned, opting for the application of building techniques and for the use of components with a low environmental impact and a long lifecycle: this would facilitate the disassembling operations of the building and the consequent optimization of the exploitation of produced waste.

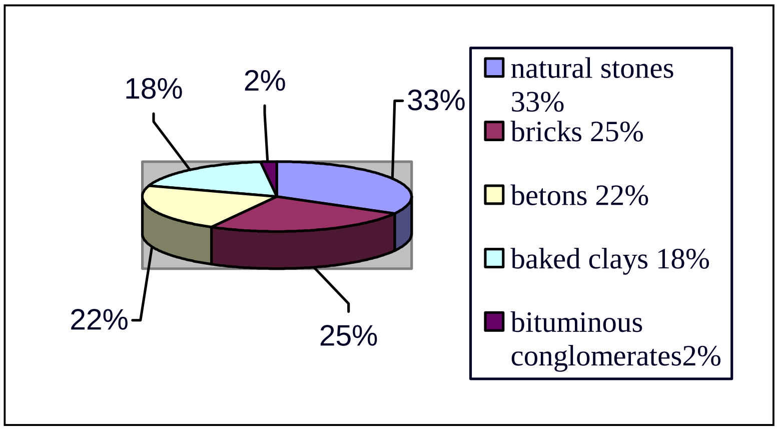

Figure 2. Materials contained in Construction and Demolition wastes (Source: **Tondi A. Delli S.** *La casa riciclabile*, Monfalcone, Edicom, 1998)

The study scope, therefore, will concern the local legislation, with particular attention to building regulations envisaging new requirements, among which those relating to sustainability, environment and users' needs (control of toxic emissions, recyclability of materials etc.).

OBJECTIVES

In the light of these considerations, the research generally aims at getting the designers to take into account, when defining the projects, the assessment of environmental compatibility of their technical choices, analyzing and forecasting their environmental impact at the end of the lifecycle.

Therefore, according to the debate on sustainable building, the research specifically aims at defining a supporting instrument already in the design phase, able to analyze the impacts of technical solutions during the use and dismantling phases, with a view to sustainable building. This instrument will be based on the assessment of environmental impact of technological solutions during the whole lifecycle: maintenance, replacement of components, recycling and disposal. The intention is thus to provide a computer-guided path, which, through appropriate parameters, identifies those single components which can be rerouted to further production cycles.

METHODOLOGY

From the knowledge acquired through a critical interpretation of the state of the art, the instrument is developed by elaborating a model of decomposition of the building and an inventory of materials used and usable in traditional and innovative technical solutions. Then, in parallel with the acquisition of data concerning the impact of use and dismantling phases, the study is articulated as follows:

- identification of criteria for assessing the separability and recyclability of components;
- identification of criteria aiming at defining parameters assessing the possibility to reinsert the component concerned into further production cycles.
- identification of performance requirements needed to facilitate disassembling
- identification of impact data relating both to use and to dismantling phase of the technical solutions concerned

By assessing the impact data, the matrix develops the guided path of choices relating to the design of technical solutions. As to the computerization of the guided path, a format for processing and comparing the impact data will be developed. This phase envisages experimenting and fine-tuning the computerized system for the design of alternative technical solutions. In order to validate the method, a case study will be identified.

POTENTIAL USERS

The instrument will make the designer aware of the impact of the technical solution in the use and dismantling phase during the design phase. Besides, the instrument can provide the designer with the data and instruments necessary in case a technical report on CDW management should be requested for the building permission. The assessment parameters will make it possible to specify whether the components of the chosen solution can be inserted into further production cycles or treated differently, e.g. destined to landfilling or incineration.

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[i] Agenda 21 local is an integral part of Agenda 21, Plain of action of the United Nations for the Sustainable Development in 21°century

[ii] The principal purpose of the guidelines is to furnish general criterion for the design of the operations of demolition to make possible the separation of the different homogeneous fractions, to the purpose to reduce and to valorize the refusals, in accord with how much established in the community center.
For the layout of the guidelines of extreme importance has been the acknowledgement in the national regulation of the directives 91/56/CEE, on the refusals and 91/689/CEE, on the dangerous refusals, (Order in Council 5/2/97 and his contained changes in the Order in Council n°389 dell'8/11/97) that it classifies the Construction and Demolition waste like special and it stimulates the prevention of the production of refusals and the relative recovery like operate priority in comparison to the disposal.
To consult the document entirely : - **UNI** *Riduzione dell'impatto ambientale dei rifiuti da costruzione – Terminologia e linee guida*,Tipografia Milanese, Milano, 1999

DESIGN FOR RECYCLING

Bart J.H. te Dorsthorst and Ton Kowalczyk (Delft University of Technology, Faculty of Architecture, Environmental Technical Design)

ABSTRACT

The production of construction and demolition waste (CDW) is growing each year and is about 19 million tons. Luckily almost all of this material is re-used, mostly as a road foundation. This re-use can be called down cycling.

In order to move from down cycling of this material to recycling (ore even up cycling) integral chain management becomes very important. Especially the early design of a construction has a great effect on the future CDW.

To improve high level recycling (construction re-use, element re-use or material re-use) constructions should be designed according to the design for recycling method. These methods can be divided into three categories:

1. Design for adaptability (construction re-use)
2. Design for deconstruction (element re-use)
3. Design for dismantling (material re-use)

In order to calculate the environmental effects of these designing methods, a new tool is under development: Building End of Life ANalysis TOol (BELCANTO).

KEYWORDS

Construction and Demolition Waste, Design for Recycling, Design for Adaptability, Design for Deconstruction, Design for Dismantling

INTRODUCTION

The total production of construction and demolition waste (CDW) in the European Union (EU) is about 450 million tonnes. If one excludes earth and excavated road materials the amount of ‘core’ CDW is estimated to be roughly 180 million tonnes per year; 480 kg per person each year. There is no need to say that this is an enormous amount of material. Recycling rates vary from lower than 5% until 95% in the different Member States. The question is how to improve these recycling, both quantitative as qualitative.

In most countries of the EU the problem of the CDW occurs at the time a construction has to be demolished. By changing this system into integral chain management, both quantitative as qualitative recycling can be improved. Three different ways of re-using can be recognized:

1 re-using the construction;
2 re-using the elements;
3 recycling the material.

Furthermore the materials can be recycled, down cycled and up cycled.

CDW constitutes a highly significant proportion of all wastes. This waste also has a very high recovery potential. However only a small proportion of these waste streams is actually recovered in the EU as a whole. There is a big difference in recycling of CDW in the different countries of the EU. The main aspects regarding these differences are natural resources, transport distances, economic and technologic situation and the population density.

Member State	Core CDW Million tonnes	Re-use or recycle Percentage
Germany	59	17
UK	30	45
France	24	50
Italy	20	9
Spain	13	<5
The Netherlands	11	90
Belgium	7	87
Austria	5	41
Portugal	3	<5
Denmark	3	81
Greece	2	<5
Sweden	2	21
Finland	1	45
Ireland	1	<5
Luxembourg	0	
EU 15	180	28

Fig 1. Re-use in the EU (Symonds, 1999)

Recycling percentages vary from less than 5% (Greece, Ireland, Portugal and Spain) to more than 80% (Belgium, Denmark and the Netherlands). About 50 million tonnes of the ‘core’ CDW are being re-used or recycled. The rest, 130 million tonnes are incinerated or dumped on landfills. The total amount of core CDW and the recycling per Member State are reflected in figure 1 (Symonds, 1999).

WASTE MANAGEMENT

The methods used to manage the CDW differ from one Member State to another. Although some countries introduced a system for managing this waste, based on the waste hierarchy (paragraph 3), the waste managed by most of the Member States is quite simply: disposal to landfill. The large number of potential sources (demolition sites) and the fact that CDW is generally inert means that it is difficult to control and creates a high risk of illegal land filling. These illegal landfills are widespread in some Member States. Despite the recycling potential, about 75% of the ‘core’ CDW in the EU are being land filled nowadays, only 25% are re-used.

In some Member States dangerous wastes, like asbestos and heavy metals, are not always separated from the rest of the CDW. Although their quantity is relatively small, their appearance can contaminate a significant part of the recycled materials or can contaminate landfills. The composition of CDW differs per Member State. This composition is affected by numerous factors, including the raw materials used, architectural techniques, local construction and demolition practices. The main wastes present in the CDW are soil, ballast, concrete, asphalt, bricks, tiles, plaster, masonry, wood, metals, paper and plastics.

The current management of the CDW, an end-of-pipe principle, can be described as waste management. The problem occurs at the end of the life cycle, as soon as a construction has to be demolished. A scheme for waste management is presented in figure 2 (Dorsthorst te, 2000).

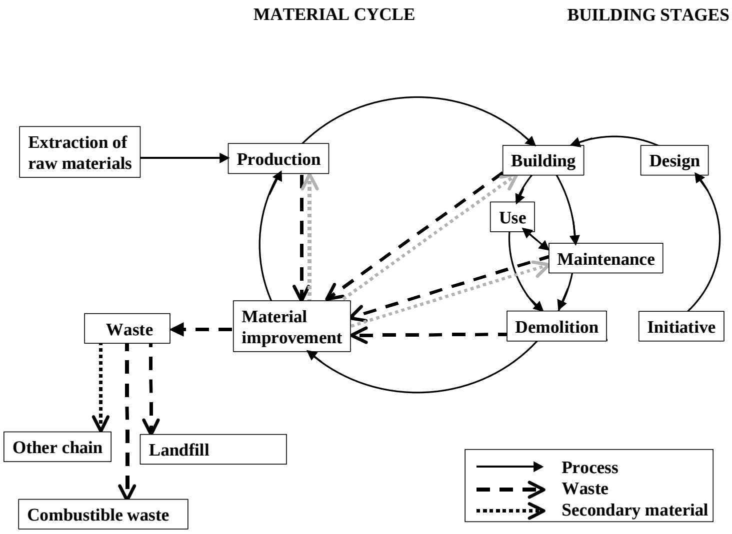

Fig 2. Waste management

The rules and regulations governing this waste stream in the Member States also reveal the diversity of approaches to its management. The regulations are rarely binding in most Member States. Very few countries have specific management legislation. However those, which have introduced measures to improve its management (like Denmark and the Netherlands), have achieved high levels of recycling.

The Netherlands have drawn up a national “Building site waste” plan for the period 1990-2000 comprising measures aimed at banning the land filling of recoverable waste. Nowadays about 95% of the CDW is recovered and re-used. Since January 2001 it is forbidden to dump reusable and combustible CDW on a landfill.

In Denmark, municipalities are responsible for the collection of the CDW. More than half of them (especially the major cities) has introduced specific regulations on sorting of that waste in order to re-use the material again.

In Germany, a voluntary agreement was concluded in 1996 between the Federal Ministry of the Environment and the federation to which most construction and demolition undertakers belong. The aim is to reduce the volume of disposed CDW to landfills by 50% between 1995 and 2005

The southern European countries (Greece, Italy, Portugal and Spain) recycle very little of their CDW. The market for recycled materials is not highly developed in those countries. Their natural resources are of sufficient quality and quantity to meet the demand for building materials at a moderate cost.

One of the possible contributions to prohibit dumping of CDW is integral chain management: to keep the building materials as long as possible in their own cycle: With integral chain management the recycling industry can be changed. A definition of integral chain management runs as follows: the maintenance of products and processes in such a way that all materials in a chain can perform their function as long as possible (VROM, 1993). So the degradation of materials must be kept at the lowest possible level.

Translating this definition for the building and constructing industry, it means that all actors, at all building stages must do all they possibly can to improve the use of constructions, construction elements or materials after the demolition-stage. Major issues concerning integral chain management are:

1. The level of re-use
2. The way of re-use
3. The building stages

Level of re-use

There are three different groups of re-use levels. The first group is prevention of waste, both quantitative and qualitative prevention (construction re-use, element re-use). The second group is re-use in a useful application (material re-use), and the third is the definite estrangement out of the building and constructing industry.

Way of re-use

CDW can be recycled, down cycled or up cycled (Hendriks 1999). When the material is used for the same function again, it is called recycling (steel scrap used for the production of steel). When the material is used for another function it is called down cycling (mixed granulates used as a road base material) and when the recycled material is used for a better function than the original material it is called up cycling (fly ash used in cement or concrete).

Building stages

Re-use at the highest level is only possible if every actor in the building cycle is aware of the fact that the used materials are to be re-used after demolition. So at every building stage, from the initiative, design, building, use, maintenance to the demolition stage, measures must be taken to improve re-use at the highest possible level. In the following diagram (figure 3) the building stages are coupled with the material cycle. The right part of the diagram shows the building cycle, the left side the material cycle (Dorsthorst te, 2000).

All actions in the right cycle have their effects on the closure of the left cycle. So maximal efforts are needed in the building cycle to close the material cycle. A problem is the lifetime of buildings. Normally these constructions exist for about 20-250 years. So the use and maintenance stage are the longest in time.

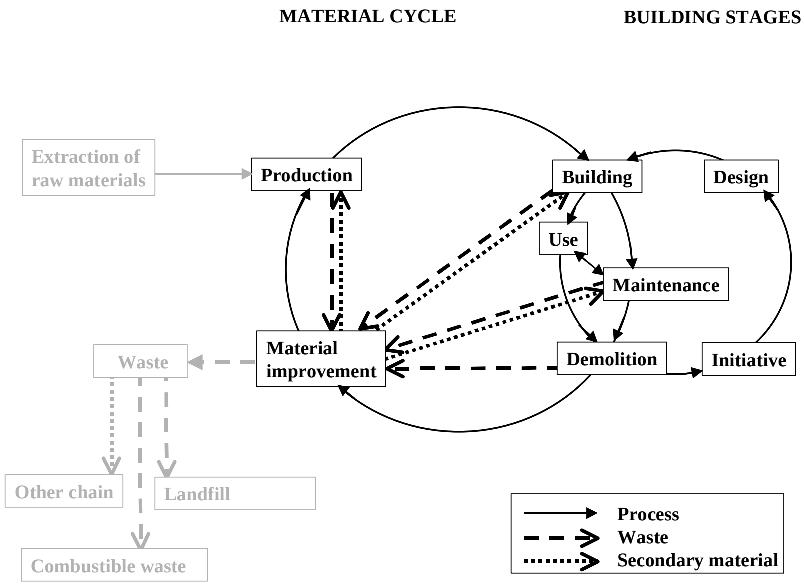

Figure 3 Integral chain management

The most important decisions, about re-using materials, can be taken in the first stages (initiative, design and building stage). So to reach an optimal re-use of the construction, construction element or materials, there are a few important preconditions: Design for Recycling:

1. Design for Adaptability (DFA). Constructions often have a longer lifetime than its function. So buildings must be easy to adapt to other functions, in order to create a longer lifetime.
2. Design for Dismantling (DFDa). Materials, which are difficult to recycle, should not be used at all, or it must be (technically) easy to separate them, before or after, demolition
3. Design for Deconstruction (DFDc). To re-use building elements, a construction should be designed to disassemble these elements at the demolition stage’
4. Assembling and dismantling techniques. To use building elements a second time they must be dismantled carefully in order to prevent being damaged as much as possible.

WASTE TREATMENT HIERARCHY

In its Community Strategy for Waste Management (COM, 1996), the European Commission describes the hierarchy in waste management. That is a three-step hierarchy with prevention of waste as first priority, followed by the recovery of waste and the disposal of waste is the last option. In some Member State this hierarchy has more steps. The Dutch government introduced a seven step hierarchy (SDU, 1980), called the Ladder of Lansink (figure 4).

1 Prevention
2 Element reuse
3 Material reuse
4 Useful application
5 Incineration with energy recovery
6 Incineration
7 Landfil

Fig 4. Ladder of Lansink

Prevention
Construction reuse
Element reuse
Material reuse
Useful application
Immobilisation with useful application
Immobilisation
Incineration with energy recovery
Incineration
Landfill

Fig. 5 Delft Ladder

A disadvantage of such order is that it is a fixed top-down approach. The first option is always better than the second and so on. Nowadays there are more sophisticated models that calculate the best results on economic and ecological level. So this fixed order should become flexible. The Delft Ladder (Hendriks, 2000) is a new, flexible model. It has more rungs, because more waste treatment options have been developed. The order can change thanks to the results of calculation methods like Life Cycle Analysis (Heijungs, 1992) and Eco-cost Value Ratio (Vogtländer, 2000). The Delft ladder is presented in figure 5.

DESIGN FOR RECYCLING

Although the Delft Ladder is a flexible waste treatment order, the ‘top’ priorities have the most effect on the reducing of the future CDW. So for reduction of CDW, the re-use of complete buildings, building parts or building materials are very important.

In case of already existing constructions the effort lies on deconstruction and separation techniques, because nothing can be done in the design stage. In case of newly built constructions, re-use of constructions, elements or materials must be in mind at the designing stage of the building; Design for Recycling.

This design for recycling can be divided into three categories:

1. Design for Adaptability
2. Design for Deconstruction
3. Design for Dismantling

Design for Adaptability

This design method opts for changing capacity of a building for different functions (construction re-use in the Delft Ladder). In some cases one already knows that the function will superfluous within years. At that time the decision can made to make building with can fulfill different functions.

Important parameters for design for adaptability are span and construction height. The frame of the construction definite future use possibilities.

Design for adaptability is useful for constructions with a long (expected) lifetime. Especially when the use of the building changes or is expected to change before the lifetime of the building (Sassi, 2000).

An example for a building that has been designed for adaptability is a combined school and apartment building in Schijndel, The Netherlands (figure 6-11). This building is located in a new neighbourhood were the expectation is that a lot of children will go to primary school in the next decade. The school is located on the ground floor. This school also has classes at the first floor, but these classrooms could be adapted to apartments when the total amount of children was falling. At the upper (second) floor the apartments were located. Originally these apartments were for rent and, when necessary, they should be adapted into classrooms. This has never happened because no property developer dare to built it this way. Now these apartments were sold to private owners. Ironically emergency accommodation must be built within five years after completing this construction.

Figure 6 Front view

Figure 7 Rear view

Figure 8 Course

Figure 9 Inner course

Figure 10 Apartment

Figure 11 Classroom

Design for Deconstruction

This design method opts for reusing hole elements after deconstruction. So when the building is constructed for the first lifecycle one should know how to deconstruct and how to rebuild. So constructing and deconstructing details are very important. Furthermore sizes, like length and height, must be standardised. Only then secondary elements can be re-used again. In the Netherlands a special program, IFD-building (industrial flexible and demountable building) was launched to reach more deconstructable buildings or building methods.

Design for deconstruction is useful when the expected lifetime of the building elements is longer than the expected lifetime of the whole building.

An example of a building that was built for deconstruction is a building in Vleuten, the Netherlands (figure 12-14). In that area a lot of houses were built and those had to be sold in a period of about 10 years. So in this building an info-centre was located for the plans of the new residential area. At the time all these houses were built, this info-centre will be deconstructed.

Figure 12 Vleuten

Figure 13 Vleuten

Figure 13 MX-5 System

This building is built with the MX-5-method, a building method with concrete walls, columns and floors. These elements are bolted together and thus they are demountable.

Design for Dismantling

This design system opts for a high level re-use of the materials. So all materials must be recognised, easy separated and reusable.

Design for dismantling is useful for constructions that have to fulfill their function during the whole lifetime. When this (functional) lifetime is as long as the technical lifetime, the construction elements should be used at the material level.

BELCANTO

When the designer of construction uses one (or more) of these three designing methods, all materials are in use for a longer period of time. But will these methods have a positive effect on the total environmental load of building (LCA) and the total price (LCC)?

To answer this question a new tool is under development. A tool for an architect, or a building product developer, or a researcher, to support the choice between re-use of the construction (DFA), re-use of elements (DFDc) and recycling of materials (DFDm) as the end-of-life scenario of a certain building product. Recently, we suggested a possible design for such a decision support system (Guequierre et al, 1999). Figure 14 shows a scheme of this system, called BELCANTO (Building End of Life Cycle ANalyse TOol). The output of BELCANTO will be at least the environmental load of a building product. However, decision-makers need also economic aspects, thus the life-cycle costs of the various ELS's must also be part of the output. Furthermore, some qualitative deliberations, like the ease of dismantling, are added to the output. The input of BELCANTO will be a building product.

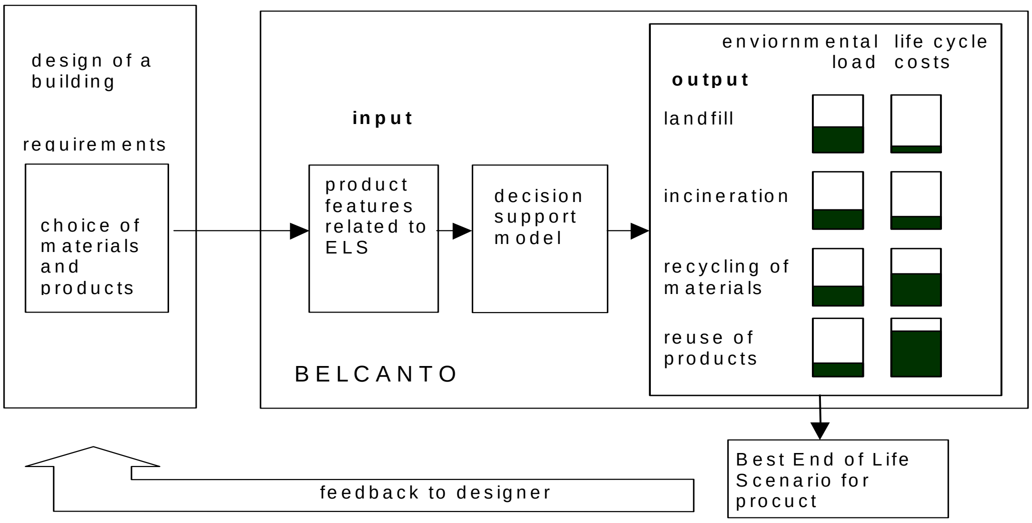

Figure 14 BELCANTO

BELCANTO IN USE

If architects use BELCANTO, they start with the first global design of the building. They need several data as input to the BELCANTO model, such as:

- Building material
- Dimensions of the building

So the model can calculate the best possible re-use option (end of life scenario). This result can be used in the design process.

If building product developers use BELCANTO, they start with the developed building product. This is almost the same as architects do, but the want to know more specific environmental data. Therefore they also need data such as:

- Production energy
- Production waste
- Other used materials
- Assembling techniques

Researchers however use BELCANTO in a different way. They mostly will use the tool as an effect analysis tool. They also need data like:

- Assembling and disassembling techniques
- Service life
- Maintenance
- Damaging of the product (during service life)

But, they also need to check the usefulness and the reliability of the data and the BELCANTO modelling.

This model will be tested (for use as researchers) in a test case. In that case the normal way of electric installations (cables and so) will be compared with a new system. In that new system, the whole electric wiring system can be changed during service life of the constructions.

CONCLUSIONS

To reduce the total amount of CDW in the future, things have to be changed in the building methods today. Design for Recycling is a way to change these building methods. Therefor action must be taken in all of the building stages. Already at the early beginning of building re-use of building materials at all levels must be in mind.

The advantages or disadvantages can be calculated with LCA-methods, and more specific with BELCANTO. In BELCANTO different end of life scenarios can be calculated and this output can be carried back to the designer.

When a building is designed for recycling (adaptability, deconstruction or dismantling) almost all materials can be re-used at the end of the lifetime of the construction, if this is not the case it can be called design for demolition.

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DESIGN ASPECTS OF DECOMPOSABLE BUILDING STRUCTURES

Elma Durmisevic, Prof. Jan Brouwer
Delft University of Technology, Faculty of Architecture, Department of Building Technology / OBOM De Vries van Heystplantsoen 2, 2628 RZ Delft , The Netherlands

ABSTRACT

Technology innovations, population growth, evolving ecology problems, changing economies and life styles are imposing new requirements on a built environment. This influence considerably the way we ought to design and build in the future.

The most important issue regarding the building today is related to the increase of its environmental efficiency which can be achieved by creating the potentials for closed loop material cycling of building products. One of crucial problems of today's building construction is that buildings are made in such a way that many alterations lead to demolition of building parts or even whole structure. The main reason for this is the fact that different functions and materials comprising a building system are integrated in one closed and dependent structure which does not allow alterations. This is one of reasons for immense waste accumulation.

In order to improve environmental efficiency of the building we need to change our perception of the building's life cycle and its technical composition. This brings a focus on building assembly and combination of building materials and their functions at connections. Herewith deconstruction can be recognized as important element of sustainable construction. By adopting the concept of design for disassembly spatial systems of a building are become more amenable to modifications and change of use. At the same time the technical composition of a building become transformable what is precondition for reuse and recycling of building components.

The aim of this research is to specifying decomposition characteristics of building structures, which will determine the future recycle potentials of the building, its components and materials. This will be done by developing performance indicators of building structures that give a measure of their effect on deconstructability and reusability. Accordingly design guidelines could be developed which will steer the design so that decomposition of building and its components is possible.

Key words: deconstruction, flexibility, dynamic structures, sustainable

INTRODUCTION

The goal of sustainable construction is to build more efficiently and profitably after adopting responsibly to wide spread concerns about waste, pollution, nuisance, quality and users satisfactions [3].

However conventional design is concentrated on the classic building properties optimizing function, construction and costs in relation to the short-term performance. Such approach does not take into consideration aspects related to the future transformation of building structure, what has environmental and economic consequences.

An all embracing opinion is that a sustainable building is a building which:

(a) consumes a minimal amount of energy over its life span,
(b) makes en efficient use of environmentally friendly, renewable or low embodied energy materials,
(c) generates a minimum amount of waste and pollution throughout its whole life span
(d) utilizes local recyclable and reusable materials avoiding use of composites since they rarely can be recycled
(e) meets its users needs now and in a future. [3]

In the wide area of researches that have been done in the field of sustainable building great attention has been given to design of energy efficient buildings and use of environmentally friendly materials. Accordingly the tools are being developed to assess the environmental impact of building materials as well as to measure energy use during the operation phase of the building. However the design of sustainable building deals, on one hand with optimization of appropriate materials and energy use and, on the other hand, with optimization of appropriate construction methods and connections between building components. This means that the construction features influence the environmental impact of the building as well. The consideration of this aspect is not satisfactory and should get grater attention. More over the construction industry is mainly focused on the improvement of assembly techniques but very little to ease disassembly process. Therefore most of transformations within the building end up with demolition and waste disposal.

For that reason the design of sustainable building runs the danger of being carried out on ad-hoc bases without disintegration aspects of the building structure being an integral part of the design process. That means that we must consider how we can access and replace parts of existing building systems and components, and accordingly how we can design and integrate building systems and components in order to be able to replace them later on.

Ultimately this means that the buildings should be designed according to the criteria that will provide easy changes relaying strongly on the manner in which the building is assembled. This articulates the concern for design of building configuration. Configuration design deals with arrangement of building elements and components by defining the relationships between them. Through such process the level of independence and exchangeability of building components (being the indicators of decomposability) can be defined.

BUILDING TRANSFORMATION

Every building represents integration of spatial, technical and material systems. Very often building structures have dependent relations between building materials, components, systems and space. They follow the pattern of *fixed* integration of materials into closed structural systems. Consequently such systems are integrated into *fixed* spatial systems of the building [5]. Taking into account such general dependency from material systems to spatial systems every change within the building can have consequences for the entire building structure. At the moment that changes and modifications of building structures are almost everyday activity, such fixed structures are no option. Modern buildings are being visualised by their makers as static and permanent structures. But, in the longer time frame the building is constantly changing due to changing user demands and the degradation of more technology dependent components.

Rather than destroying structures and systems while adopting the building to fit new requirements, it should be possible to disassemble sections back into components and to reassemble them in the new combination. At the moment that the act of demolition is replaced with disassembly building components would get a chance to have multiple lives which would drastically extend their life cycle.

Therefore one of key issues of sustainability is development of the design strategy that will transform inflexible building structures into dynamic and flexible structures whose parts could be easily disassembled and later on reused or recycled.

This would drastically improve capacity of building structure to be transformed on all levels from building to the material level with minimal environmental stress.

Three dimensions of transformation namely structural, spatial and material transformations characterize such decomposable structures.

- ☐ *Spatial transformation* ensures continuity in the exploitation of the space through the spatial adaptability,
- ☐ S*tructural transformation* which provides continuity in the exploitation of building and its components through replaceability, reuse and recover of building components
- ☐ *Element and material transformation* providing continuity in the exploitation of the materials through recycling of building materials.

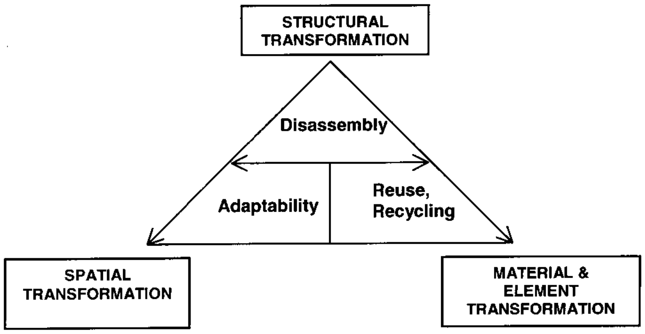

Figure 1: disassembly - the key for building transformation [5]

The key component of such three-dimensional transformation capacity of building is structural transformation with associated disassembly. Without disassembly spatial systems (whose life cycle very from 2-20 years [11] would not be easy transformable. On the other hand without disassembly the life cycle model of building materials (whose durability vary from 5-75 years) is linear and ends up with demolition and waste disposal.

INCREASE OF SUSTAINABILITY BY DESIGN FOR DISASSEMBLY

The demolition of building structures produces enormous amounts of materials that in most countries result in significant waste streams [9].
Generally problem is that the buildings and building products are not design for disassembly and repair. For that reason their life cycle is always presented as a linear system which represents one directional material flow from material extraction, manufacturing, transport, construction, operation, demolition and waste disposal. Such use/dispose scenarios are stimulated by the consumption related economy. Earth's resources are limited. But at the some time economic prosperity of modern society is based on consumption of earth's limited resources. With the explosion in world population and the increasing rate of consumption, it will be increasingly difficult to sustain the quality of life on earth if serious efforts are not made now to conserve and effectively use earth's limited resources [2].
(UN 1987) Agenda 21 from the UNCED conference in Rio 1992 states that cyclic processes must replace linear once to create sustainable development [1].

According to the EEA [7] Building industry in Europe produces 410 million tones per year (1995) with yearly increase of 9.7 million ton.
Recent studies [7] show that the largest quantities of waste are minerals originated from the structures. They also show that due to the contamination, a fairly large part of the recycled material is limited to low quality use or even landfill. This is mainly because present structures and components are not designed to be reused in new buildings since components can not be taken apart. Further more they are not designed to be recycled because they are often composed of hazardous materials.
Industrial ecology recognises the increase of the recycling rate as the most effective way to reduce the environmental impact. A major method to achieve higher rate of recycling is design for disassembly (figure2).
Looking at the last phase of the building it becomes very clear that if the act of demolition would be replaced by disassembly materials and components could be reused and finally recycled.
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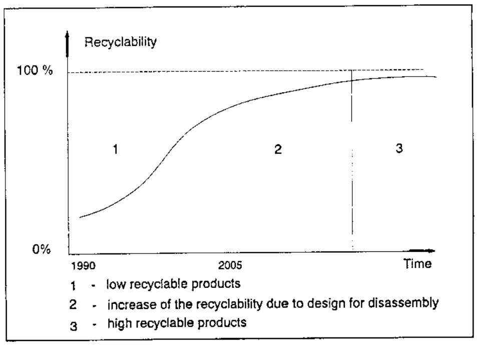


Figure2: increase of recyclability by design for disassembly

End of Life cycle scenarios

Recycling has different scenarios, which are often named as End of Life Cycle Scenarios. The environmentaly beneficial hierarchy of these scenarios which is widely accepted in product manufacturing industries can be presented as follow (Table 1):

Table 1: Hierarchy of End of Life Cycle Scenarios

		Recycling levels
I	REUSE,	Level 1
II	REMANUFACTURE,	
III	RECYCLING (up-cycling) & (down-cycling),	Level 2
IV	BURN,	Level 3
V	LANDFILL	Level 4

The aim of each of these strategies is to find a better way to make more efficient use of the limited earth's resources, minimize pollution and waste.

Reuse

This scenario is based on prolonging the life of the building or the building components by dismantling the component at the end of its functional life cycle and reusing it in a new combination. This is seen as the best environmental option because it uses minimum energy and material to close the loop of component or building life cycle.

Remanufacture

This strategy involves reconfiguration of existing component or system to restore its condition to "as good as new". This may involve reuse of existing components; replacement of some component parts and quality control to ensure that remanufactured product will meet new product tolerances and capabilities. [2] Good examples of successful remanufacture strategy are Kodak's single use camera, Xerox, Siemens computers etc. The same strategy could be applied for building systems or components.

Recycling

This recognized the fact that many of the earth's landfills are filling up at an alarming rate. Further more many of the "deposits" are hazardous and unsafe. It is therefore important to design the building components with ease of recycling so that a new product can be made from recycled material (up-cycling) or disposed so that final waste generation is disposed safly (down cycling).

Although present research and development R&D is directed mainly to energy conservation and waste management the greater effect in long term will be from reuse of the built environment on all levels from the building to the materials.

The key technical factor here is the planned ability of the building to be dismantled into its components parts. This brings a focus to the assembly and jointing methods. Easy dismantling of all components will allow a longer service life of the whole building by facilitating easily repeated repair, replacement and modification. The design of the building connections prevents us acting within level one and two (table 1). Having in mind existing building methods we are restricted to recycling level three and four (table 1).

MATERIAL LEVELS WITHIN THE BUILDING STRUCTURE

The perception of a building as one compact static product is misleading.
Duffy wrote in his book “ Measuring building performance” “..our basic argument is that there is not such a thing as a building….a building properly conceived is several layers of longevity of built components [4].

The building structure is defined as a hierarchical arrangement of elements and relations the building consist of. It represents the way parts are arranged in the group of parts (components) and the way group of parts are arranged in the whole building [10].
Traditional buildings were characterised by complex relational diagrams representing maximal integration of all building elements into one dependent structure. (Figure 3 left)
The evolution of building structure represents the transformation from the complex relational diagram to the simplified relational diagram. The first step towards simplification of relational diagrams has to do with clustering a group of parts into independent subassemblies, which will act, independently in production and assembly/disassembly phase. (Figure 3 right)

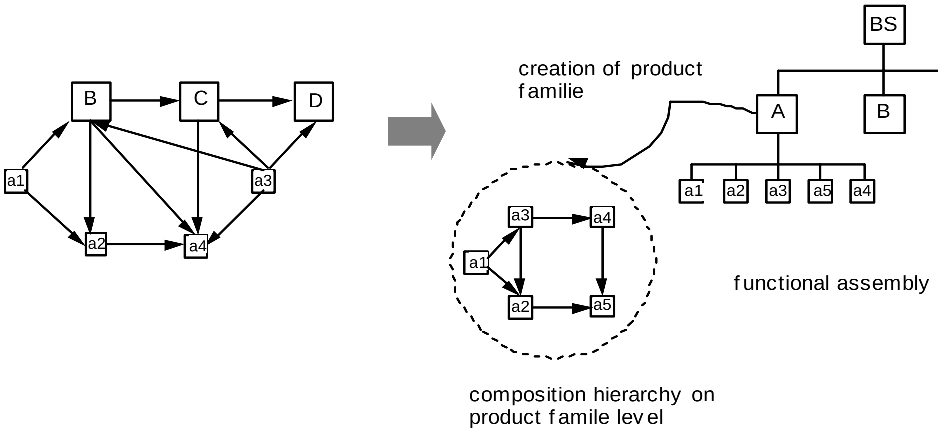


Figure3: Towards simplified relational diagrams between building parts

One subassembly is a group of parts with a property that the parts in subassembly can be assembled independently of other parts of the building. These subassemblies exist on different levels within the building.
Elements are seen as the basic parts that form the lowest level of building subassembly which is called component level in this research. In the same way that elements could be connected to form low-level sub-assembly (*component),* so this low-level assembly can be connected to form higher-level assembly (*system*).
The requirements for easy assembly and disassembly results in the selection of construction strategies that utilize prefabricated modular, dry jointed systems.

Unlike the traditional building structure which is seen as a hierarchy of elements the decomposable building structure should be seen as a hierarchy of subassemblies. It should be described at any level of abstraction: at the highest level *(building level)* as an overall assembly of systems, at intermediate level *(system level)* as composition of components and at the lowest level *(component level)* as assembly of elements/materials. (figure 4)

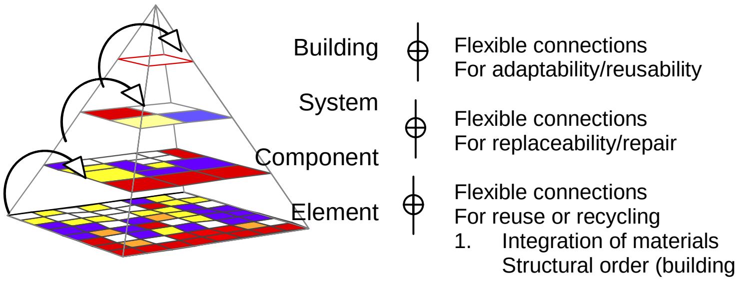


Figure 4: hierarchy of material levels

Having in mind that the structure represents functional assembly, hierarchical levels of building composition can be defined as follow:

- Building level represents the composition of systems which are carriers of main building functions (load-bearing, enclosure, partitioning, servicing)
- System level represents the composition of components which are carriers of the system functions (bearing, finishing, insulation, reflecting, distributing etc)
- Component level represents the layered or frame assembly of component functions which are allocated through the elements and materials at the lowest level of building assembly.

Bearing this in mind it is important to note that every material level within the building has to do with integration of functional and technical life cycle of building materials. This life cycle co-ordination is essential for design for disassembly. For example decomposition of one dwelling into independent levels is a top-down process. The specification of independent levels is related to desired flexibility scenario that will indicate the hierarchy of fixed and changeable components.(figure 5)
Thus the matrix of functional and technical life cycle coordination which is based on developed scenarios for future use of building and its materials is the starting point for design for disassembly.

The example in figure 5 left represents one hierarchical organization of building components. Specified hierarchy was based on the assumption that the dwelling should have maximal lay out flexibility. This includes replace-ability of the kitchen and wet units and separation walls. Herewith four independent time levels were recognized which indicated the hierarchy of building components.
Accordingly flexible technical systems were developed where water, electrical installations and separation walls were given shorter use life cycle than the rest of the building (figure 5 right). Further more the physical separation between fast cycling and slow cycling components was optimized through their interfaces.

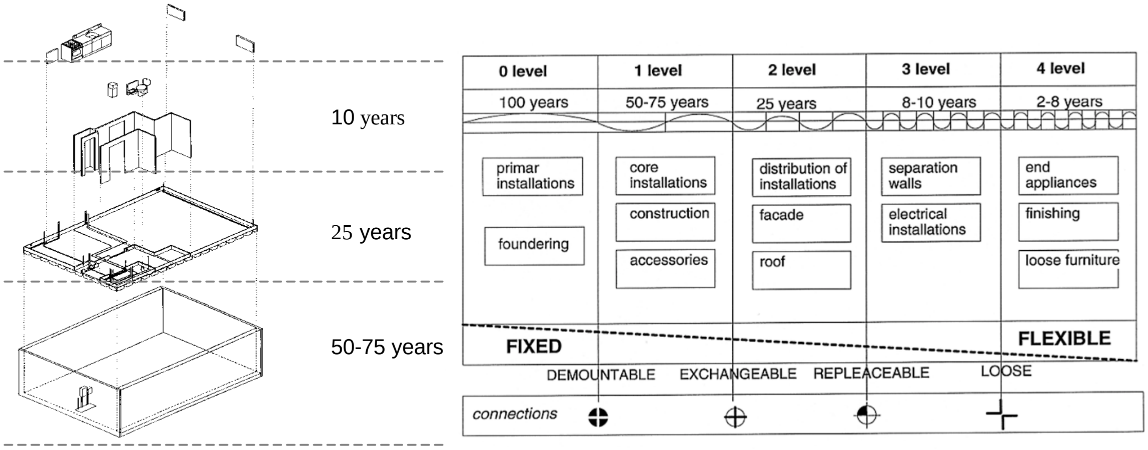


Figure 5:One proposal for systematization of building systems and their interfaces according to the different life cycles

The table on the right (figure 5) gives an overview of the use sensitive components within above defined flexibility scenario. The coordination between technical and use life cycle of building components is discussed further in the section 8.

Building Decomposition is the Sum of Decomposition Indicators on all Material Levels

A decomposable (constructed) building does not necessarily exhibit one structure but hides in its structure of components, and systems several different structuring principles that fit the building for construction, service and deconstruction.
Therefore the subassemblies of the building, their internal composition and the way in which they are built together determine the behaviour or function of the total building and its structure. Having that in mind it is impossible to speak of unstructured building, but we can speak of weakly structured buildings which we may reason from the properties “difficult to assemble”, “difficult to repair”, “difficult to change” or “difficult to disassemble”. The fact that different structures are superimposed in the final building makes the design integration and co-ordination complex and raises a need for design support tools.

A decision to create a cluster of parts is of essential importance in the design for disassembly. The more building parts are integrated into one component the less physical connections are needed on the site. In this why disassembly process can be accomplished in stages (on the site , in the working place, in the factory). Such strategy would be the first step towards greater control of efficiency of materials use.

The way we assemble the building reflects its disassembly process. Therefore the design decisions regarding the assembly, which are made, at the beginning of the design process can have consequences for the entire service life of the building and its materials.
For example one façade system can be structured following the pattern of functional decomposition (closing, finishing, isolation, water protecting ,bearing) and allocation of these functions through the independent elements which are arranged into components. This means that the components which have different functions could be independently replaced

at the end of their technical or functional life cycle. This is the characteristic of open façade system.
(figure 6 right) On the other hand the closed façade system integrates most of these functions into one composite component. (figure 6 left)

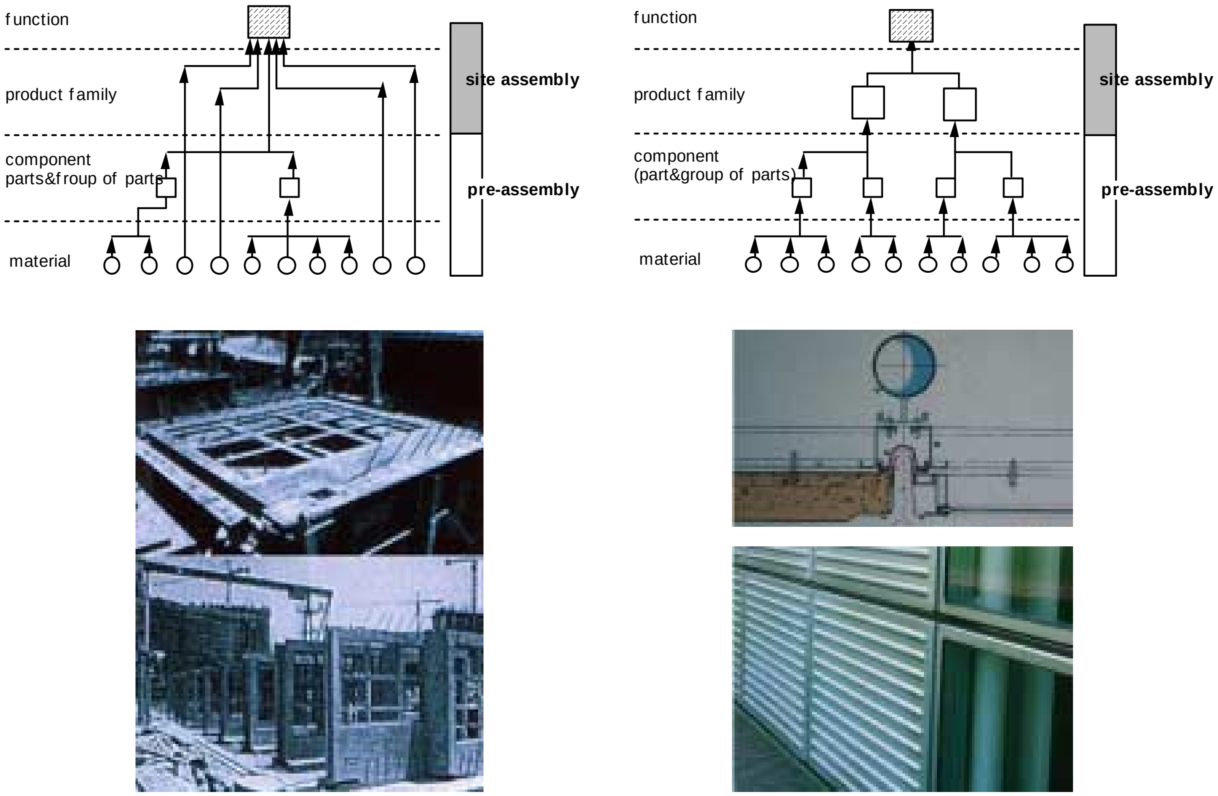


Figure 6: left closed system configuration, right open system configuration

The main disadvantage of such product structuring is in lack of transformation capacity of the systems. The second disadvantage can be recognised at the end of its service life, when the only possible scenario is demolition and waste disposal.

Having in mind that the building is the sum of structures, which are captured in a form of building, systems and components it is clear that total decomposition is related to the sum of disassembly properties on each of these levels of building integration. Thus total disassembly D(total) is sum of the decomposition on the building, system and component level (Dbl+Dsl+Dcl). Aspects, which can help to quantify "D", will be discussed in the section 6 and 7.

$$D(total) = Dbl + Dsl + Dcl$$

Generally, it is possible to make distinction between fixed, partly decomposable and completely decomposable structures. The main difference is in the level of functional, technical and physical decomposition on each level of the building structure. For example one building function can be allocated through one independent building system. On the

other hand the internal composition within the system, just as the physical relations between the components of the system could stop further disassembly. One example is composite façade panel, which can be dismantled from the main structure, but the further decomposition on system and component level is not possible. In this case the total decomposition is:
D(total)= Dbl+ 0+ 0

CONFIGURATION DESIGN -THE KEY FOR DECONSTRUCTION

The current approach to designing a building and its structure is focused on the optimization of the building method to the cost, time and short-term use requirements. Sustainable development however raises a strong need for integrated life-cycle design, where all solutions are optimized and specified for the entire design service life of the building and its components. Such approach requires the development of different end of life scenarios for the building and its materials to which building methods would be optimized.

The end of life scenarios that are possible for the product will be determined by the physical characteristics of the product [4]. That is to say that the actual design of the building configuration will determine weather it is possible to achieve the environmentally preferable scenarios of maintenance and reuse, rater than just recycling and disposal.

Two main criteria for the decomposition of building configuration are *Independence* and *Exchangeability* of building components. In other words one building product can be dismantled if it is defined as an independent part of a building structure and if the interfaces with other parts are demountable.

Decompostruction characteristics of building structure could be specified by providing the performance indicator of building structures that give a measure of their effect on deconstruction. This can be achieved by analysing three main components of every structural configuration being: product type, relation's type and connection type. (Figure 7) The design characteristics of these three components will determine weather the two main criteria for deconstruction: independence and exchangeability are provided.

The domains of deconstruction being structuring, product and connection domains (figure 7) can be distinguished but not separated from each other since they have mutual dependence in decision-making process. If one of the domains are not optimised for disassembly than the whole structure on specific level is not decomposable. For example if structuring and connection domains are optimised for disassembly the disassembly can be stopped by inappropriate geometry of product edge which is part of product domain. On the other hand we can have pre-made component with carefully specified aspects in the product domain but if the connections with other components are not designed for disassembly than the disassembly of the whole component will again not be possible and so on.

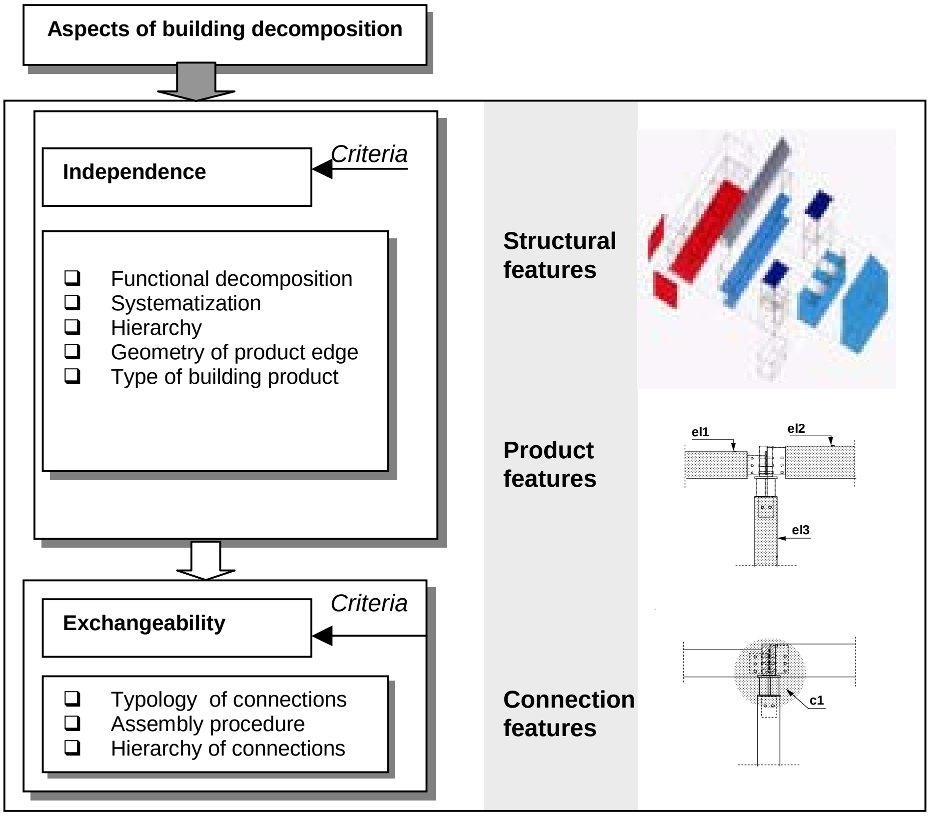


Figure 7: criteria for structural transformation

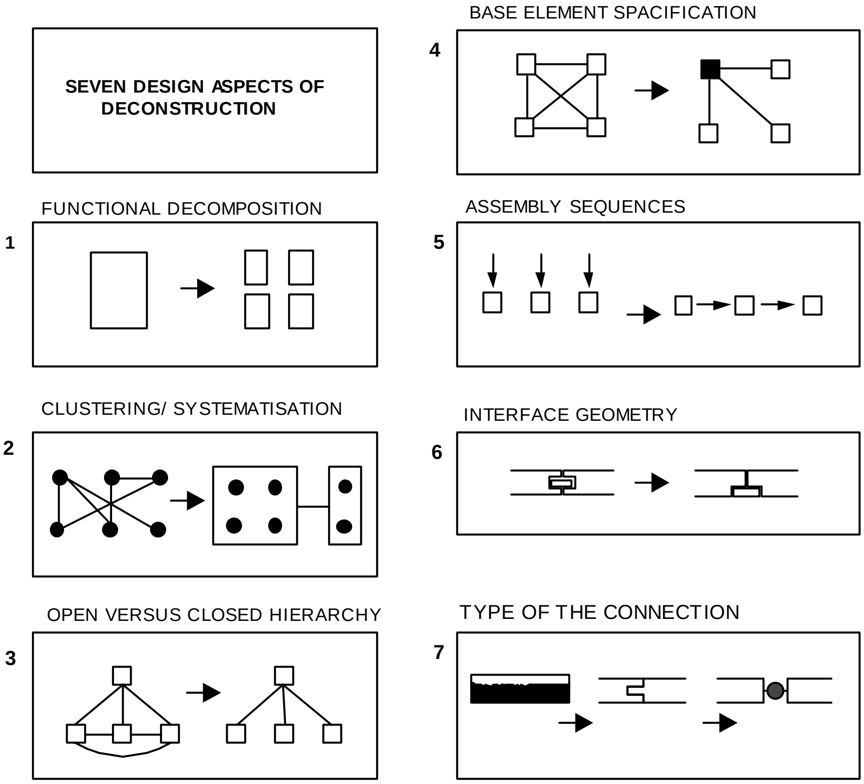
By analysing above specified aspect of structural transformation it would be possible to classify all building structures in rang from fixed, partly decomposable to totally decomposable.

Decomposable Aspects of Structural Configuration

Analysing the way building components are arranged and the relationships between them seven main design aspects of structural decomposition could be defined as listed in the table 2 below.

Specification of aspects in table 2 determines the performance characteristics of building structures and to what level they can fulfill the criteria of independence and exchangeability. Accordingly this will determine the disassembly characteristics of the structure itself.

Table 2: aspects of structural transformation



<u>Functional decomposition</u>

Decisions on whether the two or more functions are integrated into one building product or separate products are carriers of separate functions are made during structural composition design. The design for disassembly is in favour of total separation between different functions on all levels of the building's integration.

Four main building functions are supporting, enclosing, servicing and partitioning. Each of them has different behaviors and provide different effects such as heating, reflecting, distributing, ventilating, lighting or are dealing with effects such as tension , compression etc. Therefore the integration of two or more functions into one component can freeze their separation which may be necessary in order to answer new requirements.

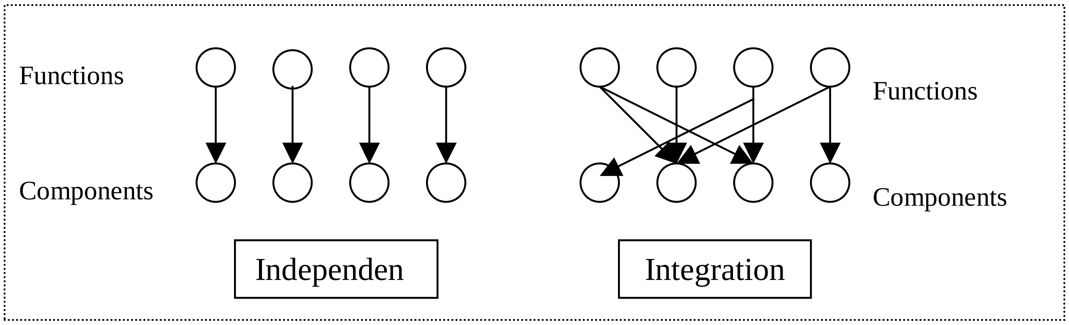


Figure 8: independence versus integration

Traditionally external walls, because of their composite and heavy structure, were seen as static and fixed parts of the building which are not supposed to be removed or transformed. Today such wall gained dynamic aspect since it has to enclose different activities, which are being changed quite frequently. Therefore there is immerging need to dismantle all functions which were kept within composite wall structure and allocate them thorough independent components so that the change or substitution of one function does not influence the integrity of others.

Clustering /systematisation

Traditionally all building elements were closely related to each other (with no respect to different functions and different Life cycles they had). In such environment the substitution of one element would have considerable consequences on all related parts at connections. One building component can be taken out from the building if it is defined as an independent part of the building structure. The first step that has to be made in that respect is to subdivide the building into different sections, which have different performances and different life cycles.

A subsystem is a cluster representing building elements which act as one independent building section in production and assembly-disassembly. The structuring principle for a subsystem aims amongst others at creating modular designs and standardization of elements on a sub-assembly level and on a component level. In that respect the development towards systematization and modulation of building parts into a subsystems presents the way to achieve more effective buildings with controlled use of row materials and less man power. The design team defines subassemblies based on required performance, production flexibility, system design and geometrical or mechanical criteria's.

Towards open hierarchy

When specifying the relations between subsystems for disassembly the hierarchy within the structure plays an important roll.

The hierarchy within the structure defines the order, which presents the path of the load through the building. This means that the hierarchy implies dependency, which is based on assembly. The load can be transferred through the building directly from one element to another.

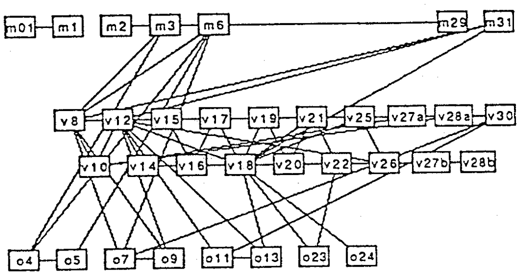


Figure 9a: close hierarchy (diagram of dependent relations within traditional building structure [12]

In such a way all elements become dependent from each other (figure 9a). The independence within a structure can be achieved by introducing a third part, which will take over the load bearing function.

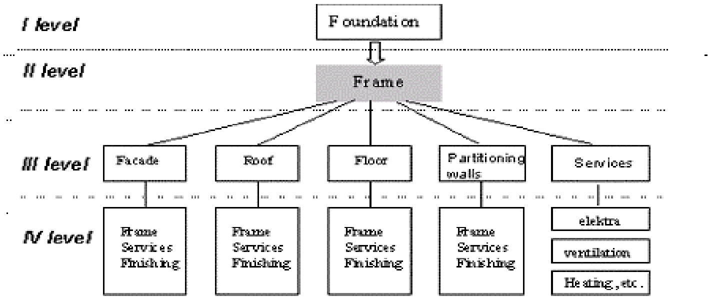


Figure 9b: Open hierarchy (principle diagram of dependent relations within decomposable building structure)

Generally if the traditional building structure = ∑ elements + ∑ relations, than the transformable building structure = ∑ clustered elements + ∑ coordinated interfaces.
Within open hierarchy building parts are kept independent from each other by creating dependent relation only to one element within assembly which is called frame or base element in this research.
Open Hierarchy can be achieved by different approach to design of building configuration. The main principle of new design approach should be recognition and separation of different time and functional layers of the building structure. This means that the design process should start with decomposition of the building into independent modules and base frame, which will connect distinct modules into one stable configuration (figure 9 b).

<u>Choosing the base part of one assembly</u>

Building product is a carrier of specific function or sub-function. Each assembled product represents a cluster of elements, which are carriers of sub-functions. In order to provide independence of elements within one cluster from the elements within the building, each cluster should define its base element which will integrate all surrounding elements of that cluster. Such element would be sheared on two levels in a building and its function would be dual: (i) to connect elements within independent assembly, (ii) perform as intermediary with other clusters.

The figure 10 shows four principles of defining the façade (for example) and the roll that specification of the base element can have on decomposition of the façade element. The principle 1 in figure 10 is based on the assumption that the building parts are assembled on the site. In this principle the elements, which according to their functionality belong to the functional assembly of the façade (f1), have direct relations with other functional assembly (load-bearing construction) (f2). The column (a) has the function of the base element for all elements in assembly, and therefore has connections with them all.
In principle 2, two functions (f1,f2) are clustered into one component. The wooden frame (b) is the base element for the whole assembly and at the same time, has load-bearing function in the building. This makes the construction process simpler but the change of one façade panel would have consequences for the stability of total structure.

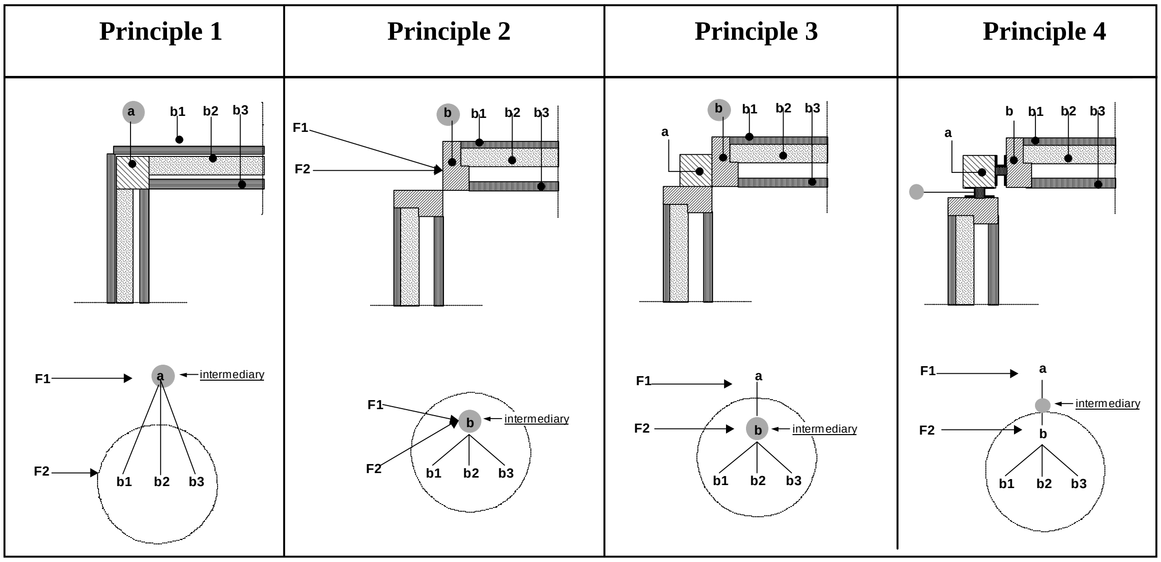


Figure 10: four principle solutions for the base part specification

Principle 3 shows the independent assembly of two independent functions (f1,f2). The elements that are assembled as façade (b,b1,b2,b3) are clustered into one component where the wooden frame (b) is chosen as the base element. Load-bearing function (a) is taken out and defined as independent assembly. In this case the load bearing elements act as the frame for whole building.

In the principle 4, a connection has function of intermediary between two independent assemblies. In this case replaceability of façade element (b,b1,b2,b3) would have no influence on the other assembly.

Product geometry

Disassembly sequences can be affected by changing the geometry of product edge. This aspect of the product feature is closely related to the interface design and specification of the connection type. Figure 11 left illustrates a standard detail which is often used in housing projects in the Netherlands. In this case disassembly of the window is not possible.

This is improved by change of the geometry of the connection figure 11right.

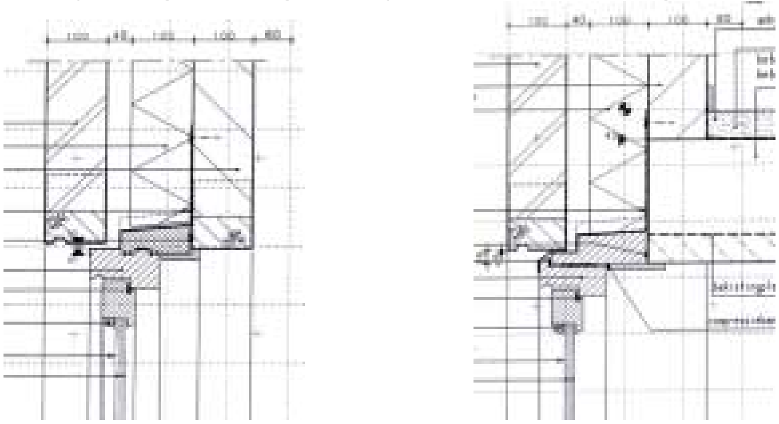


Figure 11: fixed and decomposable connection determined by the geometry

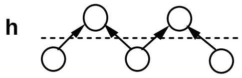
Assembly sequences gravity (attractor)

An assembly hierarchy shows the building breakdown from the assembly point of view. Two assembly sequences can be distinguished parallel sequence and sequential sequence.

Parallel assembly sequence can make the building process faster. While sequential assembly sequences create dependence between every assembled element and makes the substitution more complicated.

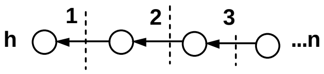
Five assembly relations could be defined based on above mentioned principles. The arrows in the figures 1 to 5 represent assembly sequences.

1 parallel



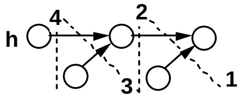
Parallel assembly. Disassembly will depend on the type of the connections between elements .

2 sequential



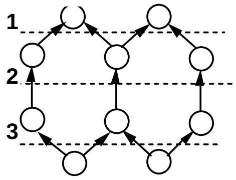
Sequential assembly. Each element in this assembly is fixed by a newly assembled element. In such a way a linear dependency is established which is proportional to the number of assembled components

3 interlock



Each element in this assembly has the same dependence as in number 2

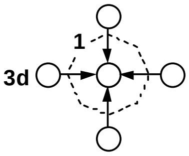
4 closed circle



This assembly scheme is a combination of 1 and 2. Transformational aspects of such a scheme will be related to the :

- Function of the elements which were assembled in the first three sequences
- Life cycle of elements which were assembled in the first three sequences
- Type of the connections

5 gravity (attractor)



This is an assembly where one element has the function of base element for all other. The key transformational aspect here is the type of connection between the distinct elements

Building interfaces

Design of building connection is the last aspect of design for disassembly. Interface defines the degree of freedom between components (figure 12), through design of product edge and specification of connection type.

In general it is possible to define three main types of connections such as direct (integral), indirect (accessory)[8] and filled.

Integral connections are the connections in which the geometry of component edges forms a complete connection. Two basic integral connection types could be distinguished (i) overlapped and (ii) interlocked. *Overlapped* (figure 12, principle II) connections are often used as connections between vertical external façade components or between vertical and horizontal components. Their disassembly depends from the type of the material which is used in the connection, assembly sequences, hierarchical position of the components and their relations with other components. *Interlocked (*figure 12, principle IV) connection is internal connection in which the component edges are differently shaped. Further on the shape of the edges allows only for sequential assembly what complicates the disassembly.

Accessory connections are the connections in which additional part is used to form a connection. Herewith two types of connections could be distinguished internal and external. Internal type incorporates loose accessory which links components. The accessory is inserted into the components. The connection possesses the advantages of identical edge shapes to the components. The dismantling of such connection can be difficult because of the sequential assembly sequences (figure 12, principle V). The accessory external joint makes the dismantling easier with applied cover strips or with combination of frame and cover strip (figure 12, principle VI).

Filed connections

Those are connections between two components which are filed with chemical material on the site (figure 12, principle III). Assembly of such components on site is more labour intensive. Those could be welded connections between to metal plates, or beam and column, or it can be connection between two concrete floor panels or bricks etc. Disassembly of such connections is often impossible.

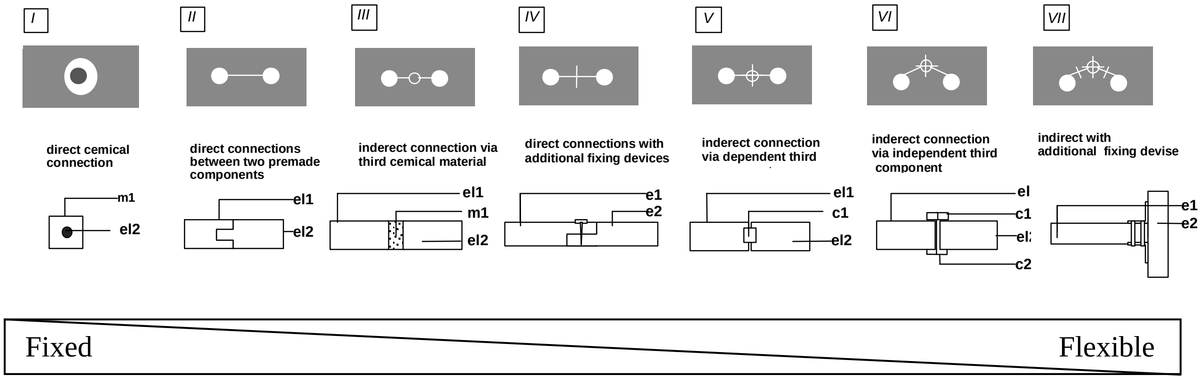


Figure 12: Seven principles of connections (m-material, c-connector, el-elements)

Four basic displacements that together make all transformations in the structure are elimination, addition, relocation and substitution. The structure of building or its parts can be transformed by the elimination of the element, it can be transformed by addition of the element, element can simply change its position in the building or element can be replaced with another one (substitution). The key technical problems here can be defined as capability of interface to provide decomposition, re-composition, incorporation and plugging in.

Two main criteria for design of decomposable connections therefore are:

1. all elements/components should be kept separated avoiding the penetration into another component or system
2. dry jointing techniques should replace chemical

These conditions should be applied accordingly on all levels in a building. In this way all systems brought together to form a building would be demountable, each component and element replaceable and all materials recyclable.

Furthermore disassembly characteristics of one connection depend on :
- The number of connection devices
- Type of the material used in connection
- Form of component edge

According to the above-specified characteristics connections could be grouped in hierarchical order from fixed to flexible. Figure 12 gives a hierarchical overview of the most common principle solution. The principle 7 (accessory connection) can provide technical solution for all four-transformation criteria. On the other hand the principle 1 represents the connection between two row materials which can only be demolished when changed. Further on principles range from direct integral connection (principle 2) whose decomposition is possible only if the whole structure is to be dismantled, principle 3 presenting connection between two elements with chemical connection and principle 4 where partial lap connection with additional fixing accessory creates precondition for decomposition and replace-ability. Finally principles 5, 6 and 7 represent dry connections where the position of accessory and its fixings determines their actual disassembly.

FROM FIXED TO DECOMPOSABLE STRUCTURES

By analysing the above-specified aspect of structural transformation it would be possible to classify all building structures in range of fixed, partly decomposable to totally decomposable structures.

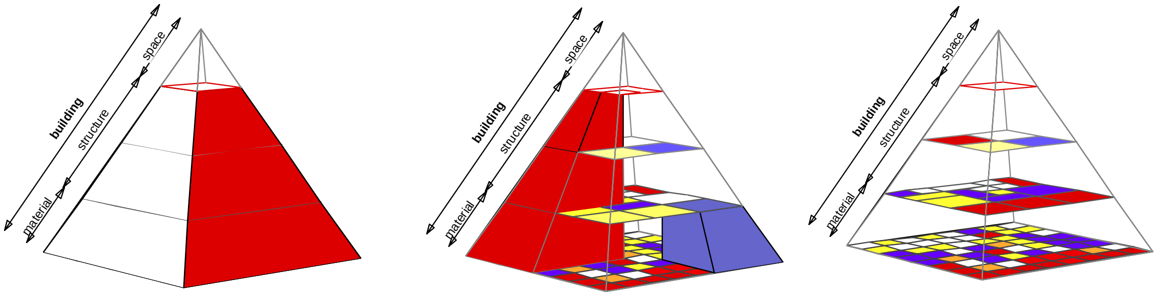


Figure 13: three principles of integration of material levels within the building [6]

<u>Fixed structures</u>
The main characteristic of *fixed* structures is maximal integration and dependence between building components caused by: (i)hierarchy of assembly which is not related to the component service life and expected time till obsolescence, (ii)application of sequential assembly sequences, (iii)design of integral joint type (components are shaped in such a way that bringing them together forms a joint), and (iv)use of chemical connections.

<u>Partly decomposable</u> structures are dependent on design strategies to which the hierarchy of fixed and flexible elements adjusted accordingly. Fixed elements are elements with high level of flexibility towards spatial and functional changes and high durability [6]. Flexible elements are elements which are frequently exposed to change.

The flexibility of such structures is restricted to the designed capacity of the fixed elements and the type of flexibility which was strategically chosen.

Totally decomposable structures can be totally dismantled at the end of their service life. That means that they could be relocated or that their parts could be reused in other combinations or be recycled. This group represents the structures which provide clear separation between all building components. They are composed of systems of modular parts that are easily transportable and usually dry assembled on site. Decomposable structures define a method of construction in which use is made of integrated structural, mechanical, electrical, envelop and partitioning systems in a way that will stimulate their independence and exchangeability. The most important aspect of such buildings is decoupling of levels that have different functional and life cycle expectancies.

The main characteristics of *decomposable* structures are (i)use of accessory joint types (they require additional third part to form the joint between two components), (ii)application of parallel instead of sequential assembly/disassembly, (iii)use of mechanical connections in place of chemical connections (iv) creation of open hierarchy of distinct modules. Such building configuration provide the precondition for independence and exchangeability of building components and accordingly their reuse or recycling.

Specification of Framework for the Diagrams of Deconstruction

Deconstruction characteristics of structural, product and connection features which are assessed through the aspects defined in this paper, can indicate the performance of the building structure in relation to its deconstruction. Through such assessment it would be possible to define the impact of different building configurations on the environment, and the potentials for building modifications. Structural, product and connection features of decomposition are mutually dependent. The disassembly of the structure is not feasible if one of these features is not optimised for disassembly. The decomposition on every level within the building can be presented through the dependent function of three variables (Sd-structural decomposition; Pd-product decomposition; Cd- Connection decomposition.
The dependence between different domains of decomposition could be presented through the 3D Diagrams. (figure 14)

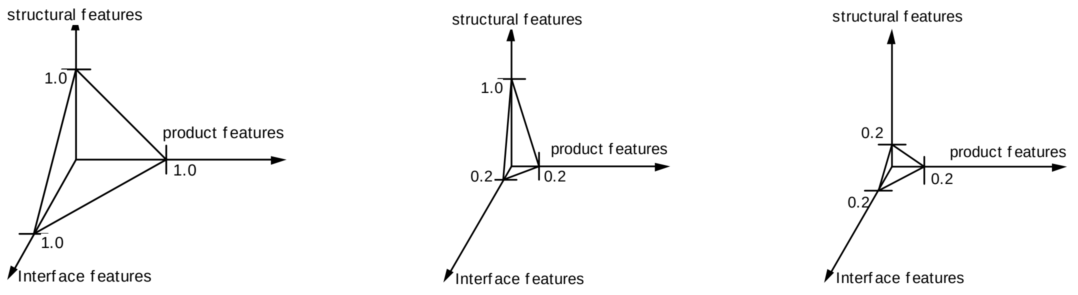


Figure 14: decomposable structure, partly decomposable structure, fixed structure

Diagram (figure 14 left) left represents a totally decomposable structure. This means that the structural decomposition features, product decomposition features and connection decomposition features are optimised for total disassembly. The diagram in the middle represent a structure which is partly decomposable like building which is constructed out of independent products but whose product features and interface features are not designed for disassembly (conventional system building). The diagram on the right is representation of fixed structure where structuring, product and interface features are not optimised for disassembly.

The success of decomposition can be measured on each level of building integration.

- ☐ Disassembly on building level deals with de-coupling of main building systems. The advantages are reuse of systems, spatial adaptability and functional adaptability of the building.
- ☐ Disassembly on system level comprises of separation between components, which are arranged into a system. The advantages are reuse of components, adaptability of system's functionality.
- ☐ Disassembly on component level deals with separation between elements and materials and its main advantage is in adaptability of the component's functionality, reuse of the elements and recycling of the materials

WHEN DECONSTRUCTION TAKES PLACE

The life cycle assessment of the deconstruction phase of the building can be measured by the energy which is being used for deconstruction and waste being created during deconstruction.

Buildings which can be easily transformed and whose components can be reused in another combination or recycled are more favorable than buildings whose only option during the deconstruction phase is demolition and waste disposal. Let us compare, for example, two brick facades. Brick elements put together in a traditional way create composite mass structure and brick elements put into a frame and fixed with bolts (R.Piano IRCAM building in Paris) compose a decomposable structure. Those are two extreme solutions showing that it is possible to design decomposable (sustainable) façades using traditional building materials such as brick, by inventing new ways of arranging bricks into a coherent configuration.

Of course the type of configuration that should be designed is related to the question of when the deconstruction will take place. Optimization of all aspects of structural transformation is related to the specification of two types of scenarios: use scenarios and end of life cycle scenarios (already discussed in previous text) of building products.

Buildings are constructed of elements and components which have different functional and technical life cycle. This can result in three lifecycle coordination scenarios.(figure 15)

1. functional durability of the component < the technical life cycle of the component.
   Such components should be reusable or recyclable
2. functional durability > technical life cycle of the components.
   Such components should be replaceable and recyclable.
3. functional durability = technical durability.

Such components should be recyclable

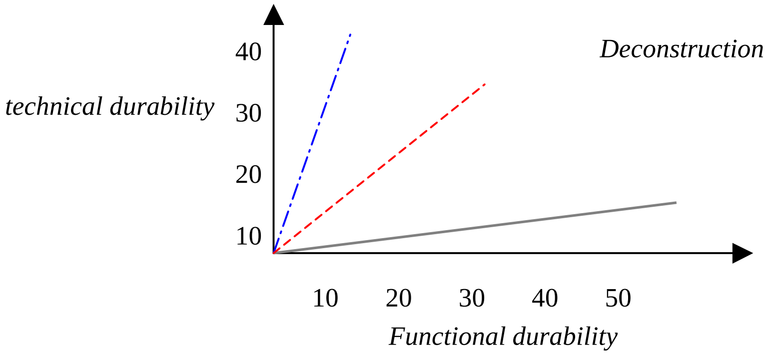


Figure 15: Technical and functional life cycle coordination

Our built environment is operating a great deal within scenario 1. Most of the social housing projects, offices and shopping molls could be located within this scenario. Those are buildings whose use sequences are relatively short compared to the technical durability of the whole building structure. Although the user requirements are often unpredictable it should be possible to define patterns of change within this group of buildings so that transformational aspects of their structures can be defined. Through building categorization it would be possible to define different morphological groups of structures and their transformational aspects.

Groups of buildings that belong to scenario 2 are monuments. For these types of buildings the maintenance of the building structures is the most important aspect.

Finally scenario 3 is to be found within a temporarily buildings. Such buildings have minimal number of time levels. The priority in configuring the structure for such buildings is in design for recycling.

Generally speaking deconstruction takes place between elements, component and systems which have different functional and technical life cycle. Theoretically speaking scenario 3 can operate within one time level. Scenario 2 can operate within 3 time levels. The number of these levels depends on the number of maintenance sensitive levels. In this case those are usually installations and finishing. Finally scenario 1 can be designed with up to X independent time levels. Their number depends on the scenarios for future use of the building and its components. The more time layers can be defined the more transformation sensitive the structure is and the longer life it can have.

CONCLUSIONS

Conventional building structures are not designed for change. For that reason every transformation within the building has to do with demolition of parts of a building or sometimes whole built structure. In order to increase the building’s transformation capacity building construction has to focus on further systematization of building and development of innovative building methods that will provide flexible structures whose parts could be easily replaced and reused or recycled. In order to achieve this we need to change our perception of the building and its structural configuration. The assessment of structural configuration can help us to understand the nature of change and to define the transformational potentials of different structural morphologies.

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RECONSTRUCTING DE-CONSTRUCTIO

John Storey (Centre for Building Performance Research, Victoria University of Wellington, New Zealand)

SUMMARY

In a recently completed project, the author carried out a major redesign and eco-renovation of a house in Wellington, New Zealand, which incorporated de-construction and waste reduction practices as major imperatives in its design approach. This paper explores the de-construction and the reconstruction of this house using components and materials recovered from the original house. The challenges, opportunities, successes and the problems encountered together with their resolution are described. Waste reduction policies employed and the use of recycled materials in the redesign are also discussed. The paper concludes with a discussion of the lessons to be learnt and how they can be applied to future work.

Fig 1 Lambie House east elevation, extensions are to north and south of central, remodeled upper floor centre and retained lower floor.

INTRODUCTION

In 1998 the author was commissioned to carry out a major domestic eco-refurbishment and upgrade of a 1950s house. The clients wanted an architectural solution which was at once ecologically and environmentally sound, aesthetically pleasing, comfortable, healthy and life-enhancing, but also built within the standard budgetary constraints of a normal home. The house had also to be adaptable to the changing needs of the owners and be a sound financial investment. The existing house was built with good quality, durable materials but was poorly planned, spatially mean, crudely built and not compatible with the user’s existing or future lifestyle intentions. It did however occupy a wonderful site, an easterly facing steeply sloping section, sheltered from the predominant northerly and southerly winds, which had delightful and expansive views across Wellington harbour and was open to the northerly sun. The redesign created an expansive, elegant, highly crafted, comfortable and life enhancing home. Scenario Planning was used to ensure that the home could be readily adapted to changing client lifestyle demands. The design successfully incorporated passive solar design principles, the use of sustainable and healthy new materials, and a series of crafted elements to give continuing delight and pleasure to the owners. Both architect and clients wanted to reuse and recycle as much of the existing house components and materials as possible.

THE BUILDER

While both the architects and the clients were committed to creating an ecologically and environmentally friendly outcome it proved to be extremely difficult to obtain the services of a building contractor who shared these intentions and was still able to produce good quality work at an affordable price. A builder was employed who had a good track record in conventional building work. Very carefully prepared contract documentation [1] and verbal dialogue with workmen were the primary methods used to try to ensure contractor compliance with the ecological and environmental design intentions.

A good deal of extra time and effort was spent on preparing this documentation and in explaining the intentions both to the main contactor and his workmen, but this approach met with only limited success. Fundamentally the principal contractor sought to avoid any extra work or costs that the ecological and environmental intentions of the project imposed and did not instruct his own workmen or his sub-contractors concerning associated contractual requirements. It was left to the architect and the clients to catch deviations from the specification and drawings. The clients remained on site for the whole of the duration of the contract and were extremely conscientious about informing the architect of possible deviations from the terms and conditions of the contract. The architect spent considerable extra time in following these reports through and insisting on compliance with the contract and in the end the contractor realised that it was going to cost him less time and expense to comply with the contract than to attempt to ignore these requirements. Things started to improve from then onwards but with a constantly changing workforce, numerous sub-contactors and an uncommitted main contractor, compliance remained an uphill battle throughout the duration of the contract.

WINDOWS AND DOORS

One of the major design strategies involved was to reuse as many of the existing building components as possible, consistent with the satisfying the stringent design intentions and the New Zealand Building Code requirement of ensuring a 50 year minimum life expectancy for the remodelled house. The New Zealand Building Code [2] is one of the few building codes worldwide that has a stringent durability clause [3]. All building materials used structurally whether new or reused must be certified by a structural engineer as lasting for at least 50 years in the specific context of use. New or reused cladding materials must have a certified lifespan of at least 15 years and all other materials 5 years. If a designer chooses to reuse components and materials they become the defacto certifier and if failures occur within the designated durability provisions, they can be sued. In this case reused structural members were examined by a structural engineer and the architect examined the other reused components and both were prepared to take the risk involved.

The reuse of doors and windows was seen from the very beginning of the design as both an economic and a resource efficient approach to the redesign of the house and a worthwhile objective. It could be argued that the reuse of the windows without upgrading the thermal performance of the glass might undermine the overall resource efficiency objectives of the design. However the reality is that the massing and fabric design is such that heat from the sun together with that emitted by the chip heater which supplies the hot water for the house means that no extra heating is required on the main upper floor apart from the occasional employment of a 2 Kw electrical fan heater for an hour or so on a few very cold days in the year. Future plans include for the utilisation of waste heat from the chip heater and kitchen areas to heat the rooms on the lower floor when finance allows.

It proved to be a challenging but not overly restrictive requirement in terms of the design development. Windows and doors have a major impact on the visual coherence of any building. Great care was therefore taken to integrate existing and new windows and doors and to create a unified architectural expression for the building as a whole and for each of the spaces, while still seeking to make a modern architectural statement. Externally, painted timber componentry is the obvious unifying factor but fitting the new windows into the existing overall architectural form of the building and retaining a similar scale and proportion in the new work are in fact the primary contributing factors to the deliberate, visually cohesive integration of old and new. Modern timber sections are deliberately used rather than seeking to replicate the original sections, as the new sections work better and are less expensive and resource intensive than the older sections, but also so that old and new could be identified by those with a discerning eye.

Fig 2 Visual integrity of reused windows, furthest away, new windows centre and retained existing windows, nearest to the camera.

Internally there are three conditions, one where the original component has been retained, one where existing components have been reused and one where new components have been used. The rules applied were that each of these conditions was to be identifiable in the final work and that within any given space only one category of components would be used for each component type. So for example, new windows and their linings and architraves were clear finished internally, reused windows and their new linings were painted internally but their architraves were clear finished and existing windows with their linings and architraves were simply repainted. Only new windows or reused windows or existing windows were however used in any single space. They were never mixed. The notion here was to combine a pleasing variety with underpinning rationale related to resource conservation and historical referentials which were understood by the clients but were not readily apparent to the casual observer.

All the existing windows except one small unit and all the existing external doors and screens except one were reused. All interior doorsets except three were also used. New windows and external doors were only necessary in the main living and dining space, entry and sunspace. Existing windows were used in the new kitchen, utility, bedroom, bathroom, hallway, study and cloakroom areas. Existing windows were retained in the new family room and in those rooms where only minor changes were effected on the lower floor of the house. Existing exterior doors and door screens were incorporated into the new bedroom spaces without adaptation. All internal window and door sills, linings and architraves had to be replaced in the reused windows and exterior door and door screens because the original sills and linings were inevitably damaged during extraction of the windows and doors from their original locations. Some limited adaptation of three of the existing windows occurred by way of removal of one of the panes in these multi-pane windows, but in all other instances the whole window was reused. All reused windows and exterior doors had their hinge actions eased and were weather-stripped to control draughts and heat loss. New hardware was fitted to provide additional security, to provide design consistency and because after nearly 50 years of constant use much of the existing hardware was in poor condition.

Fig 3 Reused window, interior view.

Fig 4 Retained existing window, interior view.

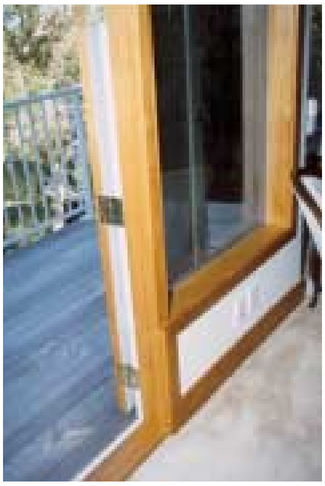

Fig 5 New window, interior view.

Interior doors were panelled to unify them visually with new doorsets and in consequence the rebates in existing frames had to be deepened. New architraves and hardware were provided for the reused interior doorsets. Three interior doorsets were riddled with borer and could not be reused. Financially the reuse of the existing window and exterior door components generated significant cost savings, but the reuse of interior doors was less financially beneficial and resulted in only marginal savings. Both resulted in considerable resource savings.

Fig 6 New entry door and reused flush door, paneled to give visual identity.

ROOF

The clients were very concerned at the lack of head room in the existing house and the architects were required to address this deficiency in the redesign. The existing roof was a minimally angled monopitch, with a multi-layered bituminous felt finish laid on timber boarding and beams with an uninsulated, flat ceiling below. The felt was at the end of its useful life; it leaked and was very unsightly. Appearance was important as the building is approached from above and the roof is in effect the fifth elevation of the house.

Fig 7 The fifth elevation.

The architects wished to retain the existing sound roof structure and decided to add a new weather skin above the existing roof supported by the existing roof. Initially the architects designed a solution which involved cutting the existing roof boarding and weather skin along the line of an existing, longitudinal structural wall and lifting the roof above an internal structural wall to create a double pitched roof with a central ridge. This involved pivoting the roof structure on the external walls and building up the central structural wall. A specially designed, structural, gusset plate connector was used to close the gap created at the ridge. The reconfigured roof plane was then to be overlain with a corrugated metal roof on battens and the gap between existing and new roof planes ventilated. The ceiling was to follow the line of the underside of the beams to maximise the spatial gain. Wool insulation was to be inserted between the beams.

Client, structural engineer and quality surveyor and architects were all happy with this solution but none of the tendering building contractors would quote for carrying out this part of the work. All were concerned about the roof being lifted off the wall and damaged by the wind during the pivoting operation. Wellington can be quite windy but in fact this site is very sheltered. Both client and architects explained this to the contractors but they were adamant in their refusal to tender for this part of the design. It may have been possible to find a builder who would have built the design but it seems likely that there would have been a cost premium involved, rather than a cost saving, which was one of the appealing aspects of this design. Reluctantly the architects redesigned the roof. In the final design the existing roof was left in place and a new metal roof weather skin fixed on top of this on battens, with a ventilation gap between the two roof finishes as in the previous design. The flat ceiling was removed and a sloping ceiling was incorporated which followed the underside of the existing beams and wool insulation was incorporated between the beams all as before.

Fig 8 Thick roof edge resulting from encapsulating existing roof within new roof.

The intention was to reuse the ceiling battens to construct the new ceiling. However some of the existing beams and battens had warped and for the eastern two thirds of the ceiling it was necessary to remove the existing ceiling battens and replace them with a low profile metal levelling laths. This lost a very precious 25mm of the floor to ceiling height but resulted in a very good quality ceiling plane in the large living area spaces. Existing ceiling battens were reused in the westerly third of the ceiling, within the utility and kitchen areas.

Initially the changed design was regarded as something of a compromise but in actuality it worked out very well. The final design was less costly than the original design and the increased height generated within the living spaces by taking the existing ceiling void into the rooms proved to be perfectly satisfactory to the clients. Indeed the new living areas have a very generous, spacious feel. The main living spaces open to the sun rather more in the final design than in the original redesign. This has the effect of making views more expansive but increasing solar penetration in summer causing some over heating on summer mornings. This is easily dealt with by opening doors and windows at either side of the house for a few minutes.

There were a number of additional bonuses associated with reusing the existing roof. Metal roofs are notoriously noisy. The noise of raindrops hitting the roof and creaking associated with thermal and wind stressing is often transmitted to interiors, and can be quite irritating. In this building the noise transmission is well muffled so interiors are significantly quieter in all conditions. Overheating of the interior through the roof in summer is mitigated by the double roof and ventilated cavity. The internal insulation value of the roof is also increased. The weather protection created by retaining the existing roof enabled work to proceed on-site even on very rainy days and protected the existing hardwood floor and the lower storey of the house, which remained predominantly unaltered.

Fig 9 Extra height gained by incorporating ceiling void into the living space.

EXISTING FITTINGS AND FIXTURES

The specification required all existing fittings and fixtures which were not required for the renovated house to be carefully removed and handed over to the client. The client in turn made strenuous efforts to re-use or sell the recovered fixtures and fittings. One of the kitchen worktops was adapted and now serves as a desktop in one of the studies. The other kitchen cupboards and worktops were adapted by the client’s son and now serve as workshop benches, cupboards and shelving in the garage. An existing bookcase was moved and adapted for use in a study area. Yet other fittings were disassembled and the timber stored for future use.

Fig 10 Kitchen worktop adapted and reused as desktop

Recycled native hardwood was used to make a purpose designed vanity unit for the main bathroom. This was costed and proved to be no more expensive than an off-the-shelf or a purpose built unit using new materials. The purpose built vanity unit has much more character and craft than either of the alternatives and is a very pleasing and successful feature of the bathroom area.

Fig11 Purpose built vanity unit made from recycled native hardwood.

MATERIALS

The general policy was to retain as much of the existing materials on-site and minimise waste sent to the landfills. Considerable efforts were made to devise ways of incorporate as much of the existing materials as possible into the renovated building.

The whole of the cedar weatherboard siding on the upper floor of the south end of the existing house had to be removed to make way for the extension. This siding was in very good condition and the extension was designed to incorporate all the recovered siding and avoid the need to purchase new weatherboards. A seemingly conservative recovery rate of 70% was presumed in the design. In the end a recovery rate of just over 40% was achieved.

The builder claimed that the cedar was very brittle, and split very easily. There was an accretion of nearly 50 years of paint on the boards, representing at least 5 layers of paint and the builder had not thought to run a knife along the interface between the boards to cut though this film. It also eventuated that the people assigned this task had little experience in this operation and had not been shown how to do to maximise recovery. In retrospect it might have been worthwhile for the architect to be present at the start of this operation to stress to the workmen the seriousness of the intent and to ensure that best practice was employed although theoretically this should not have been necessary. The suspicion remains that insufficient care or skill was exercised by the builder in springing the boards.

It did however prove possible to reuse recovered hardwood flooring from the house to board over the old stairwell and repair areas of flooring damaged during de-construction and so avoid the need to bring in new materials.

The original intention was to distribute all excavated material around the site. The quantity was quite large, but a high proportion was dealt with in this way. Again the builder's attitude to moving the excavated materials to desired locations was generally unhelpful. In the end some 20m3 of material were removed off-site when all the easily accessible areas of the site had been fully utilised, but between 100-120m3 had been dispersed on site by this stage. The general locations for disposal around the site were agreed with the builder and his workers started well, but careful placement took too long for the builder's budgetary comfort and after a while the spoil was dumped anywhere that was convenient to the builder. This resulted in acrimonious arguments between builder and the architect/clients. Both parties learnt from the encounter supervision levels necessarily increased and contractor work practices improved.

It was intended to retain as much of the existing gypsum wallboard linings as possible. However, a combination of circumstances militated against this intention. The whole of the ceiling had to be reconfigured as explained above, and virtually every wall in the upper level of the existing wall was removed or substantially changed. Some of the retained timber framing in walls had warped over the years and walls had to be realigned, using a mixture of recovered and new framing. The interior linings to all the exterior walls had to be removed to insert thermal insulation. Much of the remaining wall lining was badly damaged during removal of ceilings, doors and fittings. In the end there was so little sound gypsum board left that it would have taken more effort and resources to retain it and integrated it with the new wallboards than to remove it. There is no gypsum recovery programme at present in New Zealand and so once the gypsum board was removed there was little option other than sending it to the landfill, despite the aversion of both clients and architects to this practice. In retrospect it might have been possible to dig at least some of the wallboard into the soil to improve soil quality. However, this option was not considered at the time.

The only other items that were sent to the landfill were small quantities of concrete, asbestos based tiles and preservative treated timber and general rubbish. The asbestos tiles were carefully removed without creating dust and were dutifully double bagged before being sent to the landfill where they are located in special areas. This is the approved method of disposal in New Zealand. Even less care is taken with preservative treated timber. It was recognised that it is undesirable to incorporate hazardous wastes into landfills but there are no alternatives disposal methods currently available in New Zealand. Curiously despite the increasing awareness of the hazards associated with the disposal of such hazardous and potentially polluting materials two major recent government policy and strategy documents fail to take these matters into consideration at all [4] [5].

The remaining waste material was timber and this was handed over to the clients who stored it and cut it up for use in their chip heater. The chip heater is a solid fuel stove which is used by the clients to burn all inflammable wastes that cannot be recycled or used to make compost. The chip heater is the primary method of generating hot water for cooking and bathing in the house. Generally it only needs to operate for about one hour per day to provide sufficient hot water for these purposes. There is an electric immersion heater as back-up but this is seldom used.

CONCLUSION

The attitude if both clients and contractors are key factors to achieving successful outcomes in the area of de-construction and resource recovery. In this instance the architects and clients were in total accord on this issue and sought to practise resource recovery in all aspects of this project. These intentions were backed up by carefully written specifications and contract documentation and by close observation of the works by client and architect. Despite this not everything went smoothly.

Some of these difficulties can be attributed to the indifference of the contractors to resource issues and their unwillingness to try new ideas. The former can be observed in the very low recovery rate achieved for the cedar siding. Being more careful would have probably resulted in a significantly higher recovery rate but in theory would have cost the contractor more time while using new materials would ‘only’ cost the client and the planet. Interestingly, it proved quite difficult for the contractor to source materials of adequate quality to match the existing weatherboards. This caused delays in achieving weathertight enclosure which had quite significant ‘knock on’ effects. In the end these delays probably cost the contractor more than the extra over cost paid by the client for the new materials, so everyone was the looser in this instance. The roof turned out to be a success story but everyone; including the quantity surveyor in the design team was surprised at how timid the contractors were and were puzzled by their unwillingness to try to do anything even a little different.

With the contractor getting the resource recovery measures implemented was something of a challenge, but his work was a reasonably high standard and generally once he had committed to a course of action the result was good. This was the case in relation to the roof, the re-use of windows and doors and the removal of fixtures and fittings. Only on the areas of disposal of excavation materials and recovery of weatherboards sidings was his performance disappointing. The diligent observation of the works by the clients and the insistence in the compliance with the contract terms by the architect’s throughout the project probably encouraged all the builders to stick more closely to the contract requirements for resource conservation than they would have wished. The obvious lesson here is to only employ contractors who are sympathetic to the objectives and intentions of the clients and architects in relation to de-construction and re-use of components and materials. This is quite easy to say but not quite so easy to do. Symbiosis, the architects, know of only two builders who share these beliefs in the region, one works outside the Wellington area and the other declined to tender because the job was too big for them. Wellington needs a ‘Green Builder’ programme like that established in Austin, Texas in 1992. In this programme, builders are encouraged to learn about and adopt sustainable construction practices by participating in an active education and support programme provided free of charge by the City of Austin. Registered Green Builders are able to rate the houses they build under an environmental rating system controlled by The City and thereby obtain a marketing edge over their rivals. Providing both the educational support and business incentives to encourage the involvement of builders is a vital aspect of achieving sustainable architecture in practice in practice. Unfortunately there seems little likelihood of this initiative being replicated in New Zealand in the foreseeable future.

Material /Component	**Disposal method**	**Reason for treatment**
Gypsum wallboard.	Landfill	Badly damaged by disassembly. No gypsum recovery system available.
Excavated earth.	85% redistributed on site. 15% landfilled.	No further space on site for this low grade fill.
Timber.	100% exterior wall framing reused. 50% interior wall framing recovered and reused. 40% recovery and reuse of ceiling battens. All timber which was not reused on site or stored for future use was retained and used to fuel the water heating wood burning stove.	High grade timber with little sign of deterioration after 50 years of use. A significant percentage of the lower grade timber used in interior walls and as ceiling battens had warped badly and could not be reused.
External timber doors and screens.	100% recovery 66% reuse in house 33% retained for future reuse	It is likely that the unwanted door will eventually be sold to a building recycler. There is a good market for such items.
External timber windows.	100% recovery 92% reuse. 8% retained for future reuse.	It is likely that the unwanted window will eventually be sold to a building recycler. There is a good market for such items.
Asbestos roof soffit lining board, interior floor and exterior decking tiles.	Bagged in two layers of polythene and landfilled.	This is currently the only approved method of treatment available.
Kitchen cabinets and worktops	Recovered and adapted and reused as work benches cabinets in garage One section of worktop adapted and reused as desktop in home workspace	Existing cabinets and worktops of good quality but unsuitable for kitchen configuration required by owner.

Cedar weatherboard	Weatherboard on south wall removed 40% recovery.	Low recovery rate attributed to lack of skill and care by builder. Timber was sound and a much higher recovery rate should have been possible.
Timber floorboards	95% recovery of removed material. 90% reuse on site. 10% damaged during recovery, but retained by owners for future use	Flooring is high quality native timber (Matai) and is valuable, sought after and increasingly difficult to access.
Sanitary ware	Landfilled	Low quality items in poor condition after 50 years of continuous service, no market.
Hardware	Metal recycler	Low quality items in poor condition after 50 years of continuous service, no market other than for metal salvage.
Concrete	Landfilled	Small quantities only. No recovery programme in Wellington.
Preservative treated timber	Landfilled	Small quantities only. No other method of disposal available.
Timber Cabinets	Handed over to owners who carefully disassembled and retained timber for future use.	Timber valuable native hardwood.

Table 1 Recycling, Reuse and Disposal Methodologies Employed

On the positive side there was very little waste. Expensive, resource intensive elements like windows, doors, kitchen cabinets were virtually all reused or were handed over to the client for future use. The roof was also reused. Sanitaryware and hardware was, after 50 years of constant use, quite worn out and beyond salvage. Only small amounts of concrete, timber and assorted rubbish and modest amounts of excavated were landfilled. Despite the small quantities involved, it would have been preferable to dispose of the asbestos based tiles and treated timbers in a safer manner. Instead they were disposed of with other material in a local landfill. There is no alternative disposal method currently available in Wellington. Neither the main landfill nor the privately owned building waste dumps are lined to prevent chemicals leaching out into ground water. The Wellington region needs a hazardous building materials disposal facility but the author knows of no current moves in this direction.

In the end this renovation is an exercise in the art of the possible. Nothing has been done in this project that could not be done easily in any other project. The de-construction and recourse conservation measures taken resulted in both financial and resource savings. It could be argued that both clients and architects had to put in considerable extra time and effort to achieve the results obtained and that is certainly true; but both were committed to this course of action from the beginning and both knew that the de-construction, reconstruction process would require them both to put in extra effort and commitment to obtain the desired results. However in an age of competitive fee bargaining not many architects feel able to devote the considerable extra time to save their clients money or the world resources, and even fewer clients are prepared to pay extra fees to make such resource savings. This is a considerable disincentive for architects to undertaking resource conservation measures in the normal course of events. Discussion on the relative merits and de-merits of alternative fee structures to encourage de-construction and re-use is beyond the scope of this paper but it is a significant and germane factor in espousing the widespread adoption of de-construction and the re-use of existing components in renovation and deserves specific attention.

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UNDERSTANDING THE CONCEPT OF FLEXIBILITY IN DESIGN FOR DECONSTRUCTION

Dennis S. Macozoma CSIR Building and Construction Technology PO Box 395 Pretoria South Africa

ABSTRACT

Design for deconstruction (DFD) means the design of a building and its components with intent to manage its end-of-life more efficiently. Adopting DFD principles during the design stage of a construction project can ensure building flexibility for adaptive use and easy component and material disassembly for reuse and recycling. Incorporating DFD principles at building design stage will ensure that both the asset management and building removal processes are conducted more efficiently with minimum resource consumption and environmental impact. Building flexibility can also be enhanced through the selection of a suitable design team that is committed to environmentally responsible construction, incorporating flexibility principles and the use of innovative construction methods. A new perspective that is increasingly being debated is that of considering existing buildings as a resource pool for future building material needs. In order for buildings to fulfil this role DFD will be a key factor in the retrievability of components and materials for extended use in future projects. This paper will describe the issues that need to be considered during DFD in order to ensure building flexibility.

KEYWORDS: Durability, Adaptability, Flexibility, Design for Deconstruction

INTRODUCTION

Design for deconstruction (DFD) refers to the design of a building with the intent to manage its end-of-life more efficiently. It ensures the easy disassembly of buildings in order to reduce waste generation and maximise the recovery of high value secondary building components and materials for reuse and recycling. This process encourages designers to incorporate flexibility into buildings at the design stage in order to ensure efficient building operation, maintenance and removal. By allowing for a variety of scenarios for building management from its occupation to its decommissioning, DFD reinforces the need and advantage of considering the whole life cycle of a building and its components.

One key determinant of successful building disassembly is the ability and ease of component and material recovery. Much of the current difficulties with building deconstruction are a result of the inflexibility of existing buildings, which were not designed to be taken apart. Existing buildings are increasingly being seen as one of the preferred resource pools for material extraction to satisfy future construction needs. For buildings to fulfil this role successfully, component and material retrievability will be very important, which in turn depends on the design approach employed at the beginning.

This paper will explain the concept of flexibility and show how and where it must be incorporated in design for deconstruction to yield buildings that are fit enough to last and versatile enough to accommodate changes in the environment. Section 2 defines flexibility, sections 3-6 look at construction process considerations, section 7 presents a list of principles for design for flexibility and section 8 gives a hierarchy of end-of-life options for buildings and their components.

WHAT IS FLEXIBILITY?

Buildings are constructed to last and satisfy the needs of the user. In technical terms, they are expected to have longevity. The longevity of a building is determined by the building's ability to maintain structural integrity for a long time as well as maintain desirability in terms of its functionality and style [1]. Structural integrity is determined by the quality of construction (i.e. material strength and construction method) and the durability of materials. Desirability on the other hand is determined by the building's ability to adjust to the demands of a changing environment, termed adaptability.

Durability is a quality incorporated in the design of buildings to ensure that a building is able to withstand various conditions that it will be exposed to over time. Designing for durability can save costs and reduce the negative impacts related to building operation and maintenance e.g. the consumption of materials during renovations and the resultant waste generation. However, if a building becomes obsolete long before its intended structural end-of-life, the above can be reversed i.e. the incurred costs of durable materials (usually expensive) may not be recovered because of the building's short life [2].

Adaptability allows a building to be versatile enough to accommodate the changing requirements of the physical environment within which it exists and the users which occupy it [1]. Changes may affect the exterior and/or interior of a building. The building needs to be designed in such a manner as to allow for modifications of either of these without affecting the other.

A strike of balance between durability and adaptability in the design of a building is thus very important. This balance is called flexibility – an important quality in buildings that are designed and constructed according to the principles of sustainable construction.

Taking the concept of flexibility beyond technical bounds, one comes across the notion of process flexibility. Process flexibility focuses on the design and construction team and what influence they have on the building's final flexibility [3]. It has two areas i.e. flexibility in the decision making process of a project and the flexibility of the construction process (from idea generation to building decommissioning).

Designers are called upon to be flexible enough to identify and engage other stakeholders in the construction project. Where necessary, designers should take time to build capacity in green construction and find best practice examples of similar projects. User needs and changing trends in the surrounding environment should be incorporated in the design. Furthermore, the design team and contractors should be open to changes (where warranted) during the construction phase if this will lead to increased building flexibility.

STARTING POINT – SELECTING THE CLIENT TEAM

Decisions made during design affect the flexibility of buildings. Design also determines the retrievability of building components and materials in buildings. As indicated earlier, many of the current shortcomings of building deconstruction are because existing buildings were not designed to be disassembled. It can thus be stated that “design is at the heart of green construction”.

The client team as a whole plays a pivotal role in the direction taken by a construction project. The client (or owner) is said to be the main driver for waste prevention and green buildings [2]. This is because the client can specify what he/she is prepared to pay for and since he/she is likely to be the end user of the building, its performance is very important to him/her. However, in some cases the client is either unaware or unable to use this ability. The architect and engineer have a responsibility to look after the client’s interest, particularly if the client has limited knowledge. If designers are also unaware or lack experience in green building, then it is likely that the resulting building will lack the necessary inherent flexibility to be both durable and adaptable.

It is thus important for clients to be exposed to environmental information that can increase their knowledge of sustainable construction (this is mainly a government and construction industry responsibility). Through the implementation of programmes such as a contractor rating system and registers of green designers, clients can select a construction team that is committed to green buildings. Green designers are characterised by open-mindedness, consideration of the whole service life of buildings and concern for the environmental and social implications of construction activities (over and above the economic). Although such designers are not in abundance, more and more best practice examples are beginning to surface internationally.

Designers can contribute to achieving building flexibility by:

- Consciously incorporating principles that allow for building disassembly, and component and material reuse and recycling
- Incorporating secondary material use in new buildings
- Innovations in building conversions

It must however be acknowledged that some constraining factors need to be addressed if designers are to transform to a “Green Status”. These factors include:

- Fear of change (dependence on the norm, insecurities and misconceptions)
- Motivation (regulatory and financial incentives)
- Integrity (acceptance and certification of secondary materials)
- True vs. hidden costs (life cycle costing and environmental accounting)

- Recognition (rewarding resource efficiency not payment according to quantity or project cost)

BUILDING DESIGN

Designers are increasingly called upon to produce designs that take the entire building life cycle into consideration. Such designs are intended to accommodate issues such as the current trend of short functional tenure of specific user services in buildings with a long technical service life. Building obsolescence, whatever the cause, is becoming a major cost in the built environment e.g. capital costs of new developments replacing existing obsolete buildings, loss of value and energy embodied in obsolete buildings and costs associated with building removal, waste disposal and the associated environmental impacts.

Buildings have evolved from the age-old approach of being designed as "eternal entities" to the current notion of "finite contemporary buildings" designed to last anything from one decade to over a hundred years. The major shortcoming of the eternal building approach is the inherent inflexibility that makes building modification to suit a changing environment a cumbersome exercise. Craven *et al* point out that buildings with such inflexibility tend to generate more waste when modified and sometimes leave no other option but to be demolished [4]. Finite contemporary buildings on the other hand present a variety of design options that can be tailored to a specific user's needs. Let us look at some of the building systems that are currently used.

Open buildings (Permanent core)

Permanent core buildings are designed according to the theory of buildings layers. This is an old approach to building design that has found renewed interest in support of building disassembly to extend the functional lifespan of buildings and simplify the building modification process. In his description of the theory of layers, Crowther argues that a building is incorrectly referred to in singular i.e. "a building" because of a misconception resulting from the reading of a building in a limited timeframe [5]. He goes on to say that no single building remains in its initial "whole" state of construction for more than a few years or a couple of decades. The building is continually changed by activities such as remodelling, repair, expansions and maintenance. These activities alter the building's exterior, interior or both.

If buildings are designed in cognisance of their layered nature to begin with, subsequent modification (i.e. removing and replacing components and adding extensions) can be much easier. To this end, it is recommended that buildings be viewed to consist of the following layers [5]:

- Structure – foundation and load bearing components
- Skin – cladding and roofing system
- Services – electrical, hydraulic, HVAC etc
- Space plan – interior e.g. partitions, finishes and furniture

Modular Buildings

There are different types of modular buildings that are available in the market today. Modular construction is characterised by the industrial mass production of standardised modular building components. Modularised buildings are intended to form part of a new era of flexible construction systems that allow for user specific building configuration, having the advantage of being assembled on or off site as the need may be. Let us look at three examples of such systems.

Portable buildings

Portable buildings are designed and manufactured industrially. They are made of prefabricated modular building components that are configured according to building designs to cater for specific user needs. They are assembled in factories and transported to site. Factory assembly enables quick and flexible building configuration. It also eliminates long periods on site. The modular nature of building components enables easy component disassembly for replacement during maintenance. If no longer needed, the building can be relocated as a whole to another site.

On-site assembly buildings

These buildings are also designed and manufactured industrially. Building components are modularised and prefabricated. They are configured according to building design to suit user specific requirements. Components are assembled on site. The prefabricated system reduces the amount of time spent on site. Due to their modular nature, such buildings enable easy component disassembly for replacement and expansion purposes.

Demountable buildings

Demountable buildings are industrially manufactured modular buildings that are designed to adapt to changing use patterns [6]. They are particularly suitable for short service life building requirements. The building components are assembled on site. At the end of service life, the buildings are disassembled completely and stored for reassembly when needed (or transported to another site for immediate reassembly).

Modular buildings generally increase the flexibility of buildings by standardising processes and materials, and allowing for large-scale mass production and easy on site assembly. It must however be pointed out that there are shortcomings to this building technique as well. For instance in countries where the construction industry has a high dependency on labour, there may be problems with the industrialisation of the construction process as concerns may be highlighted of its threat to labour job security. Also, because this process will either require factory or on site building assembly the type of required labour will be specialised, thus threatening the low-skill to unskilled labour category. In addition, the standardisation of components (although not as unattractive as standardised buildings) may run a risk of not being acceptable to clients who generally want uniqueness in buildings. Other considerations include the project cost implications of industrialised buildings in terms of transportation, quality control, buildability and the possible use of composite materials.

CONSIDERATIONS FOR DESIGN FOR DECONSTRUCTION

Craven *et al* support the industrial manufacture of buildings. They make an interesting analogy of domestic products and how increasing pressure on the environmental impacts of product manufacture has resulted in tremendous innovation in this field. It is suggested that some of these technologies can be adopted for application in construction [4]. A good example of this is the concept of design for disassembly in product manufacture, which has been incorporated in design for deconstruction. However, Craven *et al* correctly point out that there is a big difference between the worlds of "construction" and "product manufacture" e.g. until recently, buildings were designed to last for long periods (sometimes over 100 years) when products generally have short lives (anything from a few months to 20 years). In addition, while appliances can easily be mass reproduced to be identical, buildings are site specific with different and, at times, unique configurations.

Lessons learned from other sectors can help improve building construction practice if carefully assessed and adapted to the conditions of the construction industry. For instance contemporary industrialised buildings that have lifespans of 15-20 years (similar to many consumer products) need to be designed for flexibility to allow for modification and component (or material) recovery. In case where different components have different lifespans, the recovery of one material should not affect the entire structure. This can also incorporate initiatives such as product branding.

Design for disassembly and modular construction encourage and promote the standardisation of component manufacture, construction methods, component fixing etc. but consciously stop short of encouraging standard buildings[1]. While it is recommended that building methods and processes be standardised to improve efficiency and allow for material life extension, the uniqueness of individual buildings remains an important performance quality of the built environment.

MATERIAL CONSIDERATIONS

When designing buildings for deconstruction, care should be taken in the selection of building materials. The material selection process must be guided by the principles of sustainable construction and design for deconstruction. Table 1 gives a summary of some of the issues that have to be considered.

Table 1: Building component considerations for design for deconstruction, source [1]

Component	Elements	Materials	Comment
Foundation and floor	Foundation Floor bed	Concrete Timber	Concrete – cannot be reused immediately, but can be recycled into secondary materials

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[1] Standard buildings are often not socially acceptable and are perceived to be of a low quality [4].

	Floor finish	Ceramics Carpets	Timber – can be reused immediately and recycled into various products Ceramics – durable, cannot be reused immediately, but can be recycled Carpets – recyclable, but process complicated, small market
Walls	Frame Siding Wall finish	Timber Steel Concrete Brick Gypsum drywall	Timber *as above* Steel – needs extra care if immediate reuse is considered, most recycled material Concrete *as above* Brick – high reuse potential, can be recycled into secondary materials Gypsum drywall – highest percentage of generated construction waste, recyclable if not contaminated, small market
Roof	Frame Sheeting Ceiling	Timber Metal Asphalt Concrete Polymers Gypsum	Timber – *as above* Metal – durable, costly initially but cheaper in long term, most recycled category of materials, established secondary market Asphalt – affordable, not reusable initially, can be recycled to road materials depending on prevailing policy Concrete *as above* Polymers – usually composite, not reusable or recyclable Gypsum *as above*

Note: All of the above components will generally be insulated. Insulation material is not directly reusable but depending on the type of insulating material, can be recycled. The market is however relatively small.

PRINCIPLES FOR ACHIEVING FLEXIBILITY IN BUILDINGS

The cornerstone of understanding flexibility in buildings is realising and acknowledging that:

- Buildings cannot live forever
- Buildings consist of layers that serve different purposes and have different service lifespans
- Building performance over time is directly related to user and environment requirements

The following principles can be used to ensure building flexibility during design for deconstruction [3][2].

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[2] All principles adopted from [3] except for principles 1 and 2 as shown.

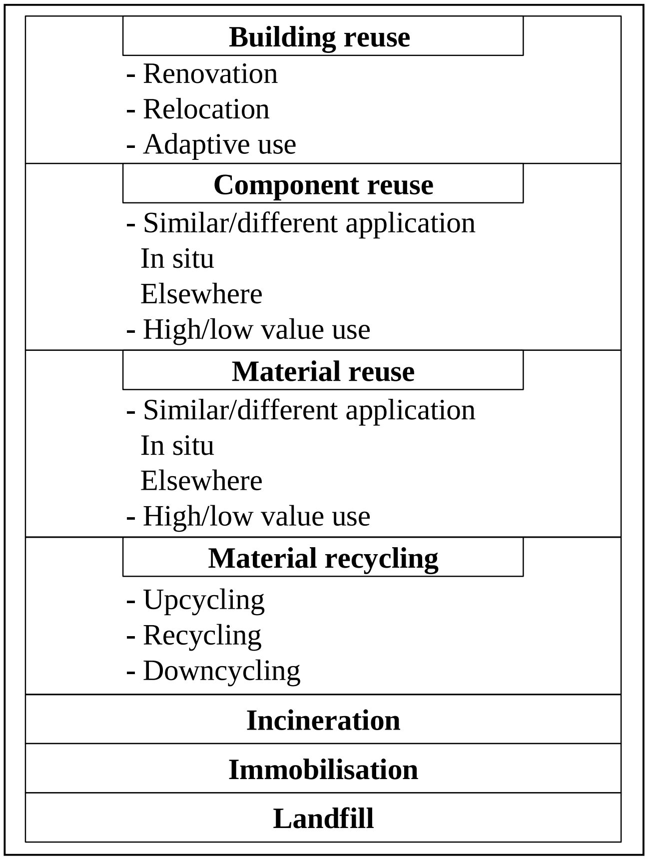
1. Be guided by the principles of sustainable construction [7]
- Minimise resource consumption
- Maximise resource reuse
- Use renewable resources
- Protect the natural environment
- Create a healthy, non toxic environment
- Pursue quality in creating a built environment

2. Use the principles of design for deconstruction [1]
- Information – Keep records of all construction documents
- Design – Balance durability and adaptability
- Materials – Use a minimum, reuse, conserve and avoid composites
- Connections – Use minimum, standardise and reuse
- Material salvage – Make decisions based on end use hierarchy options

3. Integrate the design of installation systems into the structural building design
4. Avoid running installations through structural sections
5. Separate the structural and infill elements of a building
6. Work from maximum partitioning of the building inward, not the reverse
7. Design the core structure to be partitionable
8. Give specifications for connections, structural and installations
9. Use modular coordinated systems
10. Make building components readily accessible
11. Localise services and control facilities, and provide central coordination
12. Provide capacity for future expansion
13. Restrict distribution facilities and ducts (where possible)
14. Use removable facilities instead of fixed installations
15. Ensure flexibility in the building and the process of building construction

END USE SCENARIO HIERARCHY OF OPTIONS

There is now general consensus on the destiny of a building, its components and materials at the end-of-life. Depending on a variety of prevailing conditions, the possible applications include those given in Figure 1.



Building reuse
- Renovation
- Relocation
- Adaptive use

Component reuse
- Similar/different application
  In situ
  Elsewhere
- High/low value use

Material reuse
- Similar/different application
  In situ
  Elsewhere
- High/low value use

Material recycling
- Upcycling
- Recycling
- Downcycling

Incineration

Immobilisation

Landfill

Figure 1: Hierarchy of possible end use options

Figure 1 is particularly useful if used during the design stage of the building construction process. If used in conjunction with design for deconstruction, the hierarchy of end-of-life options will help determine the implications of the decisions that are made at design stage e.g. selection of building design, construction method, materials, connections, fixtures etc. and their implications in terms of recovery, reusability, recyclability and so on.

CONCLUSIONS

- To ensure building flexibility, a balance must be struck between adaptability and durability.
- Flexibility in construction does not only mean the building's technical flexibility, it also extends to the construction process.
- Design is at the heart of green construction and selecting a good design team will improve the chances of yielding a flexible building.
- Design systems, construction methods and building materials if carefully selected, guided by the principles of flexibility, sustainable construction and design for deconstruction, will yield flexible buildings.
- Producing designs for carrying out building disassembly at the building design stage will improve the chances of success of building deconstruction.

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AN OVERVIEW OF DEMOLITION, RECOVERY, REUSE AND RECYCLING PRACTICES IN TURKEY

Soofia Tahira Elias-Özkan (Middle East Technical University, Ankara, Turkey)

SUMMARY

All over the world, buildings are being demolished everyday, as a result calamities (natural or man-made) or intentionally. When demolition is unintentional or indiscriminate, the rubble thus produced is difficult to recycle and is usually dumped into landfills or uninhabited areas in order to clear the site. On the other hand, if it is intentional, it is possible to re-use or recycle most of the materials recovered from the demolished building; provided care has been taken during the dismantling process, cartage and storage of the reclaimed materials.

In Turkey, the demolition business is a considerably lucrative source of income in larger cities, which are also the major sites of such demolition works. This study is concerned only with intentional and planned demolition of buildings within the city limits of Ankara, the capital of Turkey. Hence, this paper presents an overview of the demolition "industry" in the city of Ankara alone. It discusses the causes of building demolitions and the types of localities where buildings are being pulled down; the types of demolition companies and their contracts; the duration of demolition works; types of demolition materials recovered or dumped as rubble; and the market for such material.

Bentderesi, a main road in old town Ankara is the address of the demolition contractors' yards, where construction material and components recovered from buildings they had pulled down are stored and sold. These yards were visited and their owners interviewed for first-hand information with regards their business particulars, merchandise and clientele. Photographs of recovered building materials were also taken to visually record various features of this industry. This paper also intends to throw light on the current marketing techniques and the types of buyers of such recovered materials. The drawbacks of these techniques have been noted and some suggestions have been made for improving sales potential of second-hand building material.

KEYWORDS:

Deconstruction, Demolition, Reuse of Building Materials, Turkey.

INTRODUCTION

Turkey is a developing country with a growing population and expanding urban centers. There is also a steady stream of migrants from rural to urban areas. The rate of migration is higher for larger cities like Istanbul, Ankara and Izmir, where the present housing stock is unable to cope with this population explosion. As in the past, newcomers have coped with their housing problem in the manner they are used to in their rural domain, i.e. find a piece of land and start building. This self-help attitude has given birth to a large number of squatter settlements around urban areas. These squatters have also been instrumental in the establishment of a market for second-hand building materials.

Over the years, as the cities expanded these squatter settlements were legalized usually as a result of election campaigns in the country. Legalized settlements were then provided the necessary urban infrastructure like electricity, gas and water supply, sewage disposal, new roads etc. These facilities suddenly raised the property prices sky-high. Moreover, building bye-laws in the regularized settlements allowed the owners to build higher structures on their land and, thus, gain more covered space. Likewise, the security of land deeds was an incentive for the owners to improve their houses. This led to the demolition of single or double storied old and shabby buildings to make way for new and multi-storied buildings. At this point, the demolition contractors entered the scene; they not only earned money by pulling down the squatter housing but also by re-selling building components recovered from such structures to new squatters in outlying areas.

Within the urban center also, new building bye-laws raised the limit for permissible built-up area and the number of floors. Land being very dear in such localities, older low-rise structures were replaced with new high rise buildings. This situation gave rise to more and more planned demolition of buildings and recovery of good quality building material for resale, occasionally to a different category of clients.

Ankara, the capital city of Turkey, consists of eight municipalities; Çankaya is one of them. A survey carried out by the author in 1999 revealed that, of the 530 building permits granted by the Çankaya Municipality 123 reported the presence of rubble on site, which indicated that a building had recently been demolished on that plot of land. The amount of rubble produced within the jurisdiction of the municipality was calculated as 36 to 55 thousand cubic meters annually [1].

The tradition of recovery and re-use of building materials from demolition waste in Turkey dates back to Ottoman times, although the earliest records deciphered so far belong to mid-15th century. On the other hand, there is no documented evidence of recycling practices, especially related to construction and demolition (C&D) waste, after the declaration of Republic, in 1923. Even today, there are no regulations governing demolition works, let alone laws to promote recovery, reuse or recycling of C&D waste. Whereas, within urban centers, demolition permits are obtained prior to demolition works, however, they are not mandatory and there is no penalty for pulling down a building without obtaining prior permission. On the other hand, rubble may be dumped only in landfills assigned by the municipality; although, this not always the case [2].

DEMOLITION INDUSTRY IN TURKEY

Demolition companies exist in all large cities of Turkey. In Istanbul they are situated in Ümraniye, Günesli, Arnavutköy, Altinsehir and Mahmutbey. There is great similarity in the demand and supply patterns of this enterprise in the cities of Istanbul and Ankara. Furthermore, their clientele too hails from identical strata of the population. For instance, customers of demolition waste like doors, fenestration, bathroom fittings and hardware are usually squatters, while, timber joists and planks are mostly bought by building contractors for form-work or scaffolding. Once in a while, this merchandise is also in demand for renovation and restoration projects. This information was provided by the owners of demolition businesses located on Bentderesi Avenue in Ankara, when they were interviewed informally in March 1999 and then in February 2001 (Figures 1 and 2).

It must be pointed out here that with the exception of a few, owners of demolition yards were not too keen to discuss the details of their business; in fact some did not even want to answer questions regarding their merchandise when they discovered that the author was not a prospective buyer. This reticence on their part stems not only from the fear of the tax men but also the hostile municipality inspectors who look upon their businesses as a source for cheap building material that encourages mushrooming of squatter housing. It is also one of the main reasons that receipts of payment for second-hand building materials are not issued to the buyers, especially since they are squatters.

Demolition sites are usually located in squatter settlements within city limits that have been legitimized by government decree; for example, the Yildiz and Çukurca quarters in Ankara. Demolition companies in Ankara undertake three to four large demolition contracts per year, and approximately fifty small ones in regularized squatter settlements. The construction material and fixtures collected from the demolished structure are sold within the next few months.

According to the demolition companies, three types of contract may be undertaken depending on the estimated market potential and/or the re-sale value of recovered construction material. If the estimate is high, the demolition contractor tenders a bid for the job. If low, it is the other way around and a negotiated sum in favor of the contractor is agreed on. The third is a no-fee, break-even type of contract where neither party reimburses the other. Needless to say that since the owner of the building to be pulled down is a former squatter he is not bothered with the legality of his business. Hence, neither is permission sought before pulling down the building nor is a contract actually drawn between the parties concerned; it is more or less a gentlemen’s agreement.

Recovery and Reuse of Demolition Waste

A report in the Turkish magazine "Is Fikirleri" discloses that in Turkey, the history of recycling dates back to Ottoman times when building materials and components from demolished buildings were safely stored in warehouses until they could be used again elsewhere. Records of such material, down to the last nail, were maintained meticulously in construction account books from the 11th century onwards. These account books, which contain a wealth of untapped information, are preserved in the National Archives in Istanbul [3]. However, this claim could not be authenticated from other sources.

Detailed information pertaining to the current practice of recovery, re-use and recycling of waste from planned demolition in Turkish cities is presented in the following sections.

Modes of Recovery

Demolition companies take on three to four large demolition projects per year and they may spend four or more weeks to complete the work, depending on the size and complexity of the project. Selective demolition is done manually and the structure is first stripped of any building components that have a resale potential. Sometimes the timber fenestration or door sets need minor repairs before they can be disposed of; if and when such a need arises, the demolition companies use the services of carpenters who are in their employ or with whom they have a standing agreement.

Manual demolition of masonry and concrete building components is an expensive and time consuming process; the demolition contractors therefore prefer to use pick-axes, sledgehammers, pneumatic drills and even excavators to break down the masonry walls and RCC structure. Meanwhile, the number of workmen employed can vary from as many as fifteen to as few as five, depending upon the size of the structure to be demolished. In the case of a standard squatter house – called a gecekondu in Turkish – which is a single storey building consisting of 3 to 5 rooms, time taken by the demolition contractor to recover re-saleable material is only one day. Three workers are required to take down the roofing tiles and another two are employed in removing fenestration and timber components. This can be achieved during the first half of the day, while the rest of the day is spent in dismantling the timber roof structure and other fixtures. If the building skeleton is made up of reinforced concrete, then the rebars are also removed for recycling. The masonry walls and concrete rubble is left behind on the plot to be disposed of by the contractor who will undertake the excavation-works

The demolition waste recovered for re-sale is stored in and sold from the company's yard, after any repairs required have been completed. Yards located on Bentderesi Avenue measure approximately 600 m^2 with a covered storage area of about 400 m^2. The demolition materials are sorted and displayed in separate areas of the warehouse. The demolition rubble, on the other hand, is carted away from the site in trucks, to be dumped in one of the landfills designated by the municipality. However, most of the time it is either left on the site or dumped elsewhere, illegally, by the contractor.

Materials Recovered

The thirty-odd demolition companies situated on Bentderesi Avenue concentrate mostly on recovering timber components from the buildings they demolish. For reasons mentioned in the previous section, bricks and floor or wall tiles are rarely recovered intact from the structure. In fact, brick is usually dumped in landfills. Demolition teams concentrate on recovering those materials from the structure which provide the highest margin of profit such as boards, rafters, battens and joists, steel reinforcement, aluminum components, corrugated roofing sheets, roofing-tiles, iron grill-work, doors, fenestration, bathroom fittings and fixtures, pipes, built-in cupboards, kitchen cabinets and sinks (Figures 3 to 10).

If the building to be demolished is a factory, the contractor may salvage approximately ten to fifteen doors, three to four thousand roofing tiles and fifteen to twenty thousand corrugated fiber-concrete sheets in addition to the fenestration, sanitary ware and other waste material. The doors and windows are sold out within a period of four to six weeks, but the sale of the entire stock may take up to ten months.

It was further determined that lack of space in the yard may also be a deciding factor for dumping some demolition material that may ordinarily have a market value. Such material is usually bulky and the profit it is expected to bring in, does not justify the space it occupies. Hence, yard owners prefer to stock up on materials that not only bring in a quick profit, but that also take up less space.

Feasibility of Demolition Works

Demolition contractors estimate the amount of timber and tiles they can recover from the roof of a building according to standards set by the Ministry of Works. Likewise, these standards are also referred to while calculating the amount of reinforcement steel that may be recovered from the demolished structures. However, experience has taught them that the amount of reinforcement actually present in the building is always significantly less than the stipulated amount. Nevertheless, all iron and steel elements are recovered from the rubble, since they can be recycled completely and therefore, fetch a good price.

The demolition companies usually make a hundred percent profit on each contract, in spite of the fact that they sell the demolition waste material very cheaply. In order to provide a rough idea of these remarkably low rates, prices of various demolition materials were collected and catalogued in Table 1. These materials are listed in the first column while their size and price in terms of US dollars is quoted in columns two and three, respectively.

Table 1: Sale Price of Demolition Materials (March 1999-February 2001)

Material	Size	Price in US $
Roofing Tile	Standard unit	$0.05 - $0.08
Brick	Standard unit	$0.03 - $0.04
Door with frame	Standard unit	$17 - $27
Galvanized steel door set	Standard unit	$30 - $40
Fenestration (glazed-3-bays)	2m x 1.2m	$20 - $35
Fenestration (un-glazed-2-bays)	0.8m x 1.2m	$10 - $17
Galvanized steel windows	2m x 1.2m	$10 - $23
Kitchen Sink - ceramic	Standard unit	$6
Kitchen Sink – s. steel	Standard unit	$7 -$8
Wash-basins - white	Standard unit	$5 -$8
Wash-basins - white	Small	$3 -$5
Wash-basins - colored	Without pedestal	$10 -$12
Wash-basins - colored	With pedestal	$15 -$20
Bath-Tubs	Standard unit	$17 - $27
Shower tray	Standard unit	$7 - $10
Iron grill-fencing: balcony	0.9m x 1.0m	$4 -$5
Wrought-iron staircase	14 steps	$60
Boiler	As scrap iron	$0.05 /kg
Galvanized iron sheets	0.9m x 2m or 0.9m x 2.5m	$2
Timber grade 1	5x10x400	$1.33 - $2.00
Timber grade 2	10x10x400	$2.67 - $4.00
Timber grade 3	Varying sizes	$0.05 /kg

CONCLUSIONS AND RECOMMENDATIONS

Buildings in Turkey are conventionally constructed with a reinforced concrete structure, plastered and painted masonry walls and timber fenestration. Floor finishes are terrazzo or ceramic tiles while plumbing pipes and conduits for electric wiring are embedded in the masonry walls. Buildings constructed with such materials are not easy to deconstruct; while the type and amount of recoverable building components is limited. In order to reuse or recycle buildings, it is necessary to promote design for deconstruction; this can only be achieved by raising public awareness. In this regard, much responsibility lies with institutions of higher education and research in this country.

The task of promoting second hand building materials itself is not at all formidable, since there already exists a market for such materials in all major cities of Turkey. In fact, as one dealer of such material claims “if it were not a profitable business we would not be opening shop here every day”. If buildings were designed with the aim of deconstructing when required, public opinion would support the idea with enthusiasm.

On the other hand, much still needs to be done to improve the quality of merchandise and attract the more sophisticated clients. For instance, cartage and storage conditions need to be improved and second hand components and fixtures must be graded into categories for standardization.

Cooperatives play a major role in promoting and supporting various rural and industrial sectors in this country. Such an establishment would also benefit the demolition businesses greatly. Were they to get together to form a such a cooperative, it could easily help the members maintain a catalogue of material available at each yard. Better still, these yards could specialize in certain components or fixtures only and the cooperative could step in to collect and distribute building material from the demolished structures. To date, all but one yard owners sell all types of material recovered from the demolished buildings; the only exception specializes in brick. Establishing a web-site through the cooperative and putting the itinerary on-line will make the purchase of second hand material less of a hassle and also more accessible by advertising the available stock.

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Figure 1. Demolition companies located on Bentderesi Avenue.

Figure 2. Another view of Bentderesi.

Figure 3. Sanitary ware and fenestration for sale in Bentderesi.

Figure 4. Wash-basins and sinks of all sizes.

Figure 5. Fenestration and door sets.

Figure 6. Roofing tiles from demolished buildings.

Figure 7. Timber recovered from the roofs of demolished buildings.

Figure 8. Kitchen wall-unit displayed on the pavement in Bentderesi.

Figure 9. Demolition waste for sale on the roadside

Figure 10. Wrought-iron grilles and gates.

DESIGN FOR DECONSTRUCTION - TOOLS AND PRACTICES

James W. Hurley et al (BRE UK)

SUMMARY

It strikes me as an exciting time when considering the sustainable construction, demolition and refurbishment of our towns, villages and cities. It encourages me too that we all have a vital role to play in achieving a balance between social, economic and environmental needs that dictate local, regional and strategic development plans.

In terms of sustainable development, the European construction industry is at a turning point with regard to materials waste minimisation and management. Simultaneously, the waste management industry has been set a challenge to reduce dependence on landfill and offer materials reclamation, recovery and recycling facilities. In the medium to long term stakeholders such as clients, contractors, planners and manufacturers will play their part in achieving a more sustainable approach by extending the life cycle of materials, products and resources. Similarly, to reuse and recycle reclaimed or recovered products and materials into high- rather than low-grade applications.

A significant role for future sustainability will be that of the architect and engineer in designing for deconstruction both aesthetically and functionally. This will require the design and development of tools, techniques, fixtures and fittings that can function with current and future structures without compromising current best practice. In effect there will be demand for design for deconstruction best practice, a whole new vein of best practice guidance that will focus on that area of the market that sees deconstruction and reuse of construction materials in new designs as its forte. This will complement not supersede current best practice.

To take these steps it is important to benchmark and categorise our demolition waste streams so that we can plan and invest wisely, efficiently and practicably. There is some foundation in a commonly held view that *in order to manage something you must first of all measure it*. The BRE web-based tool, SMARTWaste^{TM} has been specifically developed to help achieve this goal and to provide a wealth of interactive information and reporting features. The data gathered using a pre-refurbishment or pre-demolition auditing system includes the source, type, quantity, reuse potential, quality, condition, fixture and whole life cost of key waste products. This information can then be used to develop material waste management strategies that are monitored using environmental performance indicators and action plans. It can also earmark suitable products and structural components for design into new structures.

This paper reviews current UK progress in pre-demolition audits and technical opinions of designing for deconstruction, mostly focusing on current practice, barriers and opportunities. It includes case study results of a government-funded project, a brief insight to the BRE SMARTWaste^{TM} auditing tool and an overview of a draft deconstruction cost model.

KEYWORDS: Deconstruction, Design for Deconstruction, Pre-demolition Audits, SMARTWaste

INTRODUCTION

The construction and demolition (C&D) industries produce vast quantities of waste components and materials that for environmental, economical and social reasons are becoming less acceptable. To effectively tackle this waste issue a more proactive approach is being sought by government and the industry. Fundamental to this approach is the circularisation of resources, the reduction of waste, and that components and materials should be readily reusable and recyclable to respond to changing requirements placed on them.

As a part of this change, the UK Building Research Establishment (BRE) is investigating what practicable options are available for the reclamation and reuse of building components. Their recent report to government advocates further investigation to develop performance-based specifications, in-situ ‘fit for purpose’ tests, technological solutions to deconstruct current structures, and development of deconstructable joints and fasteners for future designs. This latter subject, designing for deconstruction, is the predominant subject of this paper.

Designing for deconstruction will involve the design of flexible and adaptable buildings constructed of deconstructable and reusable materials and components of suitable quality for end-of-life disassembly, recovery and reuse. Therefore the development of tools to support this paradigm shift will need to optimise the life of building materials and components through monitoring and feedback of performance. This will involve developing a suitable system that will store and track relevant information on the building material and components from design through to deconstruction. This system coupled with the design for deconstruction tool (currently being developed by BRE) and the standardised tool for deconstruction of existing buildings will lead to increased reuse of building materials and components.

This is the theory, in practice there will need to be other investments to develop technologies and methodologies to improve disassembly, in-situ and on-line recovery of waste including development of novel processes for treatment, re-utilisation and safe disposal of waste. Deconstruction tools are rarely used in the design or disassembly of buildings. When deconstruction does occur, it is only materials that have a high reuse value and are relatively easy to deconstruct. At the design stage, private clients and their contracting consortia are very much project focused and prefer to only consider the costs directly related to their business and will only take wider community interests into account if required by legislation or market forces.

However, the tools BRE are developing will not be able to emphasise how this cultural change can be implemented and how to combat and capitalise on the barriers and benefits respectively. Therefore the deconstruction shift will require considerable capital investment, not only in designing buildings with future deconstruction in mind but also the development of technologies, tools, techniques and skills to optimise the reclamation and recovery of materials and components from traditionally designed buildings. This will not be an easy task at a time when, in UK, plant and machinery are replacing manual labour skills in response to the requirements of health and safety for the workers, public and the built environment.

Nevertheless, it is a time of opportunity and the benefits of deconstruction are to be felt beyond the demolition site. With increased demand and markets for reclaimed and recovered materials and components, there will be less need for primary resource extraction, reduced transport and minimal social and environmental nuisance including noise, vibration, dust, and landfill. Added to that are the environmental capital awards of reduced embodied energy, reduced CO_2 emissions and the creation of local jobs and industries.

CONSTRUCTION AND DEMOLITION WASTE

European construction industry

It is estimated that the UK generates around 40 million tonnes (Mt) per annum of core construction and demolition (C&D) waste, excluding 30 Mt of excavation waste and 20 Mt of mixed waste including inert fines, timber, metals, plastics and packaging. Across Europe (EU-15) the figure is approximately 180 Mt of core C&D waste excluding excavation and mixed, of which 28% (50.4 Mt) is reused or recycled and the remaining 72% (129.6 Mt) incinerated or sent to landfill. Construction represents 11% of the EU economy employing 30 million workers including 11 million site operatives who represent 7.5% of EU workforce to the tune of Euro 700 billion or 9.7% GDP. Of this 97% are small to medium enterprises (SME) equal to 1.9 million enterprises.

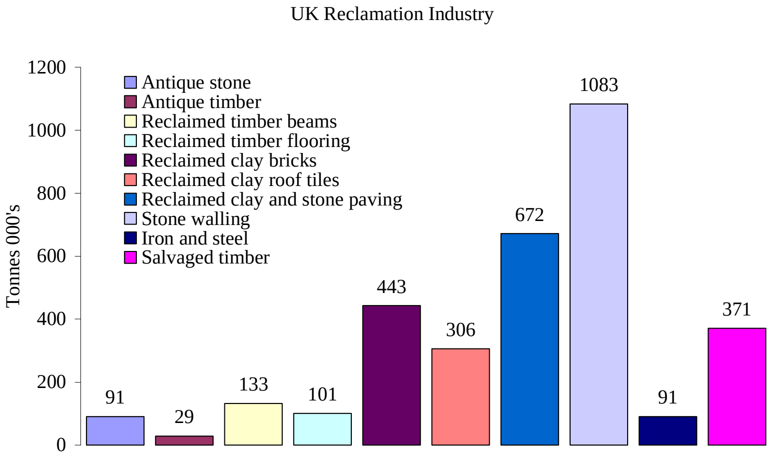
Forces, such as rising disposal costs, a general increase in the environmental awareness of clients/public, and more stringent environmental legislation means that waste management will play a key role in the long-term sustainability of the construction and associated industries. Ideally this will integrate all stages of the project life cycle including design, planning, refurbishment, demolition and construction. Given the relatively low profit margins in these industries, a leaner approach to resource use and reuse will demonstrate that reduction and recovery strategies can boost profitability and reduce the environmental impact of C&D processes. Similarly, that industry is responsive to the growing legislation and guidance generated at the Member State and Community levels.

The future for UK construction & demolition waste

In the United Kingdom (UK), the C&D industries produce vast quantities of waste components and materials that for environmental, economical and social reasons is becoming unacceptable. To effectively tackle this waste issue a more proactive approach must be taken. This sees buildings as dynamic systems, operating at a number of physical and time scales, with many changes over their lifetime.

The level of knowledge on the amounts, types and location of C&D material is at best an informed and extrapolated guess. This is not surprising, as there has been little opportunity to benchmark this waste stream. Despite this, it is commendable that an estimated 3.3 million tonnes of architectural and ornamental components are salvaged each year in UK for reuse (Graph 1). Similarly, that as much as 24 million tonnes of recycled aggregates are recycled into mostly low-grade applications and an unknown quantity of steel is recycled back into production. However, there are large volumes of potentially reusable components other than core C&D and ornamental antiques that are currently sent to landfill and lost to the system only to be replaced with similar components. In the strive for a more sustainable future and efficient use of resources, the construction, demolition and waste management industries have a vital role to play in achieving a sustainable goal.

Graph 1.



Studies by the UK Building Research Establishment (BRE) have shown that there is an array of current and proposed legislative, fiscal and policy frameworks affecting the C&D industry, and that this will become ever more stringent in the future. Initiatives such as the European waste catalogue, community wide waste management plans, national waste and sustainability strategies, the landfill directive, national acts of parliament and proposed European lists and tests will assist in the development of a normalised but adaptable system of waste management within the EU. In UK, these initiatives are to be encouraged by current and proposed fiscal measures including the landfill tax, the aggregate tax, the sustainability fund, the landfill tax credit scheme and funds for R&D from both government and private sources. Additionally there is a need to develop a UK integral waste management system that is driven by the skills, technologies and experience of the construction industry.

All the above is a tall order, and one that will take many years to develop into a confident, skilful and marketable industry that invests and reaps returns from the practicable and cost-effective reuse and recycling of components and materials. The rewards will only be realised through joined-up thinking, working together with clients, planners, engineers and designers, and demonstrating through best practice and innovative solutions where and which components and materials are best reclaimed, reused or recycled.

UK demolition waste

Limited studies at BRE (not including infrastructure and roads) have identified that demolition waste is mostly composed of concrete, ceramics, furniture, timber, metal, plastic, electrical goods and miscellaneous materials and components. The percentage composition of UK demolition waste by volume is shown in Table 1 suggesting that concrete is the largest waste stream at nearly 53% followed by ceramics (including bricks and tiles) at 22.5%. Over a third of waste materials are non-inert which is higher than previous surveys suggest. However, there is a severe lack of reliable and accurate data on demolition waste arisings and these figures must be seen as tentative as they make little reference to steel-frame or timber-frame construction. Timber is estimated to be only 3.4% of demolition waste, although this would be increased if timber furniture was to be included (furniture is 16.6%).

Table 1.

% composition of demolition waste by volume - SMARTWaste case studies

Metal	Plastic	Concrete	Timber	Miscellaneous	Ceramics	Furniture	Electrical goods
1.4	1.3	52.6	3.4	1.8	22.5	16.6	0.3

Separation at the actual point of waste generation is the most appropriate form of management. It is, indeed, preferable to separate hazardous or undesirable substances from the rest of the waste stream to avoid contamination and to ensure they are disposed of in an appropriate manner. If the same principle was applied to other reclaimable products and components then a greater amount of opportunity could be revealed. However this is easier said than done and this paper will go some way to explain these opportunities and barriers.

The UK demolition industry itself has a crucial role to play in developing a 21st Century approach to its business. For many years the industry has been developing and training itself to be more effective and considerate in performing its daily activities in a safer and healthier fashion with both care and attention to its operatives, the public and the environment. A recent study by BRE has shown what the industry has known for decades; that there are key factors that affect the choice of the demolition method and particular barriers to reuse and recycling of components and materials of the structures. For the former, most factors are physical in terms of the nature and design of the building along with external factors such as time and safety. Future factors to consider may well include the fate of the components, the culture of the demolition contractor and the ‘true cost’ of the process. For the latter, barriers to uptake include the perception of planners and developers, time and money, availability of quality information about the structure, prohibitively expensive health and safety measures, infrastructure, markets quality of components, codes and standards, location, client perception and risk.

In terms of scientific opinion, BRE experts in their chosen field –steel, masonry, concrete, timber- see similar restrictions and solutions in terms of reusing or recycling demolition components and materials. BRE digests and information papers, protocols, quality control schemes, tests for strength, quality and durability, and demonstration projects help provide the necessary confidence and opportunity in reusing components or recycling materials. The BRE Deconstruction Group also recognised that two key areas requiring investigation and demonstration in order to overcome barriers and factors will be performance-based specifications and the design of deconstructable joints and fasteners. However, in the short to medium term innovative solutions will be required to reclaim components using historic and contemporary designs, joints and fasteners. The Group therefore believes that a two-prong approach to the issue is needed; innovative solutions for historic and contemporary designs, and designing for deconstruction.

Refurbishment waste

The refurbishment of buildings produces significant quantities of waste materials and products but rarely demolishes any of the structural frame including floor slabs, columns and beams. Often the great majority of the items are sent to landfill or in some circumstances recycled. The latter mostly accounts for inert materials including brick, block and concrete. Metals such as steel and aluminium will also be recycled in the right location but otherwise there is little incentive to reclaim or recover most of the soft furnishings, white goods and operational equipment and furniture. Despite this there is a cultural change occurring in the C&D industry and considerate clients are beginning to investigate how to improve their environmental performance and provide contractors with a greater knowledge of the structures to be refurbished or demolished. This change is being driven by UK Government, the new Demolition Code of Practice BS6187-2000 and the Waste and Resources Action Programme (WRAP). Together these may eventually provide the necessary network and quality control measures to specify reclaimed and recovered materials and components. In the mean time, considerate clients are contributing to the Government's initiative and sharing their experiences to aid this cultural change.

A recent study by BRE has provided a pre-refurbishment audit of six buildings that will be refurbished during the next five years (case study 1 later in this report). It was completed ahead of the tender stage in order that the audit is included with the tendering documents, thus providing a better knowledge of the structures, the cladding and all internal fixtures and fittings. It also suggested what reuse or recycling potential exists in the best case scenario and what could be achieved in the right location and with suitable, local facilities. The report included targets for the tendering parties to suggest what they would recover or reclaim for recycling and reuse. Unfortunately the document was not written into the tender documents and was not a legal part of the bid. None of the contractors bidding for the work completed the reuse-recycling target sheets so it was not possible to award the contract accordingly. Nonetheless, this does indicate that clients are beginning to consider these issues and what now is uncommon may soon become a component part of the tender document.

Sustainable construction, demolition and refurbishment

From the above it is easy to see that the future development of a sustainable, efficient and prosperous demolition industry that sees material and component reuse and recycling as a key facet, will require considerable investment in terms of time, money, skills, tools, technologies, standards and risk. This should not be the burden of the demolition industry itself, rather it requires a holistic approach that involves all relevant stakeholders and actors. The demolition industry has demonstrated that it will reclaim and either reuse or recycle components and materials where it is encouraged to do so, and where the right conditions exist in terms of location, availability, quality of information, time and markets. The demolition industry will only be as responsive as much as other actors and stakeholders are willing to change.

An often unforeseen outcome of a more sustainable demolition and waste management system is the revelation that there are far reaching benefits beyond these industries themselves. Benefits will include direct and associative employment, market networks and regional/national storage and distribution centres. It is recognised that for markets to be less volatile, a network of storage, distribution centres and product demand is required. This type of network has already been successfully demonstrated for the reuse and recycling of architectural and ornamental components, bricks and blocks, second hand furniture, recycled aggregates and wood chip. A more integral waste management cycle will benefit by adopting the successes of other sectors of UK industry.

A TOOL FOR MEASURING WASTE

SMARTWaste™

In order to achieve better waste management through waste reduction and both re-use or recycling of unavoidable waste, there is an urgent need to quantify waste arisings. SMARTWaste™ (Site Methodology to Audit, Reduce and Target Waste) has been developed by BRE to provide a robust and accurate mechanism by which wastes arising can be benchmarked and categorised by source, type, amount, cause and cost.

Audits have been completed for construction, demolition, refurbishment, manufacturing and pre-fabrication. The data is a springboard to identifying and prioritising actions to reduce waste (producer responsibility), re-use at source (proximity principle), and maximise recovery to extend materials' life-cycle. The benefits of the software tool identify the potential true cost savings of projects and maximise the reduction, reuse, recycling and recovery options of materials. Further examination of the software provides a range of features, instant reporting tailored to clients needs, sharing of information, establishing environmental performance indicators, and development of integrated material waste management strategies.

The latest version of SMARTWaste™ is a web-based (www.smartwaste.co.uk) waste auditing tool with UK construction industry benchmark data on waste targets, environmental performance indicators and practical advice on waste reduction. There are two choices of auditing. The first is a cut-down version of SMARTWaste™ that requires information to be input on estimated breakdown of material type per skip with numbers and sizes of skips. The full version of SMARTWaste™ can be used to identify further waste prevention and develop targeted material waste management strategies that focus on action plans and key waste products.

Sites or companies who are finding their SMARTStart Environmental Performance Indicators (EPI's) higher than average will be encouraged to use the full version of SMARTWaste™ to identify and implement a waste prevention strategy. The full version of SMARTWaste™ evaluates waste as it is being generated to determine:

- Waste types and amounts
- Causes and Costs of waste
- Waste generation over time
- Waste generation per work package/ building
- Wastage rates and EPIs
- Key Waste Products

Figure 1. SMARTWaste project homepage

The SMARTWaste™ tool enables data to be filtered according to the project type, value, location, floor area, company, construction products, waste management contractor, segregated material, mixed material etc. This allows extrapolation data to be extrapolated on many different levels such as geographical and building type. The detail and accuracy of the data means that waste prevention measures are easier to identify and targets for waste prevention can be made confidently for further projects or phases within the same project. BRE anticipate that the full version of SMARTWaste™ will be used to identify key waste products and causes for companies/sites getting higher than average EPIs. We also expect that once clients specify maximum wastage rates in their contracts, an accurate tool such as this will be used to certify these targets have been met (or even improved upon).

In short, the overall features of SMARTWaste™ include:

- Overall quantity report, that can be adapted using various filters
- Overall cause report, that can be adapted using various filters
- EPI’s for project waste groups
- Project key waste products
- Project trend reports, that can be adapted using various filters
- Wastage rates of key waste products and any other selected product
- Interactive action plans for targeted wastes including targets and results
- Instant weekly and monthly reports that are automatically generated.

PRE-DEMOLITION AUDITS – A CASE STUDY FOR UK GOVERNMENT

Deconstruction and reuse of construction materials

BRE is currently undertaking a project on behalf of the UK Government Department of Trade and Industry (DTI) under the Technology and Performance Business Plan 1999/2000. The aim of the project is to investigate the possibilities of *Deconstruction and reuse of construction materials*. The project is being undertaken because construction, demolition and refurbishment wastes represent a significant environmental and social burden on the locality of their production. This is due to the waste of resources and the use of limited landfill space.

The construction and refurbishment of buildings also require a large amount of materials and products to be transported into the same area. This has the negative effect of increased traffic pollution and increased energy usage and associated carbon emissions. Better management of C&D waste components and materials in the UK means significant economic and environmental opportunities for the industry. Reclamation and reuse of C&D components will ultimately lessen the solid waste management burden and reduce environmental degradation. Conversely, lack of a recovery, reuse and recycling infrastructure contributes to excess waste and environmental degradation.

The results of this project will improve the technological performance of UK construction by increasing the lifetime of construction components and materials, thereby reducing the associated impacts of extraction, production, transport, use and disposal. The objectives of the project are to identify and advise government and industry on technical, economic and policy issues that must be addressed to make reclaimed building components and materials a viable alternative to landfill. This is to be achieved by consideration of:

- Technical issues such as the physical deconstructablity of specific components to make their direct reuse possible
- Developing existing and required tools and techniques to perform deconstruction
- Whole life costs for reclaiming components and materials, having consideration for expected income and current market values, current supply and demand, and facilitating their marketability
- Policy issues including re-certification of components and materials for reuse or up-cycling
- Wide dissemination of results.

Pre-demolition and Pre-refurbishment audits

This project is addressing the potential for reusing components and materials from buildings that are being refurbished or demolished. Opportunities to reclaim components and materials and provide environmental benefits are often missed and the majority ends up in landfill sites or down-cycled. This project is reporting on the feasibility, barriers to take-up and benefits to make deconstruction and reuse of building materials a viable alternative to demolition and landfill. The project is mainly focusing on the soft strip and demolition of the main structure, envelope and internal components of existing commercial buildings. However other components and materials including furniture are not to be ignored.

To satisfy the measurement objectives, this project is including:

- A consultative study to determine the actual and potential reuse or recyclability of components and materials arising from demolition and factors affecting the supply and demand of those materials
- The development of a method to successfully audit and assess the successful deconstructability of the building into its structural and potentially reusable parts
- Pre-demolition or pre-refurbishment audits of four types of commercial buildings
- Case study investigations of 8 live demolition and refurbishment projects
- An evaluation of the whole life cost of deconstruction, reuse, recycling & landfill

The SMARTWaste^{TM} pre-demolition and pre-refurbishment audits undertaken on a select range of buildings has shown that:

- It is possible to complete an audit of the building and its contents within a short time-frame and cost
- If performed prior to the tender stage, an audit presents greater opportunities for components and materials to be reused or recycled
- Clients are able to choose the contractor who offers best value, taking account of the triple bottom line
- Location, facilities, time, space and demand will play a vital role in balancing the decision whether to reuse, recycle or landfill
- There are often unrecognised and untapped demands for office equipment, workstations, electrical goods and furniture
- The Client should include an audit with the tender documents for demolition contractors to consider when preparing their bid
- All bids should include an audit of components and materials that will be reclaimed or recovered for reuse, recycling or energy recovery using the tables provided and setting targets
- A dedicated auditing system should be used to report on the performance of demolition contractors and to measure continual improvement.

The next stage of the project is to identify the key waste products of value and accessibility, conduct reclamation valuations of these components, assess their variable costs using the deconstruction cost model (later in this paper) and provide recommendations of the most appropriate use or disposal route of the products.

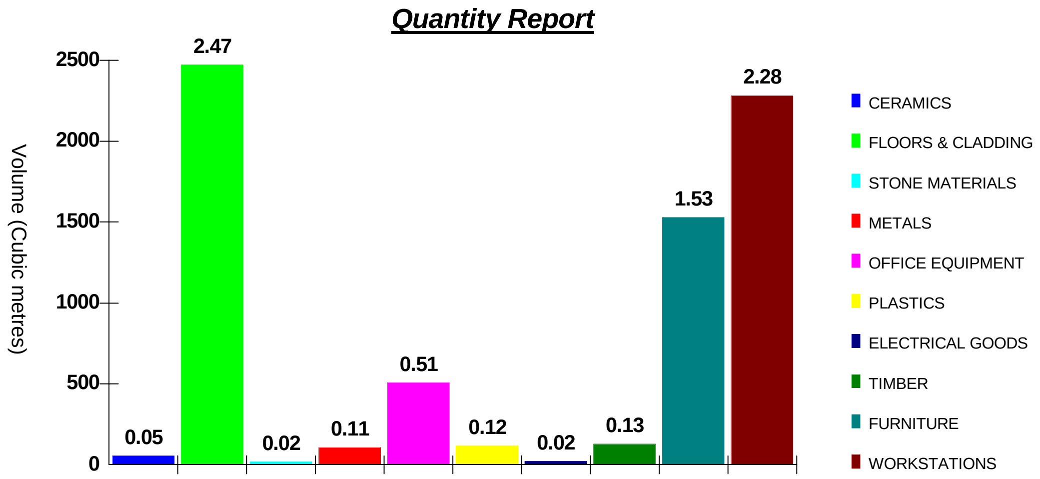
Initial case study results

Graphs 2-7 show the overall results of three case studies for the UK Government project in terms of the quantities and optimal reuse-recycling potential of the overall waste groups. A more detailed account of components within each individual group (e.g. door, door frame, floorboards etc in the Timber group) is included in each of the final case study reports to Government. An indication of these detailed reports is included in Graphs 8-9 of this paper, using metal as an example. These show the quantities and recycling potential of metals for one of the project case studies.

Case Study 1 – Office Headquarters

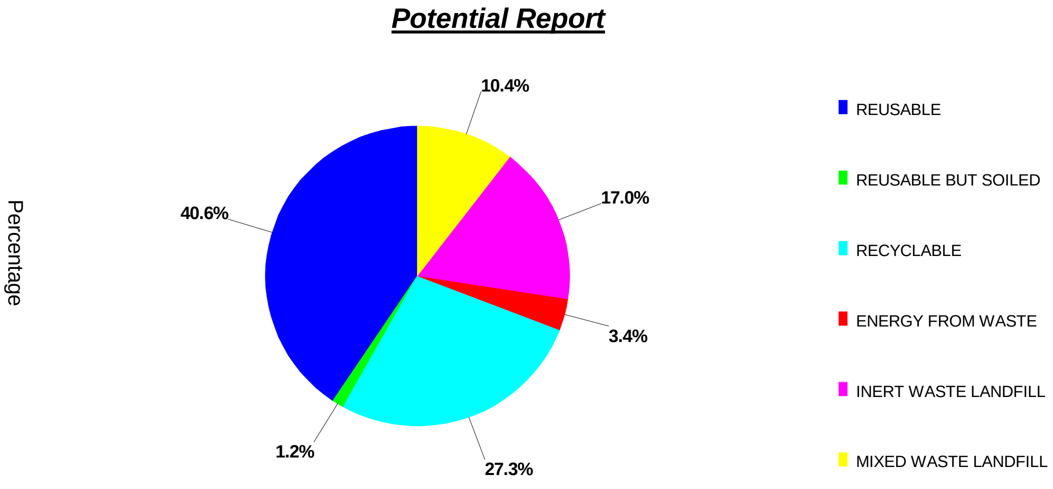
This is a collection of six 5-storey buildings in London that are due to be refurbished over a 5-year programme. A pre-refurbishment audit was undertaken to show the volumes of waste materials and products within and embodied into the buildings. Graph 2 shows the overall quantities of materials and products. Graph 3 indicates the optional waste potential, in terms of what can be reused, recycled, recovered energy or landfill.

Graph 2.



Total quantities for all groups in all buildings (©SMARTWaste)

Graph 3.

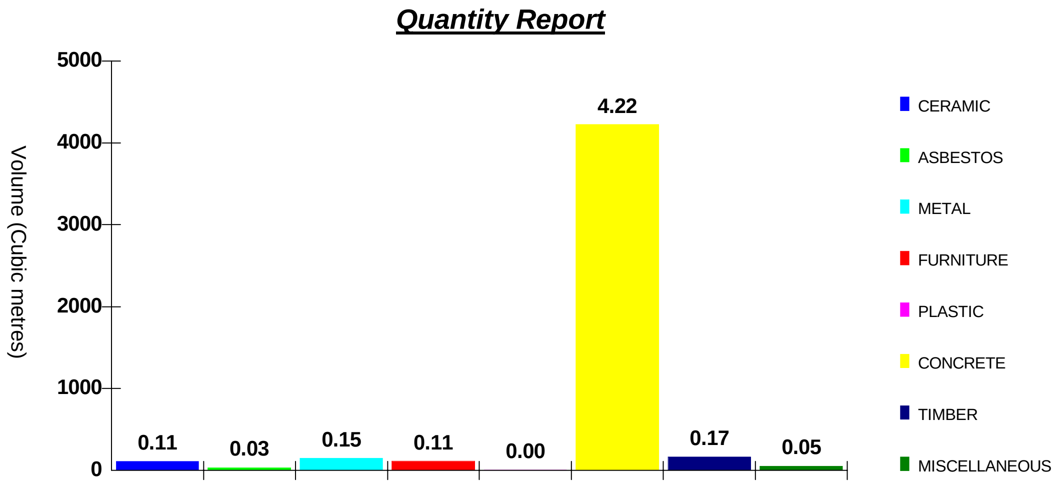


Reuse-Recycling potential for all products in all buildings (©SMARTWaste)

Case Study 2 – Tower block

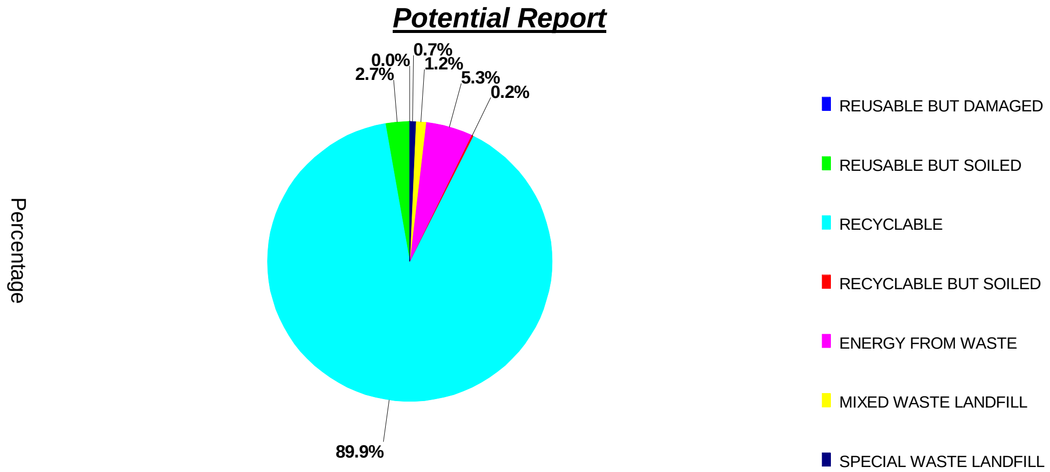
This is a 22-storey building in Liverpool that is to be demolished following the strip-out phase. At this stage it is believed that the structure will be demolished using explosives. A pre-demolition audit was undertaken to show the volumes of waste materials and products within and embodied into the buildings. Graph 4 shows the overall quantities of materials and products. Graph 5 indicates the optional waste potential, in terms of what can be reused, recycled, recovered energy or landfill.

Graph 4.



Total quantities of all groups for Willow Dene (©SMARTWaste)

Graph 5.

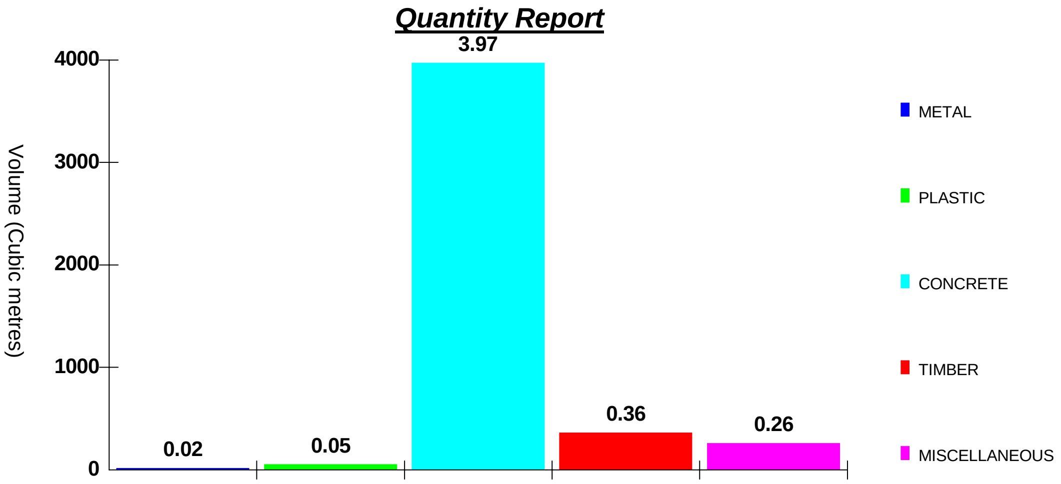


Reuse/Recycling potential for all products at Willow Dene
(©SMARTWaste)

Case Study 3 – Housing

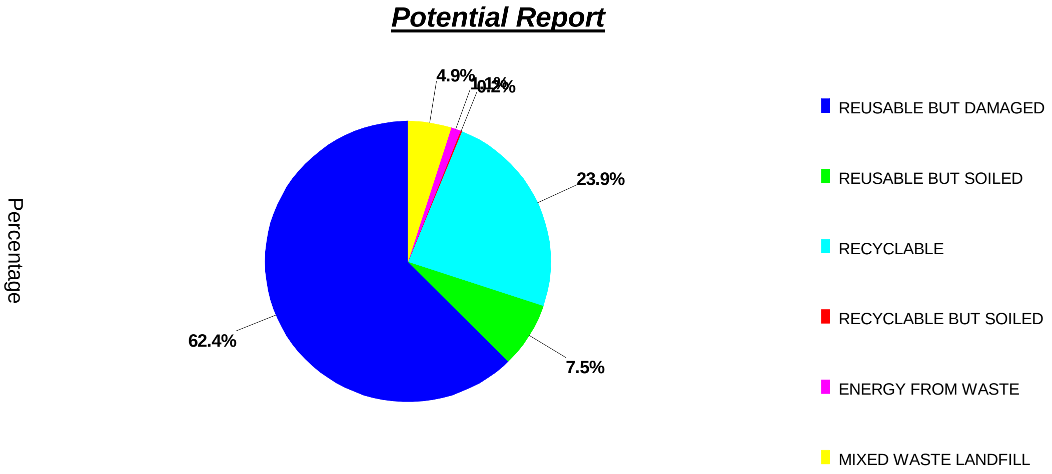
This is a 3-storey block of housing in Manchester that was demolished using traditional demolition techniques. A pre-demolition audit was undertaken to show the volumes of waste materials and products within and embodied into the buildings. Graph 6 shows the overall quantities of materials and products. Graph 7 indicates the optional waste potential, in terms of what can be reused, recycled, recovered energy or landfill.

Graph 6.



Total quantities of waste by group for Jespersen Street (©SMARTWaste)

Graph 7.



Reuse-Recycling potential of all waste for Jespersen Street (©SMARTWaste)

Other graphs

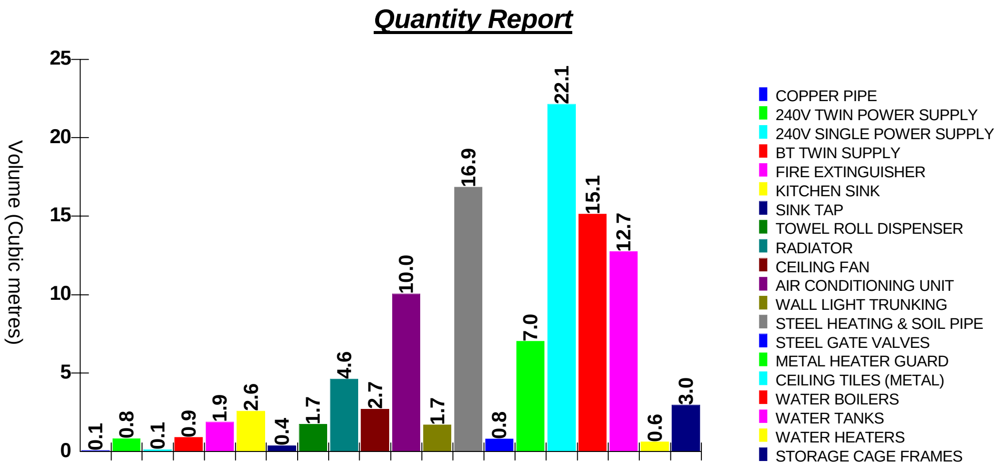
For each of the case studies, a more detailed account of each of the product groups was provided. Table 2 shows the twelve standard groups:

Table 2.

SMARTWaste waste groups	
Timber	Packaging
Concrete	Metal
Inert	Plaster and Cement
Ceramic	Miscellaneous
Insulation	Furniture
Plastic	Electrical equipment

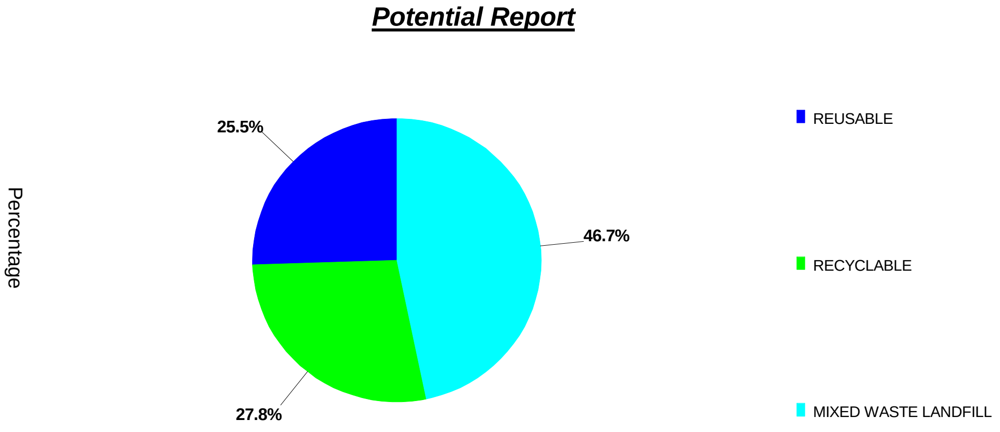
Graphs 8 and 9 indicate in more detail the waste products and reuse-recycling potential of the metals group for one of the case studies. Similar detail is provided for all twelve groups, and for each of the case studies.

Graph 8.



Total quantities of metals for all buildings (©SMARTWaste)

Graph 9.



Reuse-Recycling potential of metal for all buildings (©SMARTWaste)

In addition to the graphs, tables have been generated from the data collected during the auditing process. Proportionate examples of two types of table are included in Tables 3 and 4, the latter including % targets and achievements.

Table 3.

BUILDING FABRIC	Dimensions (cm)			Waste Potential	B13	B8	B36	Haddon	Howland	Maple	Total
	length	width	depth								
Air conditioning unit	90	90	20	Mixed landfill	0	4	51	2	5	5	62
Aluminium partitions (m)	100	269	7	Recyclable	24	34	211	162	71	0	502
Aluminium window frame	268	125	13	Recyclable	159	168	133	277	252	0	989
Ashfelt roof (m^2)	100	100	1	Mixed landfill	283	250	0	461	747	0	1741
Battery emergency light	38	14	9	Mixed landfill	7	8	12	7	9	3	46
Brick & concrete cladding	126	84	25	Inert landfill	159	168	133	277	252	0	989
BT twin supply	15	9	5	Mixed landfill	204	164	400	251	214	109	1342
Carpet (m^2)	100	100	2	Mixed landfill	260	0	890	0	0	0	1150
Carpet tiles	50	50	1	Mixed landfill	6240	8960	24920	12628	11880	3976	68604
Ceiling fan	80	80	10	Mixed landfill	8	12	18	0	4	2	42
Ceiling tiles (fibrous)	60	60	2	Mixed landfill	9066	22555	15356	8771	2376	0	57924
Ceiling tiles (metal)	60	60	2	Reusable	0	0	3072	0	0	0	3072
Ceramic tiles (m^2)	100	100	1	Inert landfill	132	176	408	469	168	72	1403
Circular light (large)	46	46	10	Mixed landfill	16	35	4	14	8	3	78
Circular light (small)	30	30	10	Mixed landfill	29	65	17	5	35	0	147
Copper pipes (m)	100	1	1	Recyclable	92	84	148	100	88	32	528
Double electric socket 240V	15	9	5	Mixed landfill	212	213	376	259	129	0	1189
Fire door & frame	218	108	10	Energy from waste	21	19	34	8	2	16	96
Fire extinguisher	50	14	14	Reusable	32	20	40	35	40	26	191
Fire hose	57	57	28	Mixed landfill	0	0	1	0	12	0	13
Kitchen cupboard	100	70	40	Energy from waste	18	26	12	23	23	2	96
Kitchen sink	105	53	33	Mixed landfill	4	0	2	6	2	2	14
Lift hardwood door frame	198	22	3	Recyclable	37	40	40	35	20	0	170
Metal heater guard (m)	100	20	1	Recyclable	483	576	938	763	625	127	3512

Table 4.

	Dimensions (cm)			Waste Potential	Total	Target	Achieved
INTERNAL FURNISHINGS	length	width	depth			%	%
Ceiling to floor cabinet	240	103	54	Energy from waste	64		
Circular table	120	120	73	Reusable	149		
Coffee table	120	60	43	Reusable	12		
Corner desk workstation	200	80	73	Reusable	815		
Desk partition (desktop)	180	49	3	Reusable	275		
Desk partition (large)	120	120	5	Reusable	479		
Desk partition (medium)	120	80	5	Reusable	21		
Desk partition (small)	120	40	5	Reusable	314		
Desk partition (X-Large)	160	120	5	Reusable	69		
Desk shelf	180	32	2	Reusable	598		
Dexion-style shelf units	220	100	32	Recyclable	216		
Dishwasher	120	80	70	Reusable but soiled	3		
Double comfy chair	200	80	70	Reusable but soiled	33		
Double filing cabinet (mid)	120	105	47	Reusable	282		
Double filing cabinet (small)	80	70	47	Reusable	173		
Double filing cabinet (tall)	196	105	47	Reusable	170		
Electric fan	50	35	26	Reusable	361		
Fancy oblong table	180	80	73	Reusable	66		
Fridge	120	80	70	Reusable but soiled	21		
Hat stand	190	5	5	Reusable	57		
Industrial cooker	100	90	90	Reusable but soiled	3		
LCD projector	40	25	12	Reusable	3		
Metal frame plywood table	114	86	74	Recyclable	918		

DESIGN FOR DECONSTRUCTION - BRE TECHNICAL OPINIONS

Overview

The deconstruction research being undertaken by BRE has seen much progress in the last two years in terms of the current industry position and barriers to uptake culminating in the publication of *BR418 - Deconstruction and reuse of building materials* market share report. The two main points of the report are:

- in the long-term, the need to design for deconstruction of buildings that will be demolished in the future (30-100 years)
- in the short- to medium-term, the need to develop tools, techniques, skills and markets to capitalise on deconstructing structures currently standing (0-30 years)

The development and specification of deconstructable joints and fixtures will be crucial to the success of deconstruction both now and in the future. Little effort has been injected into this area of study that will require much thought and testing regimes. It is the intention of the BRE Deconstruction Group to pursue this area of study in the next six months, and include experiences and examples from other countries. This should be made more apparent at the TG39 Deconstruction conference in Germany 2002, which has a theme of designing for deconstruction.

Now that the pre-demolition and pre-refurbishment auditing system has been agreed and operational (adopted by the BRE SMARTWaste tool), it is necessary to associate costs and potential revenues to those audits using a deconstruction cost model. This should also be supported by industry expertise namely reclamation valuation surveys and interviews with the reclamation and demolition industry. This should allow an appreciation of costs and revenues in the market place, and to use those to determine tentative but generic data for the cost tool. In time, the critical mass of the data being collected by various audits should help facilitate more accurate figures. This will, naturally, take time.

BRE technical opinions.

BRE material experts (timber, steel, masonry, concrete) have commented on the theme of deconstruction including designing for deconstruction, and the opportunities and barriers that deconstruction raises. This includes a review of material-specific products used in construction and a range of fixtures, fittings & joints used to secure them in place. They also provide opinions of what opportunities and barriers exist for current structures to be deconstructed. Using this evidence they have assessed how material-specific products can be –or already are– designed for deconstruction, and finally to provide recommendations that will help facilitate the deconstruction and reuse of construction materials.

The following section of this paper includes brief summary reports from the BRE material experts who are individually named.

Deconstruction of Concrete components - Chris Goodier

Key concrete products

The different types of precast concrete products produced by the members of the British Precast Concrete Federation include:

- Foundation Units & Piles
- Retaining, Revetment & Crib Walls
- Sea & River Defence Units
- Pipes & Drainage
- Tunnel Linings
- Box Culverts
- Manholes & Inspection Chambers
- Water Treatment & Storage Tanks
- Kerbs & Flags
- Paving (Block and Decorative)
- Vehicle Safety Barriers
- Lighting Columns & Poles
- Road Furniture & Bollards
- Bridge Beams & Gantries
- Railway Sleepers
- Masonry Blocks, Inner/Outer Leaf
- Concrete Bricks
- Cast Stone Architectural Units
- Lintels Sills & Copings
- Floors: Beam & Block
- Floors: Hollowcore, Composite &
- Double Tee
- Staircases & Stair Units
- Roof Tiles
- Cladding & Structural Wall Units
- Frames, Beams & Columns
- Multi-storey car parks
- Grandstands & Terracing
- Specialised Building Systems
- Agricultural Products
- Fencing
- Ducts, Conduits & Markers
- Garden Products

The largest market share of the concrete precast industry is taken up by (in order):

- Masonry blocks
- Paving slabs and blocks
- Roof tiles
- Pipes and associated products
- Floor units
- Fixtures, fittings & joints for concrete products

The main *key concrete products* (masonry blocks, paving slabs and blocks) have no fixtures, fittings or joints and therefore lend themselves to be easily dismantled and reused. Concrete roof tiles are simply nailed to roof purlins and so can easily be removed without damaging the tile itself. Concrete pipes are joined together using fixed or loose elastomeric seals. If a pipe run is dismantled then this seal would be discarded but the actual concrete pipe could be re-used with a new seal. The problem with precast floor units is that they are usually fixed in place by pouring concrete or mortar in-situ between the edges of the units, usually with steel reinforcement to tie all the units in place. It is therefore very difficult to dismantle the units without damaging them.

Opportunities for deconstruction

Some of these concrete products are already sometimes re-used, such as:

- Kerbs and flags
- Vehicle safety/crash barriers
- Lintels Sills & Copings
- Paving slabs and blocks
- Roof Tiles
- Garden Products
- Tunnel Linings

Of the *key concrete products*, masonry blocks, paving slabs and roof tiles all offer excellent opportunities for deconstruction and reuse. The opportunity for reusing pipework is small, the major problem being the cost of excavating and recovering the pipework. It is possible to recover and reuse flooring units, depending on the type of fixing and jointing used- if an in-situ joint is used then the potential is low. However, whatever physical or practical opportunity exists it will only be exploited if there is an economic gain for doing so, which is the main barrier at the present time for the deconstruction of concrete products.

Barriers to deconstruction

The main barrier to any concrete products being deconstructed and reused is an economic one. The cost of each individual unit (e.g. a tile or paving slab) is so low that it is usually more cost effective to buy new ones, especially in bulk. Many of these products can never re-used in their original form (for various reasons) such as:

- Foundation Units & Piles (virtually impossible to remove from the ground)
- Pipes and associated products (as above)
- Bridge Beams & Gantries (dimensional, safety/risk and jointing problems)
- Frames, Beams & Columns (as above)
- Multi-storey car parks (as above)

One major barrier is a dimensional one. Most orders for structural units (beams, columns etc) are for one-off bespoke structures with unique dimensions. Therefore the components have to be specially made for that particular structure and will not dimensionally fit a different structure, unless the new structure has been designed with this in mind which is rare, if not non-existent.

Other *physical* barriers include (depending upon the type of concrete product):

- Pre- and post-tensioning beam/floors- dangerous to de-stress
- Joints often mortared or glued or tied together with reinforcement
- Blockwork is usually mortared together, which therefore requires cleaning
- Concrete ages naturally due to- carbonation, weathering, colour change, cracking and chemical effects (such as sulphate attack, ASR and DEF)
- Reinforcement corrosion can occur
- Coatings (either cosmetic or protective) can deteriorate due to ageing, weathering and mishandling

Other *practical* barriers include (depending upon the product):

- Lack of information, skills and tools exist on how to both deconstruct and design for deconstruction
- Lack of big enough established market for deconstructed concrete products
- Lack of design- products not designed with deconstruction in mind, generally designed to last a ‘lifetime’
- Reluctance of manufactures- always prefer you to purchase a new product
- Composite products- many modern products are composites which can lead to contamination if not properly deconstructed/handled
- Legal obstacles- allocation of risk and responsibility when using ‘second-hand’ components, factors of safety
- Joints between components are often inaccessible

Design for deconstruction

Not many concrete products are actually designed to be reused as manufacturers would rather you bought new ones, but some can still be reused. One unique type of concrete products is temporary concrete crash (safety) barriers. These are sometimes rented out by a contractor from the suppliers and are then returned to the manufacturer when they are no longer required. They are then either cleaned and reused, or disposed of if they are faulty.

Many products can be reused but are not designed *specifically* to be reused, such as kerbs and flags, paving, roof tiles, lintels, sills and copings. If they were designed with deconstruction and reuse in mind then the design would not be very different to what it is.

However, some concrete products could be reused with only a slight alteration in their design. Although this would probably increase the initial price of the product, the whole life costs could be reduced. Example products include:

- Sea & River Defence Units
- Pipes & Drainage
- Water Treatment & Storage Tanks
- Railway Sleepers
- Agricultural Products
- Fencing
- Cladding & Structural Wall Units
- Staircases & Stair Units
- Floors: Beam & Block
- Floors: Hollowcore, Composite & Double Tee

Of the *key concrete products*, masonry blocks, paving slabs and blocks and roof tiles require little alterations to their design in order for them to be able to be reused. Similarly, pipework can be easily dismantled, the problem being getting to the pipework to do it. Floor units would require the most alterations to their design in order for them to be deconstructed and reused, especially to their fixing and jointing method.

Conclusion & recommendations

The main barrier to more concrete products being deconstructed and reused is an economic one. No matter what the practical or physical possibilities and opportunities exist, it still has to be economic to deconstruct and reuse the component. Additional problems with concrete products are dimensional (most UK structures are one-off designs) and physical or practical. The concrete products with the main share of the market (masonry blocks, paving slabs and blocks and roof tiles) require no alteration to their design, just an economic market for their reuse. Some other concrete products need just a small design alteration to enable them to be deconstructable and reusable, but a market for them would still be required for it to be economic to do so. Some concrete products will also never be reused due to their location in a structure and the difficulty in recovering them economically and practically (e.g. piles and pipework).

Deconstruction of Masonry components - Elizabeth Garrod

Key masonry products

The Romans introduced the premise of using fired clay bricks and hydraulic mortar to Europe and this basic principle of building a stable bonded stack of handleable pieces has stayed with us for centuries. The variety and availability of these 'handleable pieces' has increased, more and more building techniques have been developed and a whole range of fixtures and fittings has been created to speed up the process of construction. In the time when everyone began to want solid walls around them stone and timber were the most used building materials but brick took over from timber and became very popular in the 18th, 19th and 20th centuries.

The term masonry is very broad since the definition of a masonry structure is no longer just 'one built with natural stone'. The term masonry now encompasses all structures produced by stacking, piling or bonding together chunks of rock, fired clay or concrete to form the whole. Masonry buildings are rarely just built using traditional masonry products – there is usually concrete or timber involved but for the purpose of this section there are six main masonry products; bricks, stone, blocks, paving, slates, and tiles.

Bricks – Traditional bricks were hand made, but over time it has become necessary to standardise sizes therefore today bricks are defined by size. Generally 337.5mm long by 65mm high with a maximum depth of 102.5mm (BS6649). The standard UK brick is only 215mm in length (BS3921:1985). They can be produced from clay, calcium silicate, sand-lime and flint-lime. There are also many types described as solid, perforated, hollow, cellular and frogged. Also the way they are going to be used defines the way they are manufactured, for example 'commons' are the most commonly used; 'facings' are attractive bricks for special situations; 'engineering' are dense and strong for exposed conditions; and 'district' are made in only one district of the country. Bricks are used to maintain the structural integrity of the building, to decorate features internally and externally or as a cladding material to an inner concrete, timber or steel frame.

Stone – Wherever there was a quarry nearby the buildings were built with stone. But when bricks began to be produced very quickly and cheaply the use of stone died down except in the north of England. Now in the South it is an expensive material to build with due to the lesser amounts being available and transportation costs. In the North it is used as brick is used in the South – most popularly as an outer skin to a cavity wall construction.

Blocks – any brick that is larger than the general size is defined as a block. The standard size for blocks is 440mm long by 215mm high with a depth of 100mm. These can be the same material as brick or made from concrete. They are used in their own right as outer walling and rendered or, in the case of the recycled aggregate thermalite, as an inner skin to a brick and block cavity wall construction.

Paving – paving is generally made from concrete in our modern society. Stone is still used but is a more expensive alternative and therefore not used in modern housing estates although there has been a rise in its popularity recently.

Slates – Traditionally slates were used predominantly in the West Country and Midlands as a roofing material on a low-pitched roof. Later periods of history saw slates in more widely spread areas, tiles were more popular and cheaper in most areas.

Tiles – Traditionally those houses that were not thatched were tiled with clay tiles. These became almost the only roofing material for many decades in most of the country. The advent of speed building and the invention of concrete made a huge difference. Now concrete tiles are predominantly used in new build.

Fixtures, fittings and joints for masonry products.

There are four main masonry techniques:

- Irregular shapes and sizes chosen and placed by hand to achieve interlocking (e.g. dry stone walls).
- Medium to large blocks cut to precise sizes and placed using a grid pattern with little or no mortar.
- Small to medium bricks/blocks in a few sizes assembled in a grid pattern where inaccuracies are filled with mortar (normal brickwork).
- Irregular shapes and sizes packed apart and bonded together with mortar.

Only the fourth method relies on mortar for stability because in masonry structures mechanical interlocking is of paramount importance. But there are many fixtures, fittings and joints that are also important to different types of brick and blockwork.

In Britain the most popular building method is concrete foundations and floor, concrete block inner skin with a cavity wall and brick and cement mortar outer skin. The most popular method of connecting these two skins, and therefore the most used fitting, are stainless steel wall ties. These come in many different designs and depend on the type of wall. For example there are slope tolerant, movement tolerant, symmetrical, asymmetrical, shear, slat and slip wall ties.

Opportunities for deconstruction

Bricks - Traditionally before the need for mass housing came about, bricks were hand made and of good quality. Lime mortar was used in their construction and therefore they could be easily deconstructed and used again. If a historic building is for some reason being deconstructed nowadays the bricks are taken down by hand and hand cleaned for re-use. This is an expensive process but there is a large market for the traditional bricks. This is especially important to the conservation field as in the repair of historic structures there are almost always requirements for using like for like bricks. Contemporary bricks used in construction are often bonded using cement mortar, this makes deconstruction almost impossible. The bricks are often damaged by the wall ties and covered in mortar but they can be used as aggregate and generally recycled. The stainless steel of the ties can also be recycled.

Stone – If a lime mortar is used in the construction of a stone wall then it can be deconstructed and the stone re-used. If a different type of mortar is used and the stone is of good quality it may be possible, especially if large pieces of stone had been used in construction, to save some pieces by cutting them from the wall.

Blocks - Blockwork generally provides little opportunity for deconstruction because of the cement mortar used and the damage that can be inflicted by the wall ties and the poor quality of the first material. Again they could only be recycled as aggregate.

Paving – Deconstruction of paved areas depends greatly on what has been used to fix the paving to the ground. Most new estates will have concrete paving which will be fixed with cement and can only be broken up to be removed. In this case the material could be recycled as aggregate. If stone paving is put down (a much greater expense) there is more likelihood of being able to deconstruct the paving for re-use. But again if cement or concrete is used as a base under the stone then it will be difficult to remove.

Slates and tiles - Slates and tiles were traditionally fixed through a hole in the top to the roof purlins with first wooden and later metal pegs. These can be removed easily and the roof can then be deconstructed and the materials re-used. Modern roof tiles (usually concrete) and slates are also fixed using pegs, most commonly stainless steel which can be re-used. There is a market for the re-use of roofing materials and they are definitely easier to deconstruct than modern walls.

Barriers to deconstruction

Many barriers have already been mentioned above. The cost of time it takes to take down bricks by hand and stack and clean them for re-use is enormous. Thankfully for traditional bricks, tiles and slates there is a market for this. The only barrier apart from cost to the traditional building being deconstructed is where modern repairs have been done and cement mortar used or other contaminant materials, such as glues or modern building materials. The main barrier to deconstruction of modern building is the method of construction. Cement mortar cannot be cleaned off bricks and blocks so if they are to be deconstructed at all their use can only be aggregate.

Design for deconstruction

To design a masonry building for deconstruction it is necessary to look to the past for inspiration. When buildings were built with solid walls and lime mortar was used to hold the bricks or stones apart then it was possible to deconstruct and re-use the building materials. Whilst cement mortars continue to be used and cavity wall construction necessitates the use of block work and wall ties there will remain a major barrier to deconstruction.

Deconstruction of Timber components - Rob Grantham

Key timber products

Timber is a versatile, strong and adaptable material both in its raw form as wood and as a resource of cellulose for paper and board production. Being a natural resource timber not only requires processing to create products but also requires nurturing through forestry management to ensure the quality of resource and hence products. Products produced by the paper and board industry rely upon forestry management for the timber resource in the form of forest thinnings. After felling and debarking, the remaining log is sawn and graded for different products and applications. Generally only about 50% of a large saw log will be converted to sawn timber for structural, architectural and furniture applications. The rest is utilised in low-grade applications such as pallets and packaging and mulch for the bark. Even the sawdust is sold as a source of cellulose.

The number of different products produced from timber is immense. For example, using different combinations of board makeup, coverings and wood fibre lengths (veneers, blocks chips strands or short fibres) it is possible to produce over 5,000 different types of board product, each with different performance characteristics and potential end-use applications. Wood products can also be re-engineered for different applications for instance the use of cardboard construction for internal doors. Traditional applications for timber and timber products in construction are described below:

- Timber framed walls
- Trussed rafter roofs and bracing
- Traditional cut roofs
- Tiling battens
- Internal doors (incl. Fire doors)
- External doors
- Floor and ceiling joists
- Floorboards
- Floor coverings
- Fencing
- Garden structures
- DIY and renovation
- Windows
- Cladding
- Large timber structures
- Temporary formwork and falsework
- Scaffolding and temporary structures
- Fixtures and fittings

Surprisingly DIY is the largest market for timber and timber products. Market sectors for renovation, packaging, temporary works (formwork, scaffolding, etc.), joinery, floor and ceiling joists and fencing also have significant market share in descending order of volume.

Fixtures, fittings and joints for timber products

Timber products may be manufactured and fixed in position using any of the following types of fixings:

- **Nails –** most common type of connection requiring manual removal. This damages both the timber and nail.
- **Screws –** more easily removed than nails and less damage is caused to the screw. Manual Withdrawn screws could be re-used.

- **Bolts –** these form easily deconstructable connections with minimum damage to both the timber and connector.
- **Staples –** Commonly used for packaging although more frequently in construction. Withdrawal of staples is difficult and time consuming due to the large number of staples required for a strong connection.
- **Dowels and biscuits** – used usually in combination with glue these joints are not easily taken apart. Dowels used for green oak framing may be drilled out for demounting the structure.
- **Glued joints –** a permanent connection that will cause damage to the wood if broken. Glued finger joints are generally as strong as the wood itself and may not need to be broken for re-use applications.
- **Glue laminations** – products such as Gluelam, LVL and Paralam should be re-used without breaking the glue lines. Glue laminated products will generally have superior performance to ordinary timber and hence higher value.
- **Metal plate connectors –** These come in various forms, but most commonly as punched metal plate connectors for the trussed rafter industry. Metal connectors are usually easily removed by hand.
- **Mechanical bonding in masonry –** where timber has been built into masonry construction disassembly of timber members is easily achieved. This timber will often be preservative treated.

Opportunities for deconstruction

There are many timber products used in buildings that if deconstructed could be re-used in new build or renovation with little modification required. For example large timber beams, railway sleepers, timber doors, flooring and windows are all currently re-used to some degree through the salvage industry. The common link between these products is the high quality of timber or high value of the product which ensure profitability for relatively low volumes of re-sale. Products that may have sufficiently high re-sale value and quality for a re-use strategy include:

- Timber framed walls
- Trussed rafters
- Traditional cut purlins and rafters
- Internal doors
- External doors
- Floor and ceiling joists
- Floor coverings
- Garden structures
- Windows
- Large timber structures

Since weathering or damage incurred during deconstruction may be undesirable for re-sale, some products may require re-processing:

- Tiling battens
- Floorboards
- Fencing
- Garden structures
- Cladding
- Fixtures and fittings

Low quality or degraded timber may benefit from laminating to improve the quality and hence value. Finger jointing and glue laminating can create long marketable lengths of quality timber product from short lengths of waste timber. Weathered timber will need planing to improve the appearance and performance of the finished product.

Barriers to deconstruction

Timber undergoes a very slow process of thermal and UV degradation that occurs when exposed to the sun or in close proximity to a heat source. This results in darkening of the timber and breakdown of the cell structure. ‘Weathered’ timber will require some planning or sanding to return the original lustre of the timber and provide a suitable substrate for performance coatings. This re-processing may not be economically viable for all products.

Equally, the process of deconstruction requires careful manual removal of timber elements to ensure that they are not damaged and remain suitable for re-use. This may be labour intensive and deemed to be uneconomical. Smaller cross sections of timber will be more prone to damage and hence less suited to a deconstruction strategy.

Design for deconstruction

The ease with which timber products can be removed or dismantled during deconstruction will influence their suitability for deconstruction. This is often reliant on the type and number of connectors used in the construction. Nails and staples for instance are more labour intensive to remove, cause more damage to the timber and require a greater number to achieve a sufficiently strong connection. The use of bolts, dowels, screws or pressed metal plate connectors greatly improves the deconstructability of components.

Glazing can cause a particular problem for deconstruction of windows although modern double glazed units are much improved through the elimination of putty seals. Glazing bars are also prone to damage due to their small cross section. In general, small cross sectional timber will be more likely to get damaged during dismantling and will be less suited to deconstruction.

Deconstruction of Steel components - Tom Lennon

Key Steel Products

The steel industry provides a large number of products for the UK construction industry. These include:

- Hot Rolled Products (weldable structural steels to BS 4360:1990 and BS EN 10025:1990):
- Universal beams
- Universal columns
- Joists
- Bearing piles
- Circular hollow sections
- Square hollow sections
- Rectangular hollow sections
- Channels
- Angles – equal angles and unequal angles
- Castellated beams, columns and joists
- Structural tees – cut from universal beam or column sections

In addition compound sections can be produced by connecting two or more sections together. Common applications include compound struts formed from two channel sections back to back or from two angles placed back to back. Where the size required is outside the range of available sections plate girders are made up by welding sections of plate to form large beam sections. Such sections may have equal or unequal top and bottom flanges. Cold Rolled Sections (also known as light gauge or cold formed sections):

- Channel sections – plain or lipped, derivations include swagebeam & multibeam
- Zed sections – derivations include ultrazed profile and zeta profile
- Compound sections – formed from using two or more sections together
- Special sections – include hat and eavesbeam sections

The sections mentioned above are used for both structural and non-structural applications. Among the many other applications for buildings outside the usual beam, column, joist, stud structural member are slab bases for columns, profiled cladding and decking, access stairways and walkways and gantry cranes. Both hot rolled and cold rolled sections may be used for lattice construction to support roofs and floors or to span large distances. Typical applications would include triangulated roof trusses or large span girders. Steel is also widely used in conjunction with other construction materials. Typical examples would be the use of steel reinforcement to concrete structures or the use of composite construction where the steel and concrete together provide an optimum solution in terms of utilising the strengths of both materials. A more detailed description will be provided for the six key products identified below:

- Universal beam sections
- Universal column sections
- Profiled metal decking
- Cold-formed steel floor joists
- Bolts
- Slab bases

Fixtures, fittings and joints for steel products

Connectors (including bolts, screws rivets and nails)

Connections to hot rolled products are usually made using either bolts or welds. Bolts may be either grade 4.6 (to BS4190), grade 8.8 (to BS3692) or, less commonly, high strength friction grip bolts (to BS4395). For structural applications the most common type of bolt is grade 8.8 at a diameter of either 16 or 20mm. For cold rolled sections a large range of connectors is available including bolts, self-tapping screws, blind rivets, powder actuated pins and spot welding. In addition to mechanical fasteners adhesives may be used to connect floor boards to cold-formed floor joists.

Opportunities for deconstruction

The demolition industry is already adept at recycling steel materials even where they are used in tandem with other construction materials such as reinforcing steel. The increased use of light gauge steel for industrial, commercial and residential use provides the potential to increase the quantity of structural members that can be reused. For the key steel products identified above beam sections and column sections can be reused where it is economically viable to remove the members without causing significant damage to the connected ends. The lighter gauge steel units such as metal floor decking or floor joists are in general easier to remove without causing too much damage because they are often screw fixed as opposed to being bolted.

Barriers to deconstruction

As with other materials the most obvious obstacle to the greater use of recovered elements is an economic one. Certain elements may not be suitable for re-use because of uncertainties concerning their in-service history. For large elements such as beams or columns any significant deformation would be visible. In the absence of any significant deformation the members should be suitable for re-use. However, this rule of thumb would not necessarily be appropriate for fasteners where elongation or thread stripping may have occurred during their lifetime.

An increase in standardised dimensions for industrial, commercial and residential units in recent years has resulted in an increased likelihood of structural elements being of the required length for new projects. However, it is possible to re-use beams and columns by removing the ends. Where there are uncertainties concerning the history of the member proof testing may have to take place before members can be used on a new project.

Re-use of steel members will have an impact on the working conditions for demolition contractors. In particular there will be health and safety implications in working close to connections between beams and columns. There are technical difficulties in removing individual sections where steel is used in conjunction with other materials. This is particularly significant in composite steel-concrete construction where the beams are connected both to the supporting columns and to the floor slab. The separation of profiled steel decking from the underside of the concrete floor slab is a difficult operation although evidence from fire tests suggests debonding occurs at high temperatures.

Contamination may prove to be a significant barrier to re-use. The use of spayed products for fire protection may mean that removal and disposal of potentially hazardous materials may make deconstruction uneconomic. Corrosion of existing structural sections may also provide a significant barrier to re-use. Although members may be perfectly capable of fulfilling the design function in terms of strength and stability the measures required to provide an aesthetically pleasing finish might prove uneconomic.

Design for deconstruction

The obstacles to deconstruction outlined above are considerable. They include economic, technical, logistic and social factors. Given the current market for steel products and the relatively low cost of the material these obstacles can only truly be overcome by thinking about re-use at the initial design phase. Certain types of connections such as fin plates or cleats would be more amenable to recovery and reuse than larger more rigid connections such as welded joints or large end plate connections. Certain areas of the steel construction industry are more amenable to design for deconstruction than others. The increased use of pre-fabrication in the light gauge steel frame industry is one area where deconstruction techniques could be readily adopted. The increased use of modular construction and pre-fabricated wall and floor units mean that it is both practical and economically feasible to either re-site an existing building or use the components in a new building. Design for deconstruction is not however solely an issue for the designers of buildings. The development of suitable tools for the safe and economic removal of structural elements is an essential pre-requisite of the more widespread adoption of deconstruction.

Conclusion

A number of opportunities exist to increase the number of steel products that can be economically re-used. However, a number of barriers to the increased use of deconstruction techniques exist. These barriers are economic, social, technical and logistical. The greatest benefit will be achieved by incorporating deconstruction issues into the design and feasibility stage for all new construction. Each case can then be judged on its merits in terms of the potential cost of recovery or re-use of construction materials.

Development of the Deconstruction Cost Model - Anthony Waterman

Summary

Deconstruction requires the development of a deconstruction cost model to assess the economic and financial implications for the various methods of deconstruction of building components and elements. An early version of the model has been developed in MS Excel and list of building components have been identified against which the model will be tested for accuracy and appropriateness of use in the deconstruction arena. The model relies on a methodology that sets out the procedure for calculating the cost of deconstruction of a component. This procedure can be expressed as algebraically as:

DCa= f (Ka + La+ Ea)
Where
DCa - deconstruction cost for component named 'a'
Ka = cost of capital to deconstruct 'a'
La = cost of labour to deconstruct 'a'
Ea = cost of Entrepreneur or overhead

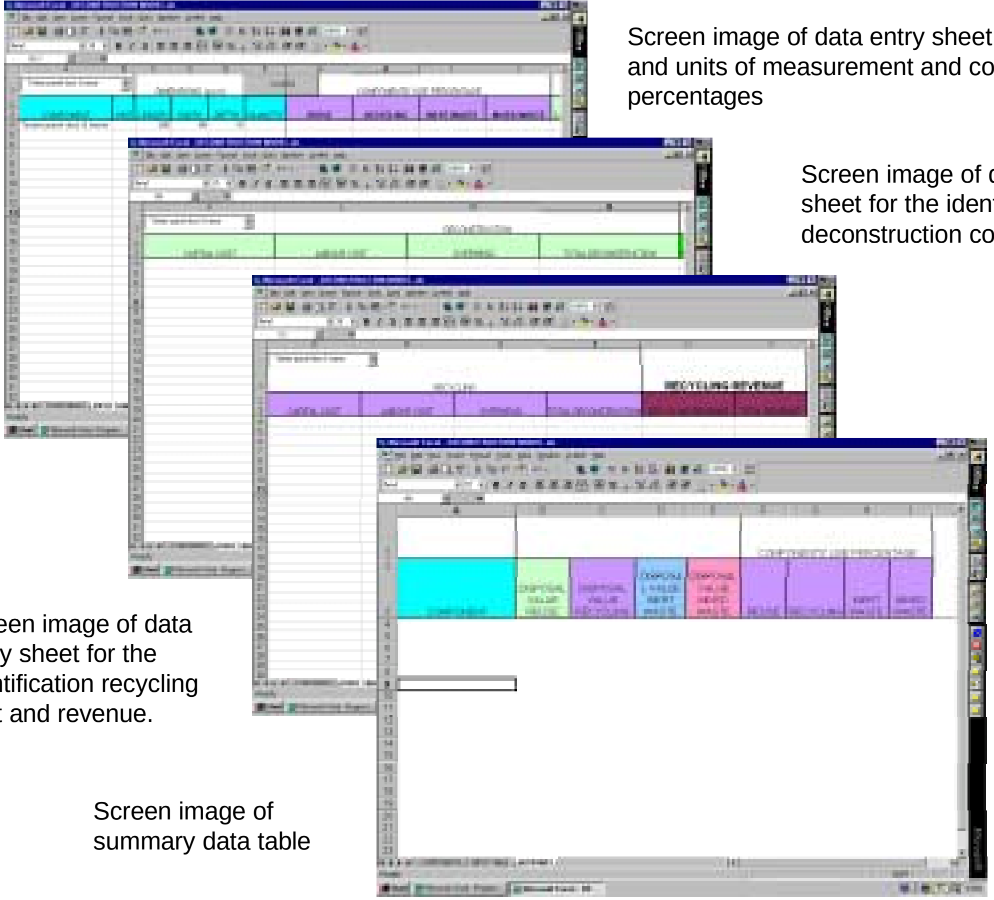
The component that has just been allocated a cost (DCa) may be able to earn an income if it is sold, and is said to have a residual value. Therefore the disposal value of an asset, or DVa, is:

DVa = Ra - DCa

The electronic version of the deconstruction cost model allows for the selection of a building component from a predetermined list (see Figure 2 overleaf). This model is currently in draft and will be completed by the end of 2002. The following four simple steps outline the model.

1. The user is prompted to specify details of dimensions and units of measurement for the component, and subsequently identify what percentages the component are expected to be reused, recycled, sent to landfill as inert waste, sent to landfill as mixed waste.
2. The model then prompts the user to identify how much it will cost to deconstruct the component in a way that would allow these quantities to be disposed as specified. The model requires the user to select a cost for capital, labour and overhead.
3. The model then identifies any revenues that would be received (for re-use, recycling) and what costs have to be paid for disposal (for elements that are sent to landfill as inert waste or as mixed waste).
4. A summary table is automatically created to show the user what the total value and cost of each deconstruction activity for the components selected.

Figure 2 - Screen Images of the Deconstruction Cost Model



Screen image of data entry sheet for dimensions and units of measurement and components 'use' percentages

Screen image of data entry sheet for the identification of deconstruction costs

Screen image of data entry sheet for the identification recycling cost and revenue.

Screen image of summary data table

Component Selection

Table 5 shows a provisional list of components to test the deconstruction model. It is expected that after consulting specialist demolition and reclamation contractors it may be appropriate to identify other components to test the model against. The component list has been chosen to represent a sample of typical components that may be found on a site prior to deconstruction. The list also includes components made from various materials to fully test the model in a wide range of scenarios.

Table 5.

	Dimensions (cm)			Total
	length	width	depth	
Timber panel door & frame	200	89	10	1
Timber fire door & frame	200	89	10	1
Steel window frame (double glazed)	250	125	13	1
Aluminium window frame (double glazed)	250	125	13	1
Timber window frame (double glazed)	250	125	13	1
UPVC window frame (double glazed)	250	125	13	1
Reinforced concrete	100	100	20	1
Timber skirting board	100	7	2	1
Timber architrave	100	5	2	1
Timber purlins	100	20	7	1
Timber ceiling joists	100	20	5	1
Timber floorboards	100	900	2	1
Timber floor boards	100	10	1	1
Aluminium & plasterboard partition	100	275	10	1
Timber & plasterboard partition	100	275	10	1
Paving stones	43	43	4	1
Slate roof tiles	100	100	1	1
Electric fluorescent strip light	120	20	10	1
Copper pipes	100	2	2	1
Concrete hollow blocks	44	21	10	1
Double faced bricks	21	10	6	1
Plywood	244	122	2	1
Chipboard	244	122	2	1
Plasterboard	244	122	2	1
Rolled stell joist (RSJ)	100	20	10	1
Radiator	100	50	3	1

Next Steps

Contact with specialist demolition and reclamation contractors to obtain the necessary deconstruction cost information to test the model. Identify the strengths and weaknesses of the current procedure. This will be achieved by interview with specialist demolition and reclamation contractors to identify the errors in the current model, and identify potential improvements to the procedure developed for assessing the economic and financial implications of reuse, recycling and disposal options for various building components.

CONCLUSION

This paper has shown that despite the lack of suitable historic data of UK construction and demolition waste, there has been much progress in the last three years since the development of methodologies for auditing waste. Most of these studies have been paper-based and undertaken over short and intermittent periods of time. However, since the development of SMARTWaste^{TM} and the subsequent redevelopment of a web-based SMARTWaste^{TM} and SMARTStart system, it has been possible to provide the first environmental performance indicators that the construction industry can use to benchmark itself.

Despite the fact that the demolition industry has been exceedingly innovative in terms of recycling materials, these practices have been mostly related to large volumes of inert materials and again down-cycling into low-grade applications. For greater access to and reuse of demolition materials, components and products, there are many barriers to overcome. Mostly these barriers are directly or indirectly related to economic restrictions, but there are other perceived rather than actual barriers. Despite the evident opportunities identified in this paper, it is difficult not to recognise the lack of investment and concerted effort that has been afforded into designing buildings with deconstruction in mind and disseminating best practice deconstruction. No doubt this will improve as more and more opportunities are realised.

It is not just cost that is the issue of preventing further growth in deconstruction and reuse of materials. After all, the reclamation and recycling industries have been very successful in sourcing valuable components and products for reuse. There are obvious physical barriers such as corrosion, damage and bonds that are worthless or difficult to separate. There are practical barriers that will include a lack of information, skills, markets and design. There are traditional barriers where products are not designed to be deconstructed and reused. However, on a more positive note there are a whole range of components and products that are available for deconstruction and reuse with little requirement for any major design changes. What is required is a stable market for these products. This is perhaps the most difficult barrier and the greatest challenge as without any markets there is little need or incentive to deconstruct, segregate and reuse.

Designing for deconstruction does create a wealth of opportunity for the future. As this paper has pointed out in the technical opinions, there is scope to design fixtures, fittings and joints that can be easily deconstructed at a later date. Most current structures, apart from those of the Victorian and earlier periods, have little opportunities despite the wealth of components and products that could be useful again if it were not the method of fixture that was incorporated during the construction phase. I think here of glues, adhesives and mortars that mould around the components without any potential to separate them later. A good case in point would be the use of ordinary portland cement in mortars to bond bricks and blocks together that is economically impossible to separate later. This is in strict contrast to earlier mortars using lime as the binding agent.

In summation, we can see that there are many future opportunities both to design for deconstruction and to selectively deconstruct components and products with a current value. This paper has made some progress in identifying the opportunities and barriers but this is not exhaustive. The final months of the government-funded project on Deconstruction and reuse of construction materials will focus more on these barriers and opportunities where relevant and practical.

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IP3/97	Demonstration of re-use and recycling of materials
Digest 433	Recycled Aggregates
IP1/96	Management of construction and demolition waste
IP5/94	The use of recycled aggregates in concrete
IP12/97	Plastics recycling in the construction industry
IP 14/98	Blocks with recycled aggregate: beam and block flooring
IP 7/00	Reclamation and recycling of building materials
Digest 447	Waste minimisation on a construction site
BR418	Deconstruction and reuse of construction materials

ANTICIPATING AND RESPONDING TO DECONSTRUCTION THROUGH BUILDING DESIGN

Abdol R. Chini and Shailesh Balachandran (University of Florida, Gainesville, Florida, USA)

SUMMARY

The construction and demolition industry produces vast quantities of waste that for environmental, economical and social reasons is becoming unacceptable. The extended chain of responsibility and the separation of responsibilities for manufacturing materials, design and construction, operations and maintenance, and eventual adaptation or disposal, have resulted in a breakdown of feedback loops among the parties involved in creating and operating the built environment. To effectively tackle this waste issue a more proactive design approach must be taken. By designing both building products and buildings for deconstructability, architects and other designers are enabling the extraction of high value materials for reuse and recycle. As there is logic in design and erecting a structure to serve a particular purpose, there should also be logic to its removal when the structure is done serving that purpose. Initial design and future deconstruction should relate to each other clearly and coherently. Designers should also have the aim of achieving the best possible disassembly. To address the challenge of how to come up with a deconstruction friendly design, a building is broken into its constituent components from foundation to the roof and then design criteria for each of these elements is suggested in a manner that would facilitate easy disassembly of the building, eventually leading to more components reuse.

KEYWORDS: Deconstruction, Recycle, Reuse, Disposal Phase, Sustainable Construction, Demolition, Construction and Demolition (C&D) Waste

INTRODUCTION:

Functional architectural concepts along with aesthetic sensibility have now replaced formal ones of the past. Functional buildings can be defined specifically by their use, a link between the free creations of architects and the bare utilitarian structures of engineers and technicians. Fulfillment of purpose has become one of the means of architectural design. Architects nowadays try to exploit the possibilities of functionalism to the full and the concept of ‘designing for deconstruction’ needs to be an integral part of this functionalism. Thus, if a building is said to be functional, it should not only satisfy the requirements for its intended use but it should also be responsive to it’s disassembly at the end of the life cycle. Typically, a building project includes five phases where it is possible to identify and apply waste prevention techniques. Some of these phases overlap with each other, because decisions made during the early stages will affect the later stages, but they can still help to clarify what necessary steps constructors can take at various instances in a project. The different phases involved and their related waste prevention objectives are listed below [1]:

- **Asset management:** To assess and make sure that existing buildings meet current needs and to optimize the use of existing and available properties to meet those needs.

- **Project planning:** To formulate a waste plan and set waste prevention goals.

- **Design:** To design the proposed structure in a manner such that, it's components address the issues of reusability, durability, and adaptability.

- **Construction:** To promote and achieve efficient procurement of materials, delivery, storage, and eventually the effective use of those materials on the jobsite.

- **Demolition:** To continuously encourage the philosophy of deconstruction and salvage of materials for future reuse, instead of total destructive demolition.

If we look back into history it is evident there has been a long established culture of reuse and recycling of building materials and, in the industrially backward societies this is still applicable today. The majority of vernacular buildings used materials that were easily available in the surrounding locality and were true to the geographic prevailing geographic conditions. Materials such as stone, slate, timber, thatch, and mud were used and these were allowed to decay naturally or could be easily reworked into newer buildings [2]. Old materials tend to have an aesthetic, authentic and antiquarian value, and are have always been considered as elements that add value to a property. Design for disassembly is not a new idea. History also tells us that traditional Japanese farmhouses were constructed without nails, and could be disassembled and reassembled like a puzzle. [3] The building industry is beginning the first steps in formalizing some of the strategies that would create benign processes, close materials loops, and make industrial systems mimic and integrate with natural processes. The writings, and the built work, of Brenda and Robert Vale illustrate a number of 'green' architecture principles that could be constituted into sustainable architectural practice. There are six basic principles that have been suggested [4], and one of them is:

- *Minimize new resources*, a building should be designed so as to minimize the use of new resources and, at the end of its useful life, to form the resources for other architecture.

Design for deconstruction is an attempt to raise materials and components up the recycling hierarchy, away from recycling, and up to a more environmentally preferable point of reuse. For these reasons design for disassembly is primarily, but not exclusively, an issue of design for the reuse of materials [4].

DESIGN FOR DECONSTRUCTION STRATEGIES

To successfully implement the concept of component reuse, the owner or the owner's representative should in the first instance put in place a program which clearly specifies the primary objectives and allows deconstructability to be assessed as a project performance attribute. The essence of this approach is that design for deconstruction and the eventual building component reuse can be enhanced by individual participants exploiting construction knowledge to maximize opportunities and develop best options to meet project objectives in coordinated way. Although setting a mechanism in place that facilitates deconstruction principles among project team members is an important aspect of implementing deconstruction, it is equally important to recognize the significance of the timing of the input by the various team members. The importance of timing is illustrated by the Pareto principle, which contends that decisions taken at the early stages in the project lifecycle have greater potential to influence the final outcome of the project than those taken in the later stages.

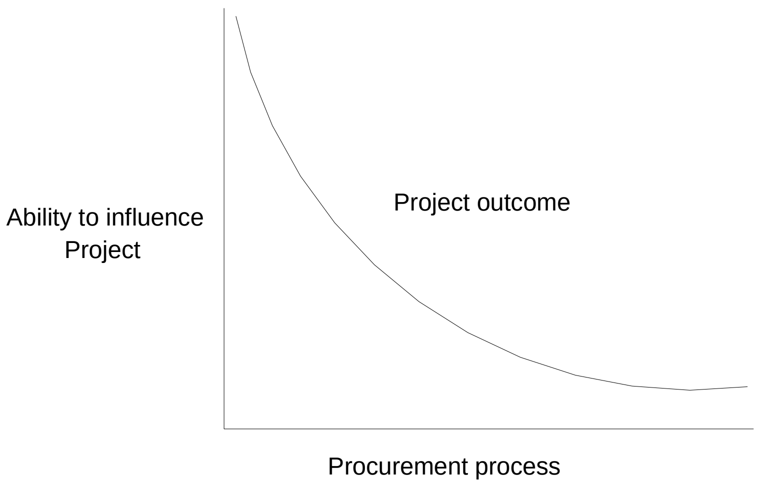

Figure 1 - Cost influence/Pareto curve

The following guidelines can be used to assess the extent to which a building can be designed for material recovery [5]. Each building project is unique and hence there can be no universal strategies that will always apply. These guidelines are presented as a starting point in thinking about design for deconstruction.

- Minimize the number of different types of materials. The more homogeneity there is between the materials of a structure the more simple it would be to sort materials on site and reduce transport to separate the reprocessing plants.

- Design for locally produced building materials.

- The designer should strive for optimal use of interior space through careful design so that the overall building size and resource use in constructing and operating the building is kept to minimum.

- Use detailing that will prevent soil contact and rot.

- Hazardous or toxic materials should be avoided. This will reduce the potential of contaminating materials that are being sorted for recycling and will also reduce the potential for human health risks during disassembly.

- Inseparable subassemblies should be made from the same material. This means that large amounts of one material will not be contaminated by small amounts of foreign materials that cannot be separated.

- Nails and bolts have appropriate uses as per the type of connection and size of the members. A variety of nails in one building cause the requirement for multiple tools for removal. A mix of bolts, screws, and nails requires constant shifting from one tool to the next.

- Permanent identification of material types should be provided. Many materials like plastics are not easily identified and should have some form of non-removable and non-contaminating identification mark to allow future sorting of materials.

- It is essential that all information on the building manufacture and assembly process be sustained. Ample measures should be taken in order to ensure the preservation of information such as ‘as-built drawings’, information about disassembly process, material and component life expectancy, and maintenance requirements.

- The simultaneous creation of a deconstruction plan along with the construction plan and labeling of components to their constituent materials, similar to plastic products label numeric codes to indicate the type of plastic will provide directions to the deconstruction contractor for the disposition of materials. An upfront deconstruction plan also allows for planning the management, scheduling and safety requirements of the deconstruction process.

- Provide realistic tolerances to allow for movement during disassembly. Handling during disassembly may require greater tolerances than the manufacture process or the initial assembly process.

- Use a hierarchy of disassembly related to the expected life span of the components. Components with shorter life span should be made readily accessible and easy to disassemble, whereas components with longer life spans may be less accessible.

- The project program should make use of optimum value engineering.

BLUEPRINTS FOR DECONSTRUCTION

In order to suggest strategies for designing for disassembly that result in component reuse, which is the core aim of this paper the following guidelines are suggested. Here a typical building has been broken down into its constituent components and suggestions have been made for each of these components. A building typically consists of the following layers:

a) Structure – foundation and load bearing components

b) Skin – cladding and roofing system

c) Services – electrical, hydraulic, HVAC (heating, ventilating, and air conditioning) etc

d) Space plan – interior e.g. partitions, finishes and furniture

Structure

Foundations

- The entire load of the building, including the dead loads of the components and the live loads of the occupants is ultimately transferred to the foundation. The foundation then disperses this load evenly to the ground base. In order to facilitate deconstruction foundations have to be designed to receive meticulously calculated loads. The general trend is to over-design the foundations with a higher factor of safety, because the owner at the project inception stage is really not sure about the future occupancy rate of his building. In order to achieve design for deconstruction goals, the owner or the owner's representatives must have a clear picture of the intended purpose of the building and any future additions to it, the loads of which have to be transferred to the existing foundation.

- Building 'thin-wall foundations' can reduce concrete usage by 20%. 'Thin-wall foundation' consists of a 6-inch foundation wall instead of the conventional 8-inch wall. This has been used primarily in residential construction till now, but, can also be applied to commercial and government projects, as long as they abide by the building codes [1].

Structural system

- A good way to think in terms of deconstruction-friendly structural system is to identify, which parts of the building can be self-supporting.

- Use a standard structural grid. Grid sizes should be related to the materials used such that structural spans are designed to make most efficient use of material type.

- It is advisable to keep the geometry of the building simple (Figure 1).

Figure 1 – Simple geometry in building design.

- Portals, which are essentially a combination of vertical and horizontal members, can be used in designing supporting systems. These in turn can be bolted to floor structure (Figure 2).

Figure 2 – Portals enable clear span solutions

- Use assembly technologies that are compatible with standard building practice. Specialist technologies will make disassembly difficult to perform and may require specialist labor and equipment that makes the option of reuse less attractive. Bolted connections favor deconstruction as compared to welded connections. When welded connections are dismantled, for example using a cutting torch, some damage to the connections will occur and there is also a loss of some material. In addition to the possibility of causing a fire hazard, disassembly involving the cutting of welded connections results in a level of uncertainty as to when the connection no longer has sufficient integrity to form a viable structural support. [6]

- Steel is a material with great utility for design for deconstruction, due to its ease of recycling through a thermal process and ability to span large distances with less mass of material than concrete for instance.

- Separate the structure from the cladding, the internal walls, and the services. This will facilitate parallel disassembly where some parts of the building may be removed without affecting other parts. This will result in the saving of sufficient amount of time.

- Buildings designed to incorporate pre-stressed and post tensioned beams, and cantilevers make the demolition process more onerous due to the presence of these complex structural elements. Stressed components pose danger to de-stress.

- Another option available when designing the structural framework for a building is Pre-engineered building. These are well known for their wide clear spans that easily accommodate production lines and changing floor layouts. Their flexible interior space facilitates storage and movement of equipment, allowing customized plant flow. Pre-engineered buildings up to 70 meters clear span and 30 meters eave height could be designed, manufactured and erected. Pre-engineered buildings are site bolted, it is relatively easy and economical to dismantle the buildings and re-erect them in another location.

Floors

- The building should be designed for standard ceiling height and standard building dimensions.

- Precast concrete floors separate the plane of the top and bottom of the wall from the plane of the floor structure facilitates mechanical separation and structural stability during the deconstruction process. In this system the walls sit on top of the floor structure and do not extend through the horizontal plane of the floor structure and the floor above rests on top of the wall.

- Raised flooring systems facilitate deconstruction by eliminating ductwork and placing wiring systems in a more accessible location in the floor plenum rather than the overhead ceiling plenum. This individual item may cost more than traditional practice but facilitates adaptability and energy efficiency (Figures 3 and 4).

Figure 3 – Access floor seen from above

Figure 4 – Access floor seen from below

Skin

Walls

- Use an open building system. Modular wall panel systems have been a major innovation in design for disassembly, which has already affected the construction industry. These replace fixed walls that make the space layout very rigid, with flexible systems that facilitate the reconfiguring of the usable space by mere disassembling and then reassembling the components. The systems also allow for simple replacement of any damaged sections [1]. According to Don Bauman, a systems-marketing consultant at Steelcase Inc., movable wall panels save time on installation and renovation, which results in money saving (Figure 5). Also, installing movable wall panels is 10 to 20 times faster than installing a standard gypsum board drywall system and that reconfiguring these panels does not even disrupt the HVAC systems (Figure 6). Using movable panels to separate work areas does not entail expensive and lengthy electrical and cabling enhancements or alterations; rather, power and communication systems can easily be added directly to the panels. This allows for great flexibility in the layout of office furniture. Considerable savings can also be achieved through reduced maintenance [7]. This will allow alterations in the building layout through the relocation of components without significant construction work.

Figure 5 – Movable wall panels provide flexibility in assembly and disassembly

Figure 6 – Deconstruction of a regular dry wall system

- Walls should be designed to be non-load bearing. A wall should be just a membrane that goes in between the structural system. This will reduce the over all weight of the building and will also facilitate the optimum use of mortar.

- Chemical bonds should be made weaker than the parts being connected. This is so that bonds will break during disassembly rather than the components. Mortar that facilitates the separation of the individual bricks should be used. Meaning, the mortar should be significantly weaker than the bricks. To elucidate this situation let’s see small case study of Hume Hall at the University of Florida, Gainesville, USA. The author of this report was involved in a one-day workshop where bricks were being salvaged from the demolished Hume Hall building, a student dormitory at the

University of Florida, to be put in use for Rinker Hall – a new facility for the M.E. Rinker School of Building Construction. It was observed that the bricks that were part of the 100 plus year old building had mortar joints that were extremely strong. This resulted in the breakage of the bricks themselves as the mortar was being cleared. This brings about a question as to, were such strong joints really necessary?

- Provide access to all parts of the building and all components. Ease of access will allow ease of disassembly. It is also preferred that components be recovered from within the building without the use of specialist plant equipment.

- Avoid foam insulations made with HydroCholroFloroCarbon (HCFC).

- Glass curtain walling has both its advantages and drawback. Firstly, it negates the use of masonry walls, which makes the building considerably lighter. This eventually results in less load being transferred to the structural systems and finally to the foundation. But huge glass curtain walling also makes the deconstruction process more difficult as extreme caution has to be taken for its disassembly.

- When designing drywall partitions it is advisable to specify the use of screws or other fasteners instead of nails or adhesives. Nail pulling has always been a time-consuming and expensive activity. In fact, the labor costs of pulling out nails often exceed the market value of the wood, making disposal more economically viable than reuse [1].

Doors & Windows

- Windows and doors must be designed for maximum standardization or repetition. This will facilitate the use of standard dismantling techniques and will also help increase the 'learning curve' of the deconstruction labor for that particular building.

- Mechanical connections should always be preferred over chemical ones. This will facilitate easy separation of components and materials without force, and reduce contamination to materials and damage to components.

Roof

- Roof should be designed as composition of assemblies, in which each component can be lowered to the ground individually by means of a crane as an intact unit. This would make the final disassembly process much safer as each of these components can then be dismantled at ground level.

- One of the principles that facilitate deconstruction is the reduced use of chemical sealants in a building. When a building is designed with a flat roof, it demands higher sealant membranes as water gets accumulated in the flat surface and that needs to be drained of mechanically. Instead, if buildings are designed with sloping roofs, water is drained off from the roof automatically by gravity. This results in less reliance on chemical sealants. But on the other hand, high slope roofs pose a problem for deconstruction working platforms Figures 7 and 8). This can be avoided by the use of ridge caps that are easily removable and allow access to the roof structure for tie off. Roofs can also be designed to support the requisite load for a worker lifeline. This would facilitate both roof repair and ultimate deconstruction.

Figure 7 – Slope of the roof and workability.

Figure 8 – Slope of the roof and workability

- The use of vinyl roofing membranes is a good option to be used in roofing systems. These can be and are being recycled into such second-generation products as speed bumps, parking curbs and asphalt patching material. Nearly all vinyl-roofing manufacturers utilize post-industrial recycled roofing scrap that has been generated in the manufacturing processes of their own products. Steel and wood are typically needed to support heavier roof systems and lightweight vinyl roof systems help reduce the need for these steel and wood members. This in turn means fewer elements to dismantle, which would eventually result in time saved in the deconstruction of the entire structure. Conversely, disposal of a built-up roof could mean high disposal costs, greater material volume in landfills, increased labor requirements and possible exposure to asbestos in the old roofing system [9].

Services

Mechanical, Electrical & Plumbing (MEP) Systems

- The building should be designed in such a manner that it admits sufficient daylight that will naturally illuminate the building interiors as far as possible during the daytime (Figure 9). This will result in less number of light fixtures, which in turn will result in less wiring and less conduits.

Figure 9 – Naturally lit interiors

- Passive solar heating, day lighting and natural cooling can be incorporated to lessen the energy consumption of the building. This will result in lesser units to be used for HVAC.

- In today's high transfer environment, where speed and low signal loss are critical parameters, it is increasingly evident that Category 5 copper wire will be inadequate for most future applications. Fiber optic cable has no such limitations. The average bandwidth for multimode fiber is 500 MHz for one kilometer. In a standard office environment, this would eliminate the need for repeaters and extra closet space. Fiber optic cable does have a premium over copper initially, particularly during installation. But as has been addressed above, the greater transfer rate, permanence and ease of maintenance causes these costs to drop over time. Because fiber is lighter and more flexible than copper, it is also easier to install and remove. Large capacity copper cables require special support structures to handle the weight. This leads to overcrowded chases and conduits eventually taking up a lot of space. Even when the individual cables are not large, the aggregate can be unwieldy and difficult to manage. This ultimately makes the deconstruction process difficult and complicated. A duplex fiber-optic cable weighs 12 lbs. per 1000 feet and is much more flexible. Additionally, the bandwidth is also much larger. Fiber optic cables can be installed in the same conduits as power cables [10].

- Lift shafts are generally made up off concrete shear walls. These play a vital role in the lateral stability of buildings. Knocking out partitions between each lift to make one large lift well would facilitate moving materials down through the building during the deconstruction phase. As lifts are structurally massive these are ideal waste chutes. In confined urban sites where land is at a premium this makes a lot of sense.

- Electrical systems should be designed in such a way that power for the entire building can be turned off conveniently during the deconstruction process.

Space Plan

Finishes

- Use lightweight materials and components; this will make handling easier, quicker, and less costly, thereby making reuse a more attractive option (Figure 10).

Figure 10 – Light-weight materials facilitate easy handling during deconstruction

- Secondary finishes and coatings should be avoided as far as possible. Such coatings may contaminate the base material and make recycling less practical. Where possible, materials that provide their own suitable surface finish should be used. If at all finishes are necessary then, mechanically connected finishes can be used. This is taking into consideration that protective coatings such as galvanizing will still be desirable in some situations for other reasons.

- Avoid vinyl wall coverings.

- One office layer where a more circular approach wherein a material is produced, used, and reused a couple of times till it eventually becomes waste, has begun to happen is the carpet layer. Interface of Atlanta Georgia, USA has been a leading innovator in the carpet sector. According to their research10 to 20 % of carpets have 80 to 90% of the wear during the course of time. So their new product line includes carpet tiles that have replaced conventional large size carpets. Carpet tiles can be routinely checked and it is also possible to replace the worn carpet tiles of all their customers. This has led to over an 80% saving in materials. Recycling a complex composite material poses a lot of problems; hence, Interface has developed a new polymeric carpet material. This can be remanufactured back into itself, producing almost 100% less waste than normal carpets. This new service and continual recycling approach has resulted in reducing the resources needed to provide carpets by over 30 times [8].

- Design cladding systems that are fixed by snap release connectors, friction, or other joints that do not require sealants.

- It is also advisable to design a building for standard colors and materials. This would lead to waste prevention because typically, when a construction project is completed, extra materials are usually kept for future repairs. Quantities of homogeneous leftovers would be easier to reuse and recycle in the future life cycle of the building.

Interiors

- Partition walls used to separate different activity space should be to the minimum. Especially in cases where the space occupied is to be used for corporate activity, an open office planning should be adopted. Interior design units like storage cabinets can separate areas with different activities that need only a visual barrier. This will reduce the number of partition walls. Creation of levels in the floor can also differentiate various activity areas.

- The building should be designed to incorporate open-ceiling systems in its interiors (Figure 11). This will minimize the materials used and thereby enhance deconstruction.


Figure 11 – Open ceiling system

- As far as possible the layout of the service areas should be such that they are grouped together at one location. This will avoid routing service lines throughout the building. This again will ease the process of deconstruction making it less tedious.

It also can be gathered from the many works of researchers that a good deal of skepticism abounds with respect to the efficacy of the concept of ‘design for deconstruction’. Many practitioners would be sympathetic to the view that such concepts are just passing phases and hence it is paramount to distinguish genuine cultural shifts in the building industry from what can simply be trendy ideas. Sometimes innovation is not a new product or a piece of equipment, but rather a new way of seeing an old problem. By viewing with a new perspective we are able to use existing technology in an entirely different way

CONCLUSIONS

When today’s buildings reach the end of their useful life, the option to demolish and send them to the landfill may no longer exist. Instead, economic and ecological realities may dictate that they be preserved, refurbished, reused, or, when none of those options is possible, that their component materials be salvaged. In such a scenario, buildings designed for disassembly—those made with durable, well-marked materials, minimal toxic constituents, and able to be easily taken apart—will have the greatest value [1].

Environmental degradation and natural resource depletion is unquestionably reaching alarming proportions. Therefore, the concept of design for deconstruction has to be realized at the programming stage. Issues of deconstruction should be included in the risk-assessment guidelines that designers use for advising their clients.
There are four different factors that go into the reuse of materials: technical, environmental, economical, and legal. Almost everything can be pulled apart or dismantled, but the question is will it be economically viable? Or does it reduce the impact on the environment? A building might meet certain regulations and codes in the time when it was built, but when it or the elements will be re-used after 50 odd years, will they meet the standards valid in that period? Design for deconstruction may in the short term have added economic and possibly environmental costs, but on the much larger scale of the life cycle of resources, the long-term benefits are potentially much greater. The future will be different, not necessarily because people decide to behave differently, but because the underlying factors will necessitate change. Design for deconstruction may not always be appropriate, as design for ease of assembly may not be. But in the construction industry, which is responsible for such a large portion of our resource use

and waste production, it is a strategy worthy of exploration.

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Design for Deconstruction and Materials Reuse

Bradley Guy, Center for Construction and Environment, Gainesville, Florida; Scott Shell, Esherick, Homsey, Dodge & Davis Architecture, San Francisco, CA

SUMMARY

The building legacy of the 20th century has been one of waste and toxicity. The US EPA has estimated that the materials debris from building renovation and demolition comprise 25 to 30% of all waste produced in the US each year. Aesthetic conventions and economic factors that influence land use and buildings over long periods of time are not predictable by the building designer, but nonetheless, buildings can be built with the intention of adaptation and / or eventual removal. Design for deconstruction (DfD) can make use of the lessons learned from product design for environment, and from the obstacles encountered in the deconstruction of modern buildings. This paper will discuss principles of design for disassembly and lessons learned from deconstruction practice to propose guidelines for design for deconstruction as a form of environmentally responsible architecture. Although there are three fundamental building types - residential, commercial and industrial, this paper will focus on the generic levels of: whole-building, elements, components, sub-components, and materials.

KEYWORDS: Building Disassembly, Deconstruction, Design for Deconstruction

INTRODUCTION

Design for deconstruction (DfD) is an emerging concept that borrows from the fields of design for disassembly, reuse, remanufacturing and recycling in the consumer products industries. Its overall goal is to increase resource and economic efficiency and reduce pollution impacts in the adaptation and eventual removal of buildings, and to recover components and materials for reuse, re-manufacturing and recycling. The practice of DfD will allow existing and new building stock to one day serve as the primary source of materials for replacement construction, in effect mining and harvesting existing building stock rather than the natural environment. This resource flow will be encouraged by aging and obsolescent buildings, dwindling natural resources, and declining population in developed countries. The population of Europe as a whole is expected to decline by 7% over the next 50 years (U.S. Census Bureau, 1999).

While the term is new, the foundation of DfD in the latter 20th century includes the work of N. J. Habakren on housing “support” systems, the Open Building movement, and the writings of Stewart Brand on adaptive architecture (Habraken, 1981; Kendall and Teicher, 2000; Brand, 1994). The International Style of architecture developed in the 1940’s, 50’s, and 60’s had attributes that are compatible with DfD such as modular construction, open floor plans, exposed structural and mechanical systems, and the use of concrete, stone, steel, and glass, i.e. recyclable materials. The dynamic technological and economic forces on commercial buildings in general have driven the development of modular and self-contained workstations, raised flooring systems, passive building integrated heating and cooling systems, and finish products that are designed for recycling. By these means, commercial building design has facilitated buildings that enable the disassembly of non-structural components. Whether there is reuse and recycling of the recovered components and materials is a separate matter.

DfD expands upon these commercial building adaptive strategies to consider the whole life-cycle of the building, not just construction and operation, and maintenance and repair, but major adaptations, and eventual whole-building removal from the building's site. If overall "sustainable development" necessitates an increase in the reuse and recycling of urban land and first generation suburbs, the trends towards renovation and rebuilding to use existing land and infrastructure will only increase. It is clearly important to address the decisions made in the design and construction of buildings that will allow the recovery of valuable resources that will be generated from building removals in the 21st century and beyond.

The economics of building-related debris disposal or recovery are driven by the relative and highly externalized costs of local debris landfill tipping fees and the presence of alternative markets for recovered materials. Two other very important factors are the labor costs and speed of the disassembly process itself. The efficiency of the deconstruction affects the direct costs of labor and equipment and also affects the time costs of a project where building removals are integral to new construction on the same site. Herein lies the opportunities and challenge for DfD. Of all of these factors, the efficiency of the deconstruction process and the cost-effectiveness of materials recovery with highest reuse or recycling value are most influenced by the designer, the architect and engineering team that determines how the building is to be assembled. These designers must understand how their decisions impact disassembly and reuse. The choices and specific uses of materials, the connections between individual materials or components, the inter-relationships of building elements, the designs of spaces and whole-building structure, and even the ability to "read" the building are within the designer's control.

Lessons learned from the deconstruction of older buildings – well-known to practitioners in the field – include: the prevalence of materials that later became environmental hazards for workers and for disposal; the entanglement of HVAC, electrical and plumbing systems within walls, floors and ceilings, that impedes the separation of building components; the use of connectors that are inaccessible and cause damage in the process of separating materials; the weakening and de-stabilization of a building during the deconstruction process; matching the scale of the capabilities of a human laborer to the scale of building components; and how the building assembly process may render materials un-reusable or un-recyclable via drilling, cutting, and use of binders, adhesives, and coatings - especially hazardous materials.

Buildings designed for deconstruction will include the dis-entanglement of systems, and reductions in chemically disparate binders, adhesives or coatings - or thermal / chemical /

mechanical means to better separate constituent materials. Ideally, the problems of maintaining as-built drawings will be overcome by the ability to visually understand the building's construction with minimal intrusion. This building transparency will in turn facilitate building engineering surveys to plan the deconstruction process. Components and materials will have a durable label like consumer product labels that list the materials' composition. This information will reduce uncertainty of planning for reuse, recycling, construction and demolition landfill disposal, or hazardous waste disposal. These buildings will have self-supporting and self-stabilizing components, component accessibility designed in, and built-in tie-offs and connection points for workers and machinery. Most importantly, buildings that facilitate reuse and recycling will use non-hazardous materials, bio-based materials, high quality and highly recyclable materials.

Design for deconstruction offers possibilities for the design of buildings that will tighten the loop of materials-use in building, and help make the transition towards minimal virgin materials use, and a cradle-to-cradle building industry instead of the dominant paradigm of cradle-to-grave. To use a spiritual metaphor, buildings would have karma, such that their spirit (materials) would be reincarnated in future lives, with designs incorporating good karma (design for deconstruction) being more enlightened (transferring materials in valuable form to the next life-cycle). Two notable examples of recently constructed commercial buildings in North America that relied heavily on recovered materials and were also designed to facilitate future materials recovery are the Phillips Eco-Enterprise Center, Minneapolis, MN, and the C.K. Choi Building at the University of British Columbia, Vancouver, BC.

STATEMENT OF THE PROBLEM

The current state of deconstruction is severely limited by numerous factors. The main obstacles can be categorized as costs and time, with these being interrelated. The main opportunity factors for deconstruction are the prohibitive aspects of building materials disposal and the value of recovered materials in environmental and economic terms. Related to the economic costs / benefits of recovered materials are the quality of materials, either for high-quality reuse and economic recycling, hazardous materials, and components and materials that quickly become obsolete, or are unfeasible to process for reuse or recycling. Last but not least, buildings in modern society are not typically *designed* to be deconstructed.

There are many efforts to redefine production and achieve "eco-efficiencies" for consumer products through dematerialization, environmental management, design for environment, design for disassembly, and design for recycling. The design, construction, and maintenance characteristics of buildings are much different than consumable goods. Buildings are expected to have much longer lives, are greater capital investments, and involve a multiplicity of actors in design, construction, regulation, financing, insurance, maintenance, repair, occupancy, and ownership over time. Housing is often seen as a psychologically and culturally more significant artifact than an automobile for instance, although some automobiles might cost more than a modest home. The perception that housing should be malleable for adaptation and disassembly carries the perception of instability, incongruent with the notion of “home as castle.” Housing in fact does share many characteristics of consumable products depending upon the culture and urban location. According to Nakajima and Futaki, the average design life of wooden residential houses in Japan is about twenty-five to thirty-five years and the average actual life cycle is fourteen to seventeen years (Nakajima and Futaki, 2001). Changing cultural expectations, economic conditions regarding land use, and technological obsolescence, especially in regard to the energy-efficiency, are key functional and environmental stresses that cause the removal of buildings from use.

Buildings also have public impacts by their creation of urban patterns such as the walls of urban streets and squares. The realization that these urban patterns, some established over generations, can be radically altered by the removal of buildings inevitably comes as a visceral shock when it occurs. Yet it does occur, and the lack of acceptance of the economics and fluidity of land uses in modern society has precluded extensive research into the realities of the need for design for deconstruction. While sustainable buildings should be designed for longevity and durability, this does not preclude the need for urban land-use diversification and flexibility via adaptation and deconstruction as well. On a global basis, transportation energy use impacts, sprawl patterns of land development, and the energy expenditure to operate buildings all told have greater environmental impacts than the use of the materials in construction and resultant waste. Therefore, design for deconstruction is an important means to facilitate the resolution of these problems as much or more than solely to reduce building-related materials waste. As an example, the ability to upgrade electrical and lighting systems in a commercial or institutional building as more energy-efficient fixtures and lamps become available might be a more significant advancement in sustainable building practices than the reuse or remanufacturing of the obsolescent fixtures or lamps themselves. If a sustainable built environment maximizes the ability to operate in a hierarchical and flexible manner, buildings will need to be multi-faceted storages of energy and materials, able to work within temporal and cultural currents of economic, social and natural environmental conditions.

A principle consideration for building adaptation is the spatial and temporal shearing inherent between the systems and materials in the building (Brand, 1994). This includes accessibility of components without conflicts between shorter-lived and longer-lived components. A key consideration for the end-of-life deconstruction of buildings is the connections between components, separation of materials into their base form, and the removal of nails, staples, paints. The contamination of base materials by the connecting devices, coatings, treatments, and the time requirements and damage resulting from the re-separation for salvage and reuse often make deconstruction extremely un-economic in a high-labor rate market.

One of the impediments for design for deconstruction is if the addition of elements that facilitate deconstruction cause an increase in first-costs of construction and clearly do not result in any near-term payback for the resultant future avoided costs or recovered value. In order for design for deconstruction to be effective, it will optimally not cause an increase in first costs and will be compatible with energy-use and other operational efficiencies. An example of an individual element that costs more than traditional practice but facilitates adaptation and energy-efficiency is raised flooring systems. Deconstruction is facilitated with this system by eliminating ductwork and placing modular re-configurable wiring in a more accessible location in the floor plenum rather than an overhead plenum, and allowing the ceiling to be eliminated altogether, providing better access to lighting systems.

The single greatest criteria for the success of design for deconstruction is that the cost of the final gross deconstruction costs do not exceed the avoided disposal costs, plus the reuse or recycling value of the components and materials, plus the removal costs of a building not designed for deconstruction, (Billatos and Basaly, 1997). The economic feasibility of deconstruction in low-disposal costs regions is therefore dependent upon the highest and best reuse or recycling value of the recovered materials and the efficiency of the deconstruction process, i.e. labor costs.

GOALS OF DECONSTRUCTION

Deconstruction serves as a means to an end, its purpose is the recovery of building elements, components, sub-components, and materials for either reuse or recycling in the most cost-effective manner. Within the theme of design for deconstruction there is a distinction between designing for reuse and designing for recycling based upon components and types of materials used in a building. Deconstruction per se implies a high degree of refinement in the separation of building components. If a building were deconstructed to some hypothetical maximum it would result in materials and components down to the level of their original form before construction. It is not practical to approach design for deconstruction at the whole-building level in this manner as some components, such as a window for instance, may be obsolete by the time the building is deconstructed and undesirable for reuse as exterior windows.

Deconstruction is also difficult to integrate into new construction. Removing materials from an existing building to integrate into new buildings requires that the demolition and building contractors become materials suppliers. In addition to the demolition and construction processes they must address issues of materials inventory and storage, additional handling and transportation requirements, and integrating what is in effect a stock component into designs where the preference might be for custom-designed components. Quantities and quality of recovered materials are a factor when a design must either match the available sizes and quantities of recovered components, or face the uncertainty that sufficient and appropriate recovered components will be found to match the design. The cost-effectiveness of recovering varied and small materials such as wiring, nails and bolts might also be negative. An exception is copper wiring.

In practical terms, some materials are not readily reusable but can be recycled in a cost-effective manner. Based upon this perspective, it is possible to approach design for deconstruction as “hierarchical design” including; 1) design for reuse, 2) design for remanufacturing, and 3) design for recycling. Primdahl uses the term “embodied energy maintenance,” or retaining the maximum amount of net embodied energy based upon each type of component or material within the structure and the available infrastructure for recovery (Primdahl, 2002). The constraints on this optimization include the scale of buildings and components, temporal forces between differing building elements, functional and service requirements of the building, relative impacts of building elements in terms of first costs and life-cycle costs, the physical forces at work in a building, the chronology of construction and hence deconstruction of the building, and the components and raw materials of the building.

As an example of the complexity of optimizing design for deconstruction, the fewer number of components to a building would appear to be highly preferable. However, this criteria alone is insufficient. A very few, and hence large, components that required expensive and large equipment to maneuver and were not readily reusable as is, due to the difficulty in matching the component to a new use, might not necessarily be cost-effective. If a material such as steel is used which is highly and effectively recycled, a highly refined deconstruction process is relative in this case since a building largely comprised of steel could be mechanically demolished and the steel separated from the heterogeneous debris through the use of magnets. The separation process after demolition supersedes the requirements to facilitate separation in the demolition phase.

Another complexity to design for deconstruction is that the energy costs of operating a building are a high proportion of the total costs of the building over its life, including construction and deconstruction. Designing for deconstruction in a manner that compromises the energy-efficiency of the building would not result in an environmentally or economically effective building over its life-cycle. An example of this situation might be eliminating moisture and air filtration chemical sealants to facilitate mechanical disassembly, but not designing a substitute means to reduce moisture and air penetration through the building envelope. A substitute for extensive sealants and adhesives in a roof system might be either mechanically fastened single-ply roof on a flat roof, or high-slope roof design to facilitate rainwater runoff through gravity. In both cases mechanical forces are used as a substituted for chemical sealants, without loss of building envelope integrity.

The design for deconstruction problem analysis for a building might be facilitated by asking questions such as:

- What parts of the building support other parts ?
- What parts of the building are self-supporting ?
- Where do specialized service inputs and outputs (telecommunications, electricity, water, gas, wastewater, supply and exhaust air) occur and how are these flow mechanisms constructed ?
- What parts of the building are subject to the most stresses from climate?
- What parts of the building are most subject to wear from human use and change from aesthetic preference ?
- What parts of the building are most subject to alteration based upon functional, economic, life-expectancy, or technological requirements?

- What parts of the building are comprised of components and sub-components based upon a complex set of functional requirements and what parts serve only one function and hence are comprised of relatively homogenous materials ?
- What parts of a building pose the greatest worker hazards in disassembly?
- What are the functional sizes of the principle elements and components of a building?
- What are the most expensive elements of a building, which have the highest reuse and recycling value and which impact the life-cycle efficiency of a building the most?

Currently, deconstruction feasibility will be heavily based on economic considerations with environmental considerations a secondary concern. The economic drivers for the future recovery of construction-related debris will be bans or economic penalties on the disposal of construction-related debris, constraints on virgin materials, and a paucity of landfill space. If manufacturer responsibility regulations expand to the building industry and its many associated products, design for deconstruction will be an integral part of enabling this process. The steel industry and to a lesser extent, the concrete industry, have established recycling infrastructures. Increasingly, other building products industries such as carpet, drywall, and acoustic ceiling tile manufacturing are developing recovery infrastructure. Deconstruction in the current state of the building industry has both opportunities and constraints as illustrated in Table 1.

Table 1 - Opportunities and Constraints of Deconstruction

Opportunities	**Constraints**
Management of hazardous materials	Increase worker safety/health hazard
Reduction in landfill debris	More time required
Economic activity via reused materials	Site/storage for recovered materials
Preservation of virgin resources	Lack of standards for certain recovered materials reuse
Removal of inefficient/obsolete structures	Lack of established supply-demand chains
Reduction in site nuisance compared to demolition	Buildings not designed for deconstruction and high variability in assembly techniques
Quality or aesthetic appeal of historic components of materials (ex., fireplace mantle, heart pine lumber)	Labor intensity in terms of skills and degree of materials processing, particularly removal of lead-based paint

Based upon possible conflicts between these factors it is important to consider the goal(s) of deconstruction when adding design for deconstruction to the many other aspects of sustainable building design and construction. Some goals for design for deconstruction might be:

- Rapid removal of building from building site.
- Reduction in environmental, health and safety stresses for workers.
- Easy access to components and materials, preventing damage in the deconstruction process.

- Reducing the costs of tools and equipment, for example scaffolding and fall protection equipment, specialized tools such as nail-kickers, and use of specialized operators or attachments for heavy equipment to facilitate the process.
- Eliminating the wastes by-products from the process.
- Materials recovery with high efficiency of reuse and recycling, i.e. requiring minimal additional processing for the highest return on investment in the deconstruction process.
- Eliminating toxicity in building materials which impacts responsible reuse and disposal and reduces reuse/recycling opportunities
- Increasing the longevity of a building such that deconstruction is actually less likely to occur via the inherent adaptability that design for deconstruction will convey upon the building.

PRODUCT DESIGN FOR DISASSEMBLY

Design for disassembly has been well-studied in the so-called consumer products industry, for example, for automobiles and computers. The automotive industry has been engaged in design for environment for some time, for example, General Motors, Chrysler and Ford formed the Vehicle Recycling Partnership in 1994 to develop means to recover materials from automobiles for reuse and recycling (Billatos and Basaly, 1997).

Examples of design for disassembly tools for products that have been recently developed include: BDI Design for Environment - Boothroyd and Dewhurst, Inc.; Ametide - University of California at Berkeley; DFR-Recy - Helsinki University of Technology; EUROMAT - Technical University Berlin; LASeR - Stanford University; MoTech - Technion University, Israel; ReStar - Green Engineering Corporation (Otto and Wood, 2001). The number of tools and disparate locations of their development indicate a widespread interest in solving the problems of consumer products designed for disassembly.

One tool is the End of Life Design Advisor (ELDA) developed by the Manufacturing Modeling Laboratory at Stanford University, which is meant to inform the design of products based upon their end-of-life (Rose, 1999). The tool is meant to help determine the paths of materials upon disassembly, either for reuse, recycling, disposal or hazardous materials management.

A list of key characteristics used in the ELDA to determine a product’s disassembly and materials reuse/recycling potential provides generic guidelines for design for deconstruction as a form of design for disassembly. By testing the ELDA on a series of consumer products it was found that the number of parts, number of materials, level of cleanliness, design cycle, technology cycle and replacement cycle are important factors for end-of-life. Size, number of modules, hazards, wear-out life, reason for obsolescence, and functional complexity were not found to be critical to prediction of end-of-life strategies (Rose, 1999). The key characteristics used to measure disassembly potential are noted below.

Critical Factors for End-of-Life

- Number of parts
- Number of materials
- Cleanliness of the product - amount of dirt accumulated by product
- Design cycle - time between new designs
- Technology cycle - time that product will be cutting edge before new technology makes it obsolete
- Replacement life - time that average user upgrades product

Non-Critical Factors for End-of-Life

- Size
- Number of modules
- Hazards and hazardous materials - components that need to be removed before further recycling
- Wear-out life
- Reason for obsolescence
- Functional complexity - high level of dependence between parts with multiple functions (Rose, 1999)

Buildings are large and subject to gravitational stresses that differ from most consumer products. The non-critical factors of size and hazards and hazardous materials for consumer products are more critical for buildings. Buildings also have the distinction of being fixed in a bio-climatic location, unlike other consumer products. For any given location and type of building there are inherent functional, cultural, climatic, geological and ecological forces that suggest certain forms, structure, envelop designs, and materials. Buildings are also subject to the depredations of weather and to the stresses of repair, maintenance and alterations that occur over time with differing ownership or functional needs. Because sustainable architecture design will have unique qualities per the location and building type, it follows that design for deconstruction would be also be specific to each building if there is consideration for sustainable design and cultural appropriateness.

Designing to allow a more rapid life-cycle for components that tend to become obsolete faster is one strategy proposed to maintain the quality and efficiency of consumer products (Sindjou, 1999). A key philosophical question is whether buildings should be intentionally designed for deconstruction as a product is designed for disassembly in order to reduce the waste and inefficiency that occurs from depreciation in the performance of the building, especially regarding energy use and technology-related components. While the remanufacturability and recyclability of components and materials would remain high with a rapid turnover it is not clear whether this would be the most environmentally sustainable strategy overall, except for those elements that directly impact the energy-efficiency of a building. Components such as mechanical and electrical equipment that are designed for deconstruction would possibly increase the efficacy of maintaining a building’s structure and envelope as long as they do not require extensive modification of the structure and envelope when they are upgraded. In any case, the point of diminishing returns will be reached by upgrading HVAC equipment for instance when the efficiency of the building envelope - as a fixed element - is low, and does not also continue to contribute to increasing the efficiency of the building operation. As illustrated in Figure 4.1, over the 30 years of the projected energy costs for the reference “bad existing” building, the lowest total energy costs will be for an immediate new high efficiency retrofit. A new low-energy replacement building will require more energy initially, but over the next 25 years it will begin to recoup that additional energy by lower operating costs overall. Beyond 30 years the new low-energy replacement building becomes more and more cost-effective. The retrofit option will be much less initial investment but at the 25-year mark begins to become less efficient on a yearly basis. Extending the projections it might be seen that at 50 years, it is appropriate for total life-cycle costs - construction, materials and operation - to completely replace this new low energy-use replacement building, and again at 50-year intervals.

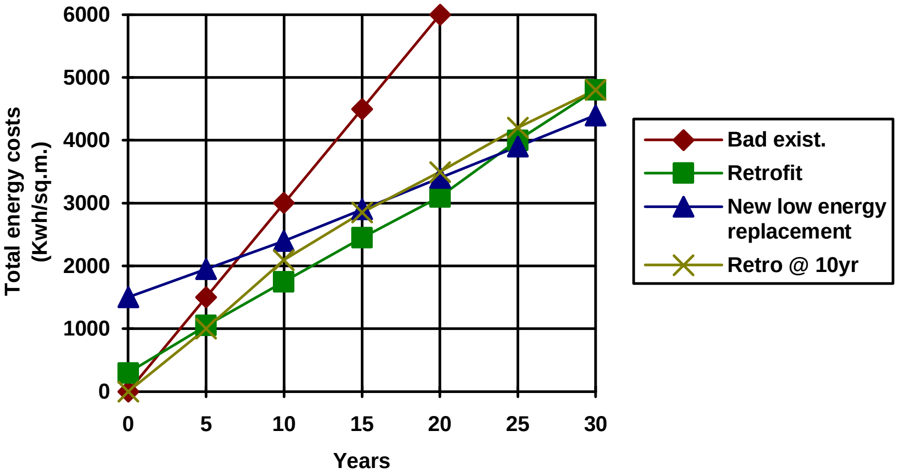

Figure 1 - Life-Cycle Costs Scenarios for an Existing Building (UNCHS, 1991).

This hypothetical replacement cycle of 50 years for an average building is very long relative to any other consumer product but could be confirmed for a specific type of construction through extensive modeling. Some assumptions would have to be made about the increasing speed of technological innovation for cutting-edge building systems such as building-integrated photovoltaics and hydrogen fuel cells. If it is presumed that overall sustainable construction requires maximizing resource-efficiency, then designing for building life-cycles, and achieving near zero-waste in the deconstruction of buildings at the end of this life will be one method for achieving this goal.

LESSONS LEARNED FROM BUILDING DECONSTRUCTION

Product analysis of design for assembly can be accomplished by disassembling products and putting them back together. This method also establishes baseline for the time and difficulty to disassemble a product (Otto and Wood, 2001). Deconstruction can be used in a similar way with the intent to heuristically analyze the critical elements necessary to design for deconstruction.

The approach to design for deconstruction suggested herein is to use the basic concepts of design for disassembly from the product industry combined with a categorization of the generic qualities of a building and its major elements, and lastly to learn from the deconstruction of buildings built in the 20th century. The authors have been involved in the demolition and deconstruction of buildings ranging from large multi-story commercial/institutional buildings, to heavy timber buildings, to light wood-frame residential buildings both pre- and post-WW II. Many themes related to future design for deconstruction were discovered from this field-based research.

Concrete and Masonry Institutional Building

Hume Hall was a 1950’s, 133,000 square foot, 4-story institutional building constructed of a concrete floor and column system with a flat concrete roof and built-up tar and gravel roof finish. The exterior and interior walls were infill concrete masonry units and the exterior finish was a double-wythe brick veneer. Windows and glazing were comprised of casement metal frames and aluminum storefront and fixed glazing, respectively. Mechanical and electrical systems were run principally in ceiling plenums formed by suspended acoustic tile ceilings. Interior finishes were comprised of resilient floor coverings, painted concrete masonry, and drywall.

The non-structural process of removal consisted of the recovery of all reusable fixtures and hardware, and the removal and disposal of windows as part of the abatement of asbestos containing caulking materials. The major elements and structural removal was comprised of a partial “stripping” of the brick veneer to separate it from the concrete structure and masonry exterior walls and the mechanical reduction of the predominantly concrete, masonry and steel reinforced structure. The only cost-effective reuse or recycling occurred from the soft-stripping of hardware and fixtures before the demolition process took place. Although the brick veneer was readily separated from the building façade for additional de-mortaring, the mortar itself was cement-based and did not lend itself to hand separation. Considerable costs were avoided by the mechanical reduction of the masonry and concrete materials and removal of reinforcing steel for recycling. Asbestos abatement was a large proportion of removal costs with no reuse or recycling potential.

Design for Deconstruction Opportunities

Masonry construction must use a mortar that facilitates the separation of the masonry back into individual units, i.e. the mortar has different strength than the masonry or other properties, such as a different coefficient of thermal expansion, that can be utilized in a separation process.

Large concrete and steel structures are constructed using mechanical equipment and therefore lend themselves to deconstruction using similar equipment. Mechanical equipment has the capacity to reduce concrete to recyclable form as long as contaminants of interior components, finishes, and thermal and moisture protection systems can be removed cost-effectively. Post and beam and/or flat plate concrete systems allow for maximum flexibility in separating all non-cementitious materials from the concrete and steel reinforcing structure of the building. Concrete is inflexible for reuse but readily recyclable, therefore the ability to recycle concrete should be prioritized over the concept of large concrete components' reuse.

Light Wood-Framed Residential Structures

More than nine residential structures have been deconstructed by the Center for Construction and Environment in the past four years. These structures were light wood construction on wood floor structures raised on piers. Walls were light-wood framing with drywall, wood lath and plaster, wood interior finish, wood exterior finish and combinations of asphalt shingle and metal roofing. Light wood framing is also known as "stick-framing" which indicates the method of construction and hence most appropriate method of deconstruction, i.e. stick by stick. As wood has considerably more value in reuse than in recycling and mechanical equipment is difficult to use at a "stick-by-stick" level of disassembly, this type of structure lends itself to hand deconstruction.

These structures were typically deconstructed by removing all interior non-structural elements, layer by layer, removing the structural elements starting with the roofs, then the load bearing walls, then the floor structure and foundation. Because workers are within the building at every step of the process, the building must be structurally sound at every stage of the deconstruction. Structure versus non-structure, sizes and weights of components and materials, and the height of exterior and interior elements relative to human scale, are key elements that control the deconstruction effort.

One of the most onerous aspects of modern architecture and construction readily found in most US buildings built before 1970 or so is the presence of lead-based paint (LBP) and asbestos containing materials (ACM). At a secondary level, PCBs, mercury, and ozone depleting chemicals are also hazardous materials that greatly complicate the recovery of building materials for reuse and recycling while not endangering workers and/or expending large sums to separate these materials from potentially reusable or recyclable base materials or sub-components. The regulatory requirements for worker protection and disposal of hazardous materials were a large cost for the deconstruction of older wood-framed residential structures, and the presence of lead-based paint is an impediment to wood reuse.

Design for Deconstruction Opportunities

High-slope roofs are problematic for deconstruction working platforms, therefore the use of ridge caps that are easily removable and allow access to the roof structure for tie off, or are designed to support the requisite load for a worker lifeline for roof finish and sheathing removal, would facilitate both roof repair and ultimate deconstruction.

Panelized roofs that allow the mechanical removal of large sections of roofs for processing on the ground would preclude the need for fall protection and risks and added time involved from working at heights.

Light wood frame construction and the properties of wood allow for drilling and cutting small sections from walls and roof structural members to run electrical conduit and plumbing fixtures. This has the unfortunate consequence of creating a layer of materials that can be embedded throughout wall cavities. In order to remove the materials, they must be cut, unscrewed, pulled and collected together. Ceiling mounted HVAC and electrical systems require ladders, scaffolding and considerable mobility to access and remove. The less of these interstitial components the better, therefore designing to consolidate mechanical and plumbing systems into fewer locations, surface mounting of electrical and telecommunications systems in wiremolds, and sectionalized gang units of electrical and telecommunications wiring with snap fitting or other screw-in connector would allow for adaptation and removal.

A notable impediment for deconstruction was often damage to components by water leakage and wood-boring organisms over time. This damage weakens the building structure and reduces the value of the recoverable materials. If nothing else design for deconstruction would also add impetus to design for durability and solve the problem that it is of little utility to efficiently disassemble a building if the materials themselves have not been protected from decay.

Although chemical sealants, coatings and adhesives add water protection and strength to building materials, they are significant prohibitions to hand deconstruction. From an environmental perspective, these types of additives should be eliminated with the recognition that mechanical methods of water protection and connections will require additional design and construction effort. The resulting reduction in performance, if one occurs, can be overcome by the ease of disassembly (by using screws and bolts for instance) for replacement and repair of components and sub-components.

Large Wood Post and Beam Structure

The Unitarian Church was a 5,000 square foot structure with slab-on-grade foundation and floor, large glu-lam arch structural frame with structural 2”x 6” tongue and groove roof planking, built-up tar and gravel and asphalt shingle roofing. The building wings’ roof structures were long span glu-lam beams supported by steel columns at one end and the sides of the glu-lam arches at the other end. Bolts were used at the connections between columns and slab, between beam and column, beam and arch, and between arch and slab and between the arch members at the ridge point. Glazing was large sliding glass doors or fixed glass, and non-structural exterior and interior partitions were comprised of light wood framing and either wood paneling or drywall. Wiring and ductwork was placed into framed ceiling cavities or interior partitions.

Upon hand removal of interior finishes and partitions and ductwork, the roof structural planking was removed by hand as well. The side wings’ glu-lam beams were unbolted and removed by a crane as were the structural glu-lam arches. The remaining debris and the concrete slab was removed by machine labor and crushed for disposal and recycling, respectively.

Opportunities for Design for Deconstruction
This building exemplified many concepts of design for deconstruction. The structural arch frame integrated both post and beam into one member that in turn was bolted at the floor structure and to each other. The horizontal beams were also bolted, as were the steel columns. The central arched section of the building was self-supporting and allowed the wings to be removed as separate elements. Structural roof planking combined structure with roof exterior sheathing and interior finish on the underside, greatly reducing materials used and layers of additional materials removal to separate the wood members. The mounting of mechanical and electrical ductwork and wiring within only non-structural wall or ceiling cavities allowed for selective demolition of these low-value components. A flat roof system on the wings of the building acted as a working platform to great effect for roof removal, whereas the high-slope roof portion presented greater difficulty. Conversely, the flat roof system used a built-up tar and gravel roof membrane over rigid insulation which was the epitome of heterogeneous, chemically bonded and heavy-weight materials that do not facilitate removal or cost-effective separation and recycling. Given the overall time and effort for each type of roof, the high-slope roof was a better option for deconstruction. A monolithic slab-on-grade foundation integrated foundation and floor structure at the grade level, facilitating ease of mechanical scraping to remove contaminating debris and then crushing the homogenous concrete element for recycling.

PRINCIPLES OF DESIGN FOR DECONSTRUCTION

According to Rose, et al, two of the most critical factors in predicting the end-of-life path of products are replacement cycle and technology cycle (Rose, 1998). According to Billatos and Basaly, the main criteria for examining a product for increasing its assembly efficiency is to reduce the number of parts and to reduce the amount of time required for assembly (Billatos and Basaly, 1997) According to Otto and Wood, critical factors in design for disassembly are the number of tasks, number of tools, and the time or degree of difficulty of the tasks (Otto and Wood, 2001). Each of these factors also has relevance for building disassembly.

Time is the single most important factor for building disassembly, unless the entire building can be removed to a separate location for disassembly, but this relocation can cost as much or more than the entire deconstruction. One alternative to the problem of demolition and new construction occurring under one contract, necessitating the fastest building removal possible, is a separate pre-construction demolition contract with a longer time frame. When demolition or deconstruction begins, time is a factor of the number of tasks, and difficulty of tasks. Difficulty includes the number of tools, height, safety precautions, etc. Replacement cycles and technology cycles generate conflicts between faster and slower cycling components and also count as critical concerns over the adaptive life of the building, but less of a concern for a whole-building removal.

Based upon generic elements of structure, building envelope, and services - including roofs and walls, and service systems such as the provision of electricity, conditioned-air, water, telecommunications, and gas, and the removal of wastewater and exhaust air - a building could be designed first to isolate these major elements from one another. A building designed for deconstruction for the purposes of first removing a building from a site might separate these major elements, i.e. roof, walls and floor/foundation as modular and pre-fabricated construction techniques do in the construction phase. Dealing with the material types and a sub-level of design for reuse, remanufacturing, or recycling, and other sustainability concerns such as human health and environmental impacts from materials and building energy-efficiency become mitigating factors to this level of building element separation.

On a fundamental level wood is a highly preferable material in design for deconstruction since it is flexible for both reuse and recycling, a “natural” material, and can be readily connected using interstitial connecting devices such as bolts. Steel is also a material with great utility for design for deconstruction due to its ease of recycling through a thermal process and ability to span large distances with less mass of material than concrete for instance. Steel also lends itself to post and beam construction via its high tensile strength. Of the other major material, concrete, its greatest utility in design for deconstruction is its durability as a structural material and its ability to act in both compression and tension, with reinforcing, for forming integral floor and ceiling elements that can also act as building envelope and finish. Concrete already is a relatively highly recycled material but is not easy to recycle when it is contaminated by other building components. Unless these components and sub-components have their own inherent value apart from allowing the concrete components to be recycled, it is not cost-effective to remove them for the purpose of recycling concrete components, unless mechanical means are used.

One means to design for disassembly is to expedite the understanding and viability of a disassembly sequence for either building elements or the entire building. The simultaneous creation of a deconstruction plan along with the construction plan and labeling of components for their constituent materials, similar to plastic products label numeric codes to indicate the type of plastic will provide directions to the deconstruction contractor for the disposition of materials. As with building energy management systems with Web based control and monitoring software, as-built drawings, deconstruction plans, detailed materials inventories and make-up can all be recorded and maintained for a building. This concept can go so far as to install this information on a computer built into the building itself.

The ability to pre-market materials for reuse and recycling based upon known types and quantities provides an economic incentive for the deconstruction process. It also allows for prioritizing materials disposition in the order of reuse, remanufacturing, recycling or disposal, depending upon local materials, reuse, remanufacturing and recycling infrastructure, with a better ability to calculate costs and benefits. An upfront deconstruction plan also allows for planning the management, scheduling and safety requirements of the deconstruction process. Borrowing from Fletcher’s hierarchy of System, Product and Materials for DfD, this hierarchy can include process as well as physical elements (Fletcher, 2000). Within each level of the building design and element hierarchy, the deconstruction process is the first step in the materials disposition process, and therefore sub-levels have an appropriate path depending upon a materials management hierarchy.

An element is defined as a major building part such as roof, vertical structure, wall, floor or foundation. A component is defined as the next level of non-structural building part such as thermal or moisture protection systems, windows and other systems such as the heating and cooling systems. A sub-component is a breakdown of a component into its smaller pieces such as the duct system of a heating and cooling system, the hardware for a door unit, or the sash of a window unit. A material is the constituent material from which all other parts are made, such as plastics, metals, wood, and masonry. Added to these physical definitions is the process of design and construction as independent levels of information that not only dictate the types of materials or connections, but can facilitate deconstruction through information management and major architectural decisions such as the slope of a roof.

An illustration of a design for deconstruction hierarchy is illustrated below.

- **Design**
  - Minimize building depreciation from poor energy-use, climatic and materials performance by performance-based materials selection
  - Substitute mechanical/gravity-based design for chemical-based design or chemical that break down when another chemical or heat is applied.
- **Construction**
  - Record as-built conditions
  - Create deconstruction plan based upon construction process
- **Elements -** design for modular and panelized elements that are readily fit into common dimensional standards and possible de-panelization
  - Principle DfD sub-goal - Reuse
- **Components** - design for ease of separation from the next higher building level, i.e. elements
  - Reuse
  - Remanufacture
- **Sub-components** - design for separation from component level
  - Reuse
  - Remanufacture
- **Materials** - design for separation from sub-component level and as homogenous materials
  - Remanufacture
  - Recycle
  - Bio-degrade

As a basic principle, matching a level of complexity and invested energy, components are designed for reuse and remanufacture, sub-components are designed for reuse and remanufacture, and materials are designed for remanufacture, recycling and bio-degradation. These hierarchies would be driven primarily by the constituent materials at each level, but a high embodied energy component should require as little additional energy and costs as possible for its continued utility.

Table 2 Relative Percent of Building Components by Different Measurement Systems (Adapted from Marshall Valuation Service, Marshall and Swift Publication Co., Los Angeles, CA. 1995 and *UNCHS, 1991)

Category	Percent of completion cost total	Percent of cost total	Percent of embodied energy*
Sitework, masonry, and concrete	12	7.0	14.6
Wood	21	17.7	9.8
Windows and doors	2	4.0	6.4
Thermal and moisture protection	10	12.8	20.0
Plumbing, electrical, and mechanical equipment	23	18.0	27.3
Interior finishes, hardware, and cabinetry	30	22.9	9.3

Table 2 is meant to illustrate well-known considerations of the cost-effectiveness of deconstruction based upon considerations of mass and embodied energy of typical building elements, components and materials. Non-structural “soft-stripping” greatly reduces the worker safety and equipment considerations and increases the cost-effectiveness of deconstruction. Wood is a high proportion of the percent of completion and cost of an “average” new building but has low embodied energy. Thermal and moisture production is a relatively low percentage of completion of a building but much higher in terms of embodied energy due to the types of materials used. Plumbing, electrical and mechanical equipment are a high percentage of completion and also a high percentage of embodied energy. Interior finishes, hardware and cabinetry are the single greatest percentage of completion and costs and yet relatively very low in embodied energy principally due to the much lower mass of these types of components in a typical building. At the whole-building level, high embodied energy components such as thermal and moisture protection and mechanical, electrical and plumbing systems would not only be subject to more rapid functional, climatic and technology life-cycle stresses but inherently are environmentally and economically valuable components to be targeted for design for deconstruction. Interior finishes also have a high value to mass ratio making them an obvious target for non-mechanized, i.e. high labor rate, removal for remanufacturing and recycling. A confirmation of this type of analysis, looking at major elements of the building and deconstruction constraints is presented below in Table 3.

Table 3 Design for Deconstruction Analysis of Wood-Framed Residential Building
Assuming wood windows and doors, wood light-frame construction, drywall interior finish, asphalt shingle roofing, wood floor structure and masonry or concrete foundation, wood floors, H = high, M = medium, L = Low, Y = yes, N = no, Value = potential revenue from reuse or recycling, Mass = higher mass avoidance of disposal, Ease of removal = relative less time, equipment

Element	Internal cycling rate	Value	Embodied Energy	Mass	Ease of removal	Structure
Windows/Doors	L	H	H	L	M	N
Appliances	H	L	H	L	H	N
M, E, P Equipment	M	M	H	L	M	N
Cabinetry	H	H	H	L	H	N
Int Finish	H	M	M	L	H	N
Duct, Pipe, Wire	**L**	**L**	**H**	**L**	**L**	**N**
Int Wall/Ceiling	L	L	L	L	M	Y
Roof	L	H	L	M	L	Y
Ext Wall/Structure	L	L	L	H	M	Y
Floor/Structure	L	H	L	M	M	Y
Foundation	L	L	L	L	H	Y

Based on this simple residential building analysis, the inherent deconstructability of most non-structural elements indicates fewer impediments to deconstruction for these components in traditional design and construction methods. The clear exception is duct, pipe and wiring. The low mass of a very dispersed elements with a high degree of entanglement and low reuse value all combine to make these components an impediment for selective disassembly and whole-building deconstruction. For this type of building, exterior and bearing walls have a high mass but low reuse value and medium level of effort required for removal within a sequence requiring the removal of the roof element first. One indicator from this analysis is that bearing wall construction is not conducive to cost-effective deconstruction. The roof element is relatively independent, yet requires additional time and equipment due to height

General Design Concepts

A list of design concepts and components for facilitating deconstruction of buildings is provided below.

- Compressed wheat-straw interior partition panels with integral paper facing are an example of self-supporting elements that can be disassembled as a unit and have the additional benefit of being a homogeneous and natural/recyclable material as a substitute for drywall and light wood 2”x 4”framing.
- Bolted roof trusses and offset tie-downs or roof to wall connectors that are attached at a point away from the actual point of contact of the roof structure to the wall. This would require an additional element such as a knee-brace to bridge between the two elements and increase the distance between the points of connection to roof and wall, but allows for ease of access to the connectors.

- Platform-type wall construction whereby the walls sit on top of the floor structure and do not extend through the horizontal plane of the floor structure and the floor above rests on top of the wall element. Separating the plane of the top and bottom of the wall from the plane of the floor structure facilitates mechanical separation and structural stability during the deconstruction process. Pre-cast concrete floor panels act in this manner.
- Light-weight materials for instance integral and modular elements combining finish, thermal and moisture protection, and structure, for roof structure, sub-structure and finishes to reduce the stresses on the lower portions of the building and reduce work at height and use of equipment. These impediments of height can be somewhat mitigated by integral worker stations and point of connections for equipment and handling. An example of this principle would be structural insulated panels (SIP). Substituting a glued and heterogeneous SIP system for individual wood roofing members must be weighed against the potential for reuse and recycling of the panels.
- Simple consolidation of plumbing service points within a building has the benefit of reducing the length of lines, but also reduces the points of entanglement and conflict with other elements such as walls and ceilings/roofs.
- A separation of structure from enclosure, will greatly facilitate adaptation and deconstruction however it is important to remember regional climatic forces, whereby a building in a temperate climate will not be as penalized by a possible variety of enclosures and loose-fit as will a building in a high heating load climate.
- Hazardous materials such as asbestos and lead-based paint have been outlawed. The next generation of these materials will include fibrous insulations, chemical treatments for wood, and many synthetic materials used as sealants, caulking, coatings, binders, and adhesives. All materials should be examined using a precautionary approach to eliminate possible toxicity or future regulatory constraints to their use and disposition.
- Nails and bolts have appropriate uses as per the type of connection and size of the members. A variety of nails in one building causes the requirement for multiple tools for removal. A mix of bolts, screws, nails requires constant shifting from one tool to the next. 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 “de-materialize” 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.
- The requirement for access to connectors is a functional requirement that in turn dictates a building aesthetic. Access areas for maintenance are well-understood

but little dealt with even in conventional design, due to the need to maximize habitable and income-producing square footage, and maintain a highly refined aesthetic. The design for deconstruction aesthetic is modeled in the "high-tech" architecture aesthetic.

- Elimination of caulking and sealants and high-tolerances 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.

CONCLUSION

Design for deconstruction has much to learn from product design for disassembly. It also has unique qualities based on buildings as significantly different artifacts than consumer products. Buildings have much greater life cycles than consumer products and engage a larger number of actors over their lives than consumer products. It is not well-understood whether design to facilitate a more rapid turnover, if not for whole buildings, then for major energy-use and technology-oriented components of buildings will inherently make them more efficient to operate and therefore assist in maintaining their long term value. The commercial building industry has already adopted many techniques to allow for internal adaptations with reduced waste and costs in order to meet service sector demands for technological and economic flexibility. Design for deconstruction can be studied from the perspective of deconstruction of existing buildings and the lessons learned from this research can be used to design for deconstruction in the future.

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Designing for Deconstruction Safety

Jimmie Hinze, University of Florida

Introduction

Throughout the life of a facility, resources are consumed. One goal of sustainability is to economically utilize the resources that are consumed by the facility. Resources are utilized when a facility is constructed, as it is occupied and used, and finally, when it is deconstructed. A significant influence on the efficient utilization of resources starts with the design decisions. Many decisions made by the designer of the facility will dictate, to a large extent, how efficiently resources will ultimately be utilized by the facility. Unfortunately, designers have historically viewed their role as being largely confined to addressing the needs of the occupants or facility users. That focus should logically extend to the life cycle of the facilities being designed and this would naturally include the deconstruction phase. A broad view of some of the key considerations to design for deconstruction will be examined. Particular focus will be on the design decisions that impact the safety of the workers performing the deconstruction work.

The objective of this paper is to enlighten designers about their range of influence and to encourage designers to consider the issue of worker safety in their design decisions. This would include the safety of the construction workers when the facility is initially constructed and when the facility is deconstructed. Worker safety should play a stronger role in the design of facilities.

The term sustainability embodies the concept of efficiency. While the use of materials and energy are commonly considered as measures by which the success of sustainability can be evaluated, human resources must also be considered. The efficiency of the use of human resources is important during construction, during occupancy, and during deconstruction. One aspect of the use of human resources or labor is to evaluate the level of productivity. However, an even greater measure relates to the safety and well being of the workers. There are no formal or generally accepted procedures that are utilized that address the sustainability of the labor component. While the United States construction regulations of the Occupational Safety and Health Administration (OSHA) address worker safety to a considerable extent, the Code of Federal Regulations (CFR) address deconstruction work to a limited extent. In fact, the 29 CFR 1926 Construction Regulations that address deconstruction would be found in Subpart T that briefly addresses demolition work.

While reclaiming materials is an important objective, the safety of those performing the work must not be ignored. The most valuable resource that is consumed by a facility is labor. Much attention is often paid to the efficient utilization of labor. Of course, from a sustainability point of view, it is even more important that the safety and wellbeing of the workers are preserved. Workers, more than any materials and equipment that are utilized, are the most important resources that are required to deconstruct facilities. Their safety and health is certainly worth preserving. The life of a worker cannot be restored or replaced. Some degree of project failure occurs whenever there is a loss of life or a serious injury to an individual. It behooves the industry to begin to address deconstruction activities and their safe performance. It is appropriate to address these concerns when facilities are designed.

Safety is important in any work setting. Because of the potential hazards, it is particularly important when deconstruction work is performed. One of the reasons that worker safety is important to address during deconstruction is that deconstruction itself is a relatively new activity, one that historically has not been utilized at the end of the useful life of most projects. As a result of this historical background, there is virtually no recorded documentation of specific means by which to safely deconstruct facilities. In the United States, the OSHA regulations give only limited guidance and these are considered minimal standards. While deconstruction work is generally done on a project-by-project, it would appear prudent to devise a standard set of safe work practices that can be generally applied to all deconstruction projects.

Safety on Deconstruction Projects

In order to address safety on a deconstruction project, it is important to first conduct a job hazard analysis. This is a procedure whereby all the work activities are examined to identify hazards that will be faced by the workers as the deconstruction work is performed. This is followed by the preparation of a project specific safety program that outlines the specific procedures to be followed to eliminate, minimize or avoid the serious hazards. Training is a key component of the safety program as it is crucial for the information about safety practices to be communicated to all workers involved in the deconstruction effort.

The job hazard analysis on most deconstruction projects begins with an assessment of the presence of any hazardous materials. On the deconstruction of most older buildings, this assessment will include the determination of the presence of asbestos, lead, and other hazardous materials. Asbestos was a widely used construction material in past decades and could be found in insulation (pipes, boilers, ceilings, walls), siding, roofing, caulking for windows, texture on walls and ceilings, flooring tiles, adhesives, and a variety of other building products. When asbestos materials are encountered during deconstruction, the deconstruction activities can contribute to making harmful asbestos particles become airborne. When asbestos particles are inhaled, they can be taken deep into the lungs. This inhalation of asbestos has been linked to several lung ailments, including mesothelioma, a fatal cancer that forms in the lining that surrounds the lungs. Mesothelioma, lung cancer, and asbestosis are to be avoided and this mandates that the asbestos-containing materials must be removed prior to continuing with other deconstruction activities.

Lead is another material that is commonly found on older facilities. There are fewer building materials that contain lead. The most common materials that contain lead include pipes (including piping components), flashing, and paint. Lead is almost always present in the paint of older facilities, including paint on wood siding, wood trim, exterior siding, piping systems, and structural steel. In deconstruction work, lead is most commonly a health concern when it is airborne. Lead may become airborne by abrading painted surfaces that contain lead. In some instances, heat is used to remove the lead paint as heat causes the lead paint to peel off. These procedures cause the lead to become airborne. For workers, this can result in elevated lead levels in the bloodstream. The ill effects of lead exposure are almost immediate, unlike asbestos exposure that can often take years.

The utility services and the presence of other hazardous materials should also be examined. This investigation should extend to services that may have been disconnected but which may still pose a hazard. This would include any type of hazardous materials that may have been stored or spilled in the facility. Even sewer gases pose a threat to deconstruction workers. The refrigerant lines in abandoned cooling systems might release toxic gases if not carefully deconstructed. Even natural gas lines might be damaged during deconstruction to pose a threat to workers. It is important that many different potential hazards be anticipated and taken into consideration whenever deconstruction work is performed. The type of structure and the use made of the facility will dictate the basic concerns to be addressed.

As the job hazard analysis continues, specific focus is placed on the work tasks to be performed. In some respects the deconstruction process is the construction sequence in reverse. The only major intervening element is that many of the facilities being deconstructed have aged and may no longer have the structural integrity that once existed. The job hazard analysis of the facility to be deconstructed will include the identification of the load-bearing walls and an examination of the integrity of the structural components. This information will be crucial for the preparation of the safety program.

Many of the hazards posed by deconstruction projects are associated with the potential for falls. Of course, the unanticipated collapse or partial collapse of the structure may also subject workers to struck by or caught in or between accidents. These must all be anticipated. On deconstruction projects, the electrical power will generally be disconnected from the facility, so the potential for electrical shock will be confined to faulty extension cords and tools operated by electric generators. The job hazard analysis would also take into consideration the presence of any overhead electric power lines. Naturally, it will be imperative to ensure that the electrical power to the facility has indeed been cut off.

Before the deconstruction work commences to the structure of the facility, an examination must be conducted of the soundness of the various structural components. These members are often hidden by wall or ceiling coverings. Unless this examination is conducted, it is often uncertain how structurally sound the facility really is. Without this assessment, the well being of the workers might be in jeopardy. Thus, this assessment is essential. Such an assessment must be made whenever any structural changes are made during the deconstruction process.

When the actual deconstruction work is ready to commence, the deconstruction workers must be diligent to ensure that all phases of the work are performed safely. One of the best techniques to ensure that safety is at the forefront of every task is for the crew to perform a pre-task safety plan. This consists of planning the procedures to be performed with safety being an integral component of that effort. Pre-task safety planning begins with the workers speculating on how the work might cause them harm. Means are then devised to reduce or even eliminate those hazards. Otherwise, workers try to work around the hazards. These pre-task safety plans are to be documented and they are to be performed prior to each task. On some projects, this means that several such plans will be prepared in a single day.

Facility Design Decisions that Address Deconstruction Safety

The deconstruction of facilities would be much safer for the deconstruction workers if safety had been addressed when the project was first designed. This is not a task that designers have customarily addressed. Perhaps this is a practice that should change so that the life cycle safety of a facility is assured. Naturally, the focus of the designer will continue to be on the occupancy and use of the facility, but some consideration should be given to the deconstruction effort. The safety of the workers who will build the facility should certainly be addressed and, as will be pointed out, design decisions that address construction worker safety generally will also contribute to the safety of the deconstruction workers.

If designers had anticipated worker safety in deconstruction activities over the past decades, many of the current day problems faced by deconstruction workers would not exist. First of all, some designers would not have incorporated asbestos or lead into their designs. Fortunately, these materials are no longer permitted to be incorporated in projects being constructed today. If designers had considered the safety of deconstruction workers when facilities were originally designed, some facility features would accommodate the safety of workers. Unfortunately, deconstruction has not been a phase of the life of facilities that designers have customarily addressed. Perhaps this will change in the future.

Since an increasing number of buildings are being deconstructed, instead of simply demolished, it would appear prudent to give greater consideration to the deconstruction process and especially to how worker safety is impacted by the decisions of designers. Designers will directly impact the degree of safety that is inherently embodied in the facilities that are deconstructed.

How could designers address the safety of deconstruction workers when they design their facilities? There are perhaps numerous means that would be quite effective in improving the safety of deconstruction workers when they perform their activities. A brief description of some of the methods that would improve deconstruction worker safety will be provided.

The greatest danger to deconstruction workers generally occurs when structural components are being dismantled. One basic consideration for safe deconstruction is to design facilities in which the basic shell or structure is permitted to remain intact. This might permit the structure to be reused for a different occupant without destroying the structure itself. The deconstruction activities on such a facility would be confined to the removal and salvage of non-loadbearing walls and various furnishings. With the inherent risks posed in the deconstruction of the structural elements of a building, preserving the structural elements intact is a viable means of greatly reducing the risks faced by deconstruction workers. This would essentially be a partial deconstruction project in that the facility would not be destroyed in its entirety as is common on many deconstruction projects. Thus, the design would be sufficiently flexible as to accommodate a variety of end users or occupants. Of course, it is important to then design the facility so that the non-structural aspects are not tied or directly integrated into the structure itself, i.e., it must be easy to remove the non-structural components.

When deconstruction projects are considered, these generally call for the complete dismantling of the structure. This presents a greater challenge for the designer. The structure of the facility is a key aspect of any design. From a deconstruction perspective in which the safety of deconstruction workers is to be assured, the designer’s decisions are very important or even crucial at this stage.

The selection of the structural materials to be used is the first consideration of the designer. Regardless of the type of material selected; however, the safety of the deconstruction process can be addressed. A key issue with the design of the structure relates to the ease and safety with which the work will proceed to dismantle the structure. One consideration might be to have the structure, especially the roof structure, composed of assemblies of components whereby each assembly can be lowered to the ground by means of a crane as an intact unit. Final disassembly would be much safer as this would take place at ground level. Another consideration with the disassembly of the structural members has to do with the certainty of predicting when a unit is actually ready to “come down.” This point will be made clearer in the following examples.

Suppose the structure is to be made of timber. What are some key considerations? The focus is primarily on the roof structure. The first consideration might be to design the roof structure that is composed of a series of trusses. If designed with the intent of addressing deconstruction safety, the trusses could be lowered to the ground as single units and possibly reused as trusses or dismantled further. Another consideration will be the type of connections to be incorporated in the design. For timber structures, the basic choices are to use either bolted or nailed connections. From a deconstruction point of view, bolted connections would generally be preferred as these do less damage to timber members than do nails. From a safety perspective, bolted connections are also preferred because it is easier to assess when a connection is no longer attached and when it is ready for removal. With a nailed connection that contains four nails, it will be difficult to assess when the connection is no longer intact. The connection might hold reasonably well when one nail is withdrawn, but the connection might fail once the second or third nail is withdrawn. Of course, with nailed connections, it may be difficult to withdraw nails one at a time. Instead, the wood members might be forced apart by means of an impact blow, as from a sledge hammer. This will generally do additional damage to the wood. In the deconstruction process, it is best for safety when the workers have a good assurance when a connection is intact and when it is ready to be dismantled.

A structure composed of steel would be addressed in a similar fashion. First of all, the feasibility of designing the roof structure as a single unit or a series of assemblies would receive initial attention. If assemblies of steel members can be removed and lowered to the ground during deconstruction, the deconstruction worker safety will be accommodated to a greater extent. As with timber, the connections should also be given serious consideration. The basic choices will be whether the connections are to be welded or bolted. From a material salvage perspective, bolted connections would generally be the preferred approach. When welded connections are dismantled, as with a cutting torch, some damage to the connections will occur and there is also a loss of some material. In addition, to cut welded connections will entail grinding or, most probably, hot work that could subject the structure to the potential of a fire. In addition to the fire potential, disassembly involving the cutting of welded connections results in a level of uncertainty as to when the connection no longer has sufficient integrity to form a viable structural support. This is an important consideration for the safety of the deconstruction worker. With bolted connections, there is greater predictability as to when the connection is solid and when it is not. It is important for workers to know or be able to predict with high certainty when a connection is loose, as this is when the structure is no longer capable of supporting itself.

Design considerations involving concrete are similar to that of timber and steel, but the choices are perhaps more basic. The basic considerations are between cast-in-place concrete versus precast concrete. The implications of this decision are considerable, especially from the point of view of sustainability and safety. From a purely sustainability perspective, the end results are vastly different. If the structure is cast-in-place, the deconstruction of the structure will probably consist of the destruction of the structure itself. Reuse of the concrete will probably require the concrete to be crushed and used as aggregate. If the structure is composed of precast concrete, the structural members might be reclaimed and reused as structural members. Of course, precast concrete units are often joined by some case-in-place concrete, so the separation of these units will not occur without some difficulty. Steel connections of precast units offer a better alternative for disassembly. Naturally, from a material sustainability perspective, precast concrete would generally be the preferable choice. Of course, cast-in-place concrete structures might consume less concrete. There are perhaps other considerations that must also be addressed.

Consideration might also be given to the decision of whether the concrete members will be pre-stressed or post-tensioned. The steel in concrete structures that are pre-stressed or post-tensioned will create additional concerns for the deconstruction workers. From the designer’s point of view, the decision will consider the weight reduction realized when the steel is stressed versus the additional hazards posed by concrete members that are pre-stressed or post-tensioned as the energy may be released in a violent fashion during deconstruction.

From a deconstruction safety perspective, precast concrete would generally be the preferred approach. Dismantling a cast-in-place structure generally requires that the structure be destroyed. This process often results in the emission of dust that can be harmful to workers and it may also result in a high concentration of small particles of concrete becoming airborne. This will depend on the nature of the means used to dismantle the structure. The preference would generally be to use precast units. Since these members can often be reused, there is little destruction of the members themselves. Regardless of the type of structure, heavy equipment will need to be utilized during deconstruction.

Decisions about deconstruction safety might very well extend beyond the structural considerations. For example, consider the material used to form the roof membrane. In residential construction, most homes in the United States are roofed with asphalt or fiberglass shingles. These roofing systems rarely survive the life of the building itself. In some cases, when the roofing system begins to fail, another layer of roofing shingles is simply placed over the first layer. As the second layer fails in subsequent years, a third layer may be placed over the second layer. Some find it more effective to remove the previous layers of shingles before a roof is re-shingled, but this does increase the cost of the work. When a building with a sloped roof is deconstructed, many different roofing conditions will be found. These are particularly hazardous as some of the small aggregates imbedded in the asphalt or fiberglass shingles will become dislodged and begin to form a dangerous slipping surface for the deconstruction workers.

The unsafe conditions posed by the eventual deterioration of roofing shingles are worthy of a designer's consideration. Note that this is also a sustainability concern as these roofing systems are not generally long lasting when compared to the life of most structures. Designers may do well to consider other types of roofing systems. For example, standing seam metal roofs and tile-type roofs are worthy systems to consider. While these may have a higher initial cost and possibly greater weight, they generally have a much longer life and the eventual reuse of the materials is also quite likely. In addition, the safety of the deconstruction workers is also addressed. Of course, roof slopes that are less than 18 to 20 degrees, when measured against the horizontal, will also be easier for the workers to establish solid footing. Thus, the slope of the roof might be a serious consideration for the designer. In addition, the designer might also incorporate anchors into the structural design of the roof so workers have points of support. These anchors, or tie-off points, will help reduce the risk of fall hazards. These anchors could be used whenever work must be performed on the roof, including routine inspections of the roof membrane or maintenance and repair work.

The design of a long-lasting roof membrane has obvious implications for safety. A similar argument could be made for the protective coating for the exterior walls of a building. Is the sustainability of workers being properly addressed if a coat of paint must be applied every three or four years? Workers are exposed to fall hazards each time the structure is painted. Some exterior envelope materials (bricks, vinyl siding, aluminum siding, and so on) require no paint or have reduced maintenance requirements. Thus, safety is addressed if materials are selected that have a long-lasting life.

Conclusions

From the examples given, it can be observed that the structural approach that is preferred from a safety perspective is also the approach that would generally be preferred from a sustainability perspective. Decisions related to the sustainability of materials are often consistent with decisions related to the sustainability of deconstruction worker safety and well being. Another observation that quickly comes to light is that design decisions that make a facility safer for deconstruction are also those that tend to make the facility safer for the construction workers and for the personnel involved in maintaining the facility during its occupancy and useful life. Thus, addressing the safety of deconstruction workers compliments efforts to address the safety of workers when structures are constructed. While designers may not be very inclined to devote much attention to the safety of deconstruction workers, they have a moral obligation to specifically address the safety of construction workers.

If the examples about deconstruction safety had focused on construction safety, the same conclusions would have been drawn. That is, designer decisions that promote deconstruction worker safety are also those that promote construction worker safety. Thus, the impact of designer decisions is evident when facilities are constructed and this is certainly less remote than thinking about only the end of the life of a facility. The paradigm does not need to change in order to address the safety of deconstruction workers, as it is the same as that for addressing the safety of construction workers.

DECONSTRUCTION’S ROLE IN AN ECOLOGY OF CONSTRUCTION

Charles J. Kibert (University of Florida, Gainesville, Florida USA)

SUMMARY

By definition, practitioners of sustainable construction should apply ecological principles to the design and operation of the built environment. Recent work on developing a theory of sustainable construction leans heavily on the inclusion of ecology as the fundamental theory and philosophy for a sustainable built environment. Deconstruction has emerged in the past 5 years as a significant consideration in improving the productivity of materials in construction and is an important step in the practical sense of allowing both effective materials reuse and enhanced recycling. Construction ecology seeks to provide a theoretical basis for understanding the optimal design of the built environment and relies heavily on several branches of ecology, such as systems ecology, adaptive management, and exergy analysis. This paper addresses the role and position of deconstruction in the framework of construction ecology and shows how it plays a key role in insuring optimal and effective use of materials in a construction context. The work of several ecologists and industrial ecologists will be presented and compared with ongoing efforts of deconstruction. Design for deconstruction will be compared to the inherent design of natural systems for effective recycling of the materials that comprise ecological systems. Several basic rules will be presented to better direct the design of buildings in the direction of true ecological design.

KEYWORDS: Deconstruction; Design for the Environment; Industrial Ecology; Construction Ecology; Waste Streams; Supply Chains

CONSTRUCTION INDUSTRY CONSUMPTION AND WASTE

Materials consumption by construction industry dominates worldwide materials consumption. About 40% of all materials extracted annually in the U.S. end up in the built environment [1]. Because construction activity amounts to about 8% of U.S. GDP, the materials impacts of construction far outweigh its relative size in the economy. Materials consumption by construction industry is enormous. In 1993, over 2.1 billion metric tons (BMT) of materials were incorporated into buildings and built environment infrastructure. In 1999, cement consumption in the U.S. was 105 million metric tons (MMT). It has been estimated that over 90% of all the materials ever extracted in the U.S. are in today’s built environment. Consequently policy must address this enormous, burgeoning stock of materials to insure that it becomes, to the greatest degree possible, a resource for future generations rather than an enormous waste disposal problem.

Waste from Construction Activities

Waste from construction activities is also enormous. At present, in the U.S., over 145 MMT of construction and demolition waste are created annually. This is the author’s estimate of 2002 quantities based on the 1998 U.S. Environmental Protection Agency report of about 136 MMT at that time [1]. This compares to a municipal solid waste (MSW) stream of about 280 MMT, meaning that construction and demolition waste comprises about one-third of the total materials being landfilled. Of the total construction and demolition waste stream, about 92% is attributed to demolition activities and 8% is waste from construction activities, either new buildings or renovation of existing structures. Waste from new construction amounts to 27 Kg/m^2 while from renovation activities in typical commercial buildings, the quantity of waste can be as much as 320 Kg/m^2.

The Ecological Rucksack of Construction

Of possibly greater consequence is the Ecological Rucksack of construction or the total quantity of material that must be extracted to obtain a unit of pure material. For example, for iron ore extraction, the Ecological Rucksack can be expressed as the ratio 14:1, that is, 14 metric tons of waste in the form of tailings or mine waste is the result of producing 1 metric ton of iron. For rarer materials, such as gold and platinum, the ratio can range up to 350,000:1. For the most massive quantities of materials used in the built environment, sand, gravel, and stone, the Rucksack is not so unfortunate with a ratio of 1:0.86 for gravel and 1:1.2 for natural stone. Coal extraction's ratio is 1:5 while that for petroleum is 1:0.1. In addition to the Ecological Rucksacks , the relative scales of extraction need to be considered. For the materials mentioned here, 10 BMT of sand and gravel, 5 BMT of stone, 5 BMT of coal, 5 BMT of petroleum, 0.5 BMT of iron, and 0.0001 BMT of gold were extracted worldwide in 1994 (see Table 1) [2].

Material	**Ecological Rucksack**	**Scale (BMT)**
Oil	1:0.1	5
Sand/Gravel	1:0.86	10
Natural Stone	1:1.2	5
Coal	1:5	5
Gold	1:350 000	0.0001

Table 1 Ecological Rucksack and scale of selected materials

Although Life Cycle Assessment (LCA) of products is being used to sort out the impacts or materials and products, issues such as the Ecological Rucksack tend to be forgotten in spite of the increasing consequences as resources, particularly fossil fuels and metals, become scarcer and more dilute. Deconstruction, which seeks to maximize the productive use of materials by enhancing reuse and recycling, would be a strategy that could directly and dramatically reduce the Ecological Rucksack of construction. This is an important step forward in the overall process of reducing waste and the consequences of creating ever more built environment for a burgeoning world population.

BUILDING SPECIFIC MATERIALS ISSUES

Buildings, the most significant components of the built environment, are complex systems that are perhaps the most significant embodiment of human culture, often lasting over time measured in centuries. Architecture can be a form of high art and great buildings receive much the same attention and adoration as sculpture and painting. Their designers are revered and criticized in much the same manner as artists. This character of buildings as more than mere industrial products differentiates them from most other artifacts. Their ecology and metabolism is marked by a long lifetime, with large quantities of resources expended in their creation and significant resources consumed over their operational lives.

Built Environment Effects

The main purpose of the built environment is to separate humans from natural systems by providing protection from the elements and from physical danger. Modern buildings have increased the sense of separation from the natural climatic processes and have made the underlying biological and chemical processes of nature irrelevant for their occupants. Until humans achieved space travel, the extraction and conversion of materials for building construction has been the highest expression of dominance over the constraints of natural bio-climatic and material constraints. This "constructed" ecology has in turn created an ecological illiteracy and had profound psychological and human health impacts [2]. Concentrations of buildings effect micro-climate (heat islands), hydrology (runoff), soils and plants (suffocation and compression), and create false natural habitats (nests on buildings). This increasing separation of ecological feedback loops inherent in the design, construction and use of buildings since the Industrial Revolution has brought many architects back to an era of reconsideration of this de-evolutionary and unsustainable path. The construction industry is extremely conservative and subject to slow rates of change due to regulatory, liability, and limited technology transfer from other sectors of society. The extended chain of responsibility and the separation of responsibilities for manufacturing materials, design and construction, operations and maintenance, and eventual adaptation or disposal, have resulted in a breakdown of feedback loops among the parties involved in creating and operating the built environment. Modern buildings, although products of industrial societies, are perhaps unique among modern technologies in terms of the diversity of components, unlimited forms and content, waste during the production process, land requirements, and long term environmental impacts

Buildings as artifacts of human society are also distinguished to a large extent by their relatively large land requirements and the environmental effects of the cooption of this valuable ecological resource.   The built environment significantly modifies natural hydrologic cycles, contributes enormously to global environmental change, has tremendous effects on biodiversity, contributes to soil erosion, has major negative effects on water and air quality, and, as noted above, is the source of major quantities of solid waste. In the U.S., as noted earlier, construction and demolition waste is the major source of industrial waste, amounting to perhaps 500 Kg per capita or on the order of 145 MMT annually. In the U.S. the reuse and recycling rates of this waste is not well known but is probably under 20% of the total mass and probably closer to 10%. Only concrete recycled for its aggregates and metals are recycled at high rates because of their relatively high economic value.

The built environment interacts with the natural environment at a variety of scales, from individual structures affecting their local environment to cities impacting the regional environment, affecting weather by changing the Earth's albedo [1] and other surface characteristics, altering natural hydrological cycles, and degrading air, water, and land via the emissions of its energy systems and due to the behavior of its inhabitants.

Classifying Building Products

Buildings can be distinguished from other artifacts by their individuality and the wide variety of constituent parts. Buildings are assembled from a wide array of components that can be generally divided into 5 general categories:

1. Manufactured, site-installed commodity products, systems, and components with little or no site processing (boilers, valves, electrical transformers, doors, windows, lighting, bricks);
2. Engineered, off-site fabricated, site-assembled components (structural steel, precast concrete elements, glulam beams, engineered wood products, wood or metal trusses);
3. Off-site processed, site-finished products (cast-in-place concrete, asphalt, aggregates, soil);
4. Manufactured, site-processed products (dimensional lumber, drywall, plywood, electrical wiring, insulation, metal and plastic piping, ductwork);
5. Manufactured, site-installed, low mass products (paints, sealers, varnishes, glues, mastics).

Each of these categories of building components has an influence on the potential for reuse or recycling at the end of the building's useful life and the quantity of waste generated during site assembly. Category 1 components, because they are manufactured as complete systems, can be more easily designed for remanufacturing, reuse, and disassembly, and thus have a excellent potential for being placed into a closed materials loop. Category 2 products also have this potential although engineered wood products, a relatively new technology, have not been scrutinized as to their fate. Concrete products fit into the first 3 categories and the extraction of aggregates for further use is technically and, in many cases, economically feasible. Category 4 products are in some cases more difficult to reuse or recycle, although metals in general are recycled at a very high rate in most countries. Category 5 products are virtually impossible to recycle and in many cases are sources of contamination for other categories of products, making their recycling very difficult.

Construction industry also differs from other industrial sectors in that the end products, buildings, are not factory produced with high tolerances, but are generally once-off products designed to relatively low tolerances by widely varying teams of architects and engineers, and assembled at the site using significant quantities of labor from a wide array of subcontractors and craftspeople. The end products or buildings are generally not subject to extensive quality checks and testing and they are not generally identified with their producers, unlike, for example, automobiles or refrigerators. Unlike the implementation of Extended Producer Responsibility (EPR) in the German automobile industry which is resulting in near closed loop behavior for that industry, buildings are far less likely to have their components returned to their original producers for take-back at the end of their life cycle. Arguably EPR could be applied to components that are routinely replaced during the building life cycle and that are readily able to be decoupled from the building structure (chillers, plumbing fixtures, elevators). The bulk of a building's mass is not easily disassembled and at present there is little thought given in the design process to the fate of building materials at the end of the structure's useful life.

Building and Building Component Service Life

Most industrial products have an associated lifetime that is a function of their design, the materials comprising them, and the character of their service life. The design life of buildings in the developed world is typically specified in the range of 30 to 100 years. However, the service lives of buildings are unpredictable because the major component parts of the built environment wear out at different rates, complicating replacement and repair schedules. Stewart Brand [5] describes these variable decay rates as “shearing layers of change” that create a constant temporal tension in buildings. Brand adapted O’Neill’s [6] hierarchical model of ecosystems to illustrate the issue of temporal hierarchy in buildings that can be related to the spatial decoupling of components (See Figure 1). Faster cycling components such as Space Plan elements are in conflict with slower materials such as Structure and Site. Management of a building’s temporal tension might be achieved with more efficient use of materials through spatial decoupling of slow and fast components. Components with faster replacement cycles would be more readily accessible. This hierarchy is also a hierarchy of control, i.e. the slower components will control the faster components. However, when the physical or technical degradation of faster components surpasses critical thresholds, they begin to drive changes to the slower components such that dynamic structural change can occur. For example, in a typical office building, electrical and electronic components wear out or become obsolete at a fairly high rate compared to the long-lived building structure. At some critical threshold the motivation to maintain the overall building ebbs and the building rapidly falls into disuse and disrepair due simply to the degradation of the faster, more technology dependent components. H.T. Odum [7] developed the concept of EMERGY, the energy embodied in the creation and maintenance of a factor or process, as a means to quantify the relative contributions of different components to the operation of a hierarchy. Odum’s theory predicts that the control of faster components by slower components is reflected in the latter’s higher EMERGY transformity values. Transformity values are efficiency ratios of total EMERGY to actual energy, normalized in solar equivalent joules, that enumerate a process’s relative capacity to influence system behavior. Using EMERGY to more carefully distinguish between slower and faster components and processes would allow designers to more rationally couple buildings to external processes of manufacture, reuse, and recycling. As such this theory provides a quantitative framework for relating building design to its material components based on their relative contributions to the functions of an ‘ecosystem’ that includes the built environment and the materials and processes that sustain it.

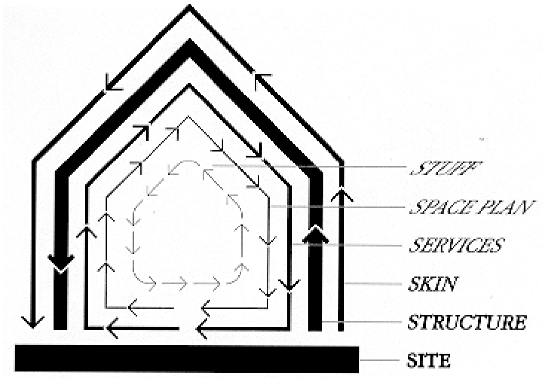

Figure 1. Temporal hierarchy of building components. Thicker lines correspond to longer lived components [5]

Understanding component service life and the interaction of the various shearing layers of change should lead to different thinking about buildings with respect to both the products that comprise buildings and the assembly of products into buildings. In discussing deconstruction and the design for deconstruction, the varying rates of change of building components and the issues of how best to separate these layers for ease of replacement are of paramount importance.

APPROACHES TO CREATING A SUSTAINABLE MATERIALS INDUSTRY

There are a number of potential approaches for creating a system of sustainable materials use. Several recent attempts have been made to articulate principles or rules that can help direct not only sustainability, but ultimately policy. Several of these are described in the following paragraphs.

Golden Rules of Eco-Design

Stefan Bringezu [8] of the Wuppertal Institute suggests what he terms the Golden Rules of Eco-Design:

1. Potential impacts to the environment should be considered on a life cycle-wide basis.
2. Intensity of use of processes, products and services should be maximized.
3. Intensity of resource use (material, energy, and land) should be minimized.
4. Hazardous substances should be eliminated.
5. Resource inputs should be shifted towards renewables

These rules are based on several management rules for sustainability. First, the use of renewable resources should not exceed their regeneration rate. Second, non-renewable resources should only be used if physical and function equivalents are provided such as investing in solar-derived energy from the profits of fossil fuel consumption. Third, the quantity of waste released must not exceed the absorptive capacity of nature. Finally there must ultimately be a balance between materials inflows and outflows to/from the economy because physical development cannot continue indefinitely and without bound.

Bringezu also suggests that there are four basic construction activities that must be kept in mind to examine materials impacts on a life cycle basis: (1) Design of construction products and buildings; (2) Materials management; (3) Planning of infrastructure; and (4) Product, facility, and building management.

In effect most of these Rules are being implemented in this new era of green building. Life Cycle Assessment (LCA) of products is becoming more widespread, buildings are being designed to more adaptable and materials more durable, and the emphasis is on shifting away from hazardous materials and non-renewables to renewable and recyclable resources. For all practical purposes we do know how to implement the Golden Rules although the meaning of ‘maximize’ and ‘minimize’ in two of the Rules is very much subject to interpretation.

General Rules of the Production-Consumption System

James Kay, an ecologist at the University of Waterloo in Ontario, Canada, suggests that the human means of producing artifacts for use or ‘consumption’, should respect a set of rules that recognize the capacity and limits of natural systems [9]. A brief description of these rules is as follows:

1. The interface between man-made systems and natural ecosystems should address the limited ability of natural ecosystems to provide energy and absorb waste before their survival potential is significantly altered. Additionally, the survival potential of natural ecosystems must be maintained. This is referred to as the problem of *interfacing*.

2. The behavior and structure of large scale man-made systems should be as similar as possible to those exhibited by natural ecosystems. This is referred as the *principle of bionics*.

3. Whenever feasible the function of a component of a man-made system should be carried out by a subsystem of the natural biosphere. This is referred to as *using appropriate biotechnology*.

4. Non-renewable resources should be used only as capital expenditures to bring renewable resources on line.

These Rules are far more difficult to implement than the Golden Rules of Eco-Design, largely because the scale of these rules is generally very large, focusing on very large systems such as bioregions. In southern Florida, for example, it is thought that much of the movement and storage of stormwater could be accomplished by creating appropriate interfaces with the watersheds, swamps, rivers, and lakes of the region, rather than creating numerous, expensive manmade stormwater conveyance and storage systems for individual developments and even buildings. This is clearly a win-win set of rules is they can be implemented because the result is the replacement of complex, costly human designed and produced systems with their natural system counterparts.

Industrial Ecology Strategy

Fritz Balkau [10] suggests that industrial ecology can be used as a framework for developing appropriate policies with respect to sustainable materials use. He focuses on implementing and operationalizing industrial ecology through management and policy instruments. In reviewing the concept of Industrial Ecology, he suggests that it might be defined as the study of materials and energy flows, population dynamics, and the operational rules and interrelationships of the entire production system. The challenges in implementing this strategy are insuring the Industrial Ecology concept is complete so that it addresses all policy areas and that an effective combination of management instruments is available for applying the concept in real situations. The main elements of Industrial Ecology that have been suggested are industrial metabolism, industrial ecosystems or associations, materials cycles in nature and industry, and the evolution of industrial technologies. These in turn have resulted in a number of concepts for operationalizing sustainability: the precautionary principles, the prevention principle (cleaner production and eco-efficiency) life-cycle management, the zero emissions concept, dematerialization (the factor 10 concept), and integrated environmental management systems. He suggests that we have not yet seen a mature industrial ecosystem where management systems have evolved sufficiently to produce a true artificial ecology. However a number of management elements have appeared which give us hints at how these management systems may eventually appear. Among the existing dynamic management elements are corporate decisions on sustainability; the adoption of environmental management systems (EMS); the practice of supply chain management; central infrastructure management; cooperative environmental programs; and government industrial development policy. The challenge is to combine these management instruments in an intelligent and systematic fashion.

Balkau suggests that the construction sector also needs to stay abreast of emerging environmental problems and adapt the design, operation, and disposal of the built environment to address new issues. The construction industry also needs to be more aware of the secondary impacts of its activities, that is, the damage done during the extraction of the resources needed for creating the products that comprise buildings and infrastructure. Quality of life as affected by construction also needs to be included in the array of issues for industry awareness and possible action. For example, congested transportation systems, increased noise, and increased municipal solid waste are also outcomes of construction activity. He concludes by suggesting a management framework for Construction Ecology. A wide variety of instruments from environmental standards to building codes and financial criteria can be applied to Construction Ecology and assist its implementation. However the primary prerequisite for creating a framework of management instruments is the definition of environmental goals. To accomplish this, construction industry itself must come up with a common view of its environmental agenda to include parameters such as energy efficiency.

The final lesson provided by the Industrial Ecologists is that implementation of both Industrial Ecology and Construction Ecology must be carried out using the appropriate policy instruments by a variety of entities to include government, corporations, and developers. An environmental agenda that construction industry can agree to is particularly important as it would set the parameters for behavior of the many actors in the construction process. Coordination in the application of policy instruments such as building codes and standards for building products would help orchestrate a steady march toward a system of creating the built environment that pays careful attention to resource and environmental issues. Coherent action is important to be able to produce change and the establishment of an agenda to integrate policy and technical issues is needed to create this coherency.

DESIGN FOR THE ENVIRONMENT AND DECONSTRUCTION

Industry is beginning the first steps in formalizing some of the strategies that would create benign processes, close materials loops, and make industrial systems mimic and integrate with natural processes. Industrial Ecology and Design for the Environment are two of the leading efforts in this movement. Industrial Ecology can be defined as the application of ecological theory to industrial systems or the ecological restructuring of industry. In its implementation it addresses materials, institutional barriers, and regional strategies and experiments. One major direction of Industrial Ecology is the optimization of materials flows by increasing resource productivity or dematerialization. The notion of a service economy, alternatively referred to as ‘systemic dematerialization,’ which sells services instead of the actual material products, is considered the sine qua non of this strategy.

An emerging discipline, Design for the Environment [DFE] has as its goal the creation of artifacts that are environmentally responsible. DFE can be defined as a practice by which environmental considerations are integrated into product and process engineering procedures and that considers the entire product life. This proactive approach to creating artifacts that can be readily adapted, removed, reprocessed, recycled and reused, embodies the concept of “front-loaded” design. Front-loaded design is simply insuring the end-of-life fate of artifacts is not waste but other artifacts. Applying Industrial Ecology and DFE to buildings is the cornerstone of Construction Ecology. Relative to buildings, Industrial Ecology underpins Construction Ecology by providing a framework for the construction materials and products industry to follow to place its activities on a sustainable path. As products of service, all building components could be leased to the owners and be returned to their manufacturers when obsolete, worn-out, or needing replacement. Architects and engineers would design buildings with decoupled systems that allow ready removal at periodic intervals and for large scale deconstruction when necessary for economic or planning purposes.

Efforts to change the close the materials cycle in construction are hampered by many of the same problems facing other industries. The individuality and long life of buildings poses some additional obstacles. Three fundamental difficulties arise when considering closed loop materials cycles for buildings:

1. Buildings are not currently designed or built to be eventually disassembled.

2. Products comprising the built environment are not designed for disassembly.

3. The materials comprising building products are often composites that make recycling extremely difficult.

Clearly a new concept for materials and energy use in construction industry is needed if sustainability is to be achieved. As noted at the start of this chapter, industrial systems in general are beginning to take the first steps toward examining their resource utilization or metabolism, and beginning the process of defining and implementing Industrial Ecology. In this same spirit, a subset of these efforts for construction industry, Construction Ecology, would help accelerate the move toward integrating in with nature and behaving in a 'natural' manner. Construction Ecology should consider the development and maintenance of a built environment (1) with a materials system that functions in a closed loop and is integrated with eco-industrial and natural systems; (2) that depends solely on renewable energy sources, and (3) that fosters preservation of natural system functions. Construction Metabolism is resource utilization in the built environment that mimics natural system metabolism by recycling materials resources and by employing renewable energy systems. It would be a result of applying the general principles of Industrial Ecology and the specific dictates of Construction Ecology.

The outcomes of applying these natural system analogues to construction would be a built environment (1) that is readily deconstructable at the end of its useful life; (2) whose components are decoupled from the building for easy replacement; (3) comprised of products that are themselves designed for recycling; (4) whose bulk structural materials are recyclable; (5) whose metabolism would be very slow due to its durability and adapatability; and (6) that promotes health for its human occupants.

As its primary purpose, deconstruction seeks to maintain the highest possible value for materials in existing buildings by dismantling buildings in a manner that will allow the reuse or efficient recycling of the materials that comprise the structure. Deconstruction is emerging as an alternative to demolition around the world. Generally the main problem facing deconstruction today is the fact that architects and builders of the past visualized their creations as being permanent and did not make provisions for their future disassembly. Consequently techniques and tools for dismantling existing structures are under development, research to support deconstruction is ongoing at institutions around the world, and government policy is beginning to address the advantages of deconstruction by increasing disposal costs or in some cases, forbidding the disposal of otherwise useful materials. Designing buildings to build in ease of future deconstruction is beginning to receive attention and architects and other designers are starting to consider this factor for new buildings.

CONCLUSIONS

A new concept for materials and energy use in construction industry is needed if sustainability is to be achieved. Construction Ecology can be considered as the development and maintenance of a built environment [1] with a materials system that functions in a closed loop and is integrated with eco-industrial and natural systems; [2] that depends solely on renewable and recyclable materials, and [3] that fosters preservation of natural system functions. A key element of construction ecology must be deconstruction and, more importantly, design for deconstruction, which creates the conditions for enabling materials to remain in productive use. By designing both building products and buildings for deconstructability, architects and other designers are enabling the extraction of high value materials for reuse and recycling. In closing it is important to note that it is of the utmost importance that materials having secondary value be used in buildings.

RECOMMENDATIONS

Materials that have no further possibility for reuse and recycling need to be reconsidered for their use in buildings, and for that matter, in all industrial products. This implies the wholesale reexamination and probable redesign of virtually every artifact. Materials used in construction and all other industrial sectors need to be kept in productive use and their reuse and recycling should be maximized. Deconstruction provides the best hope for the construction sector for recycling and reusing materials and components of buildings in fuiture applications. Deconstruction, coupled with products ‘designed for the environment’ and appopriate integrated national and international policies give the best hope for attaining sustainability in the sense of suatainable construction.

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CHARACTERIZATION OF AGGREGATES FROM RECYCLED C&D WASTE: A PROPOSAL FOR ITS USE AND COMMERCIALIZATION IN BARQUISIMETO, VENEZUELA

Suárez C.J., Malavé R.E., (School of Civil Engineering, Central-Western University "Lisandro Alvarado", e-mail address: cjsuarez@intercon.net.ve)

ABSTRACT

In the last five years, Civil Engineering Department of the Central-Western University "Lisandro Alvarado has conducted research work on use of recycled aggregates from C&D waste. It includes: non-structural concrete, mortar for masonry applications, concrete block production, as well as, industrialization of the recycling processes and commercialization of recycled products.
This paper presents the results from laboratory tests to characterize recycled aggregates and a technological and financing proposal leading to the installation of one or more recycling plants for the commercialization of C&D waste in a city of about one million people. The proposal is based on subjects evaluated such as: the volume of waste generated in the city, the recyclable fraction allowing the industrialized recycling process, the applications of recycled aggregates, the cost comparison between natural and recycled aggregates, and the technical feasibility of construction waste recycling with conventional crushing and screening equipment. Finally, the environmental impact of construction waste production and handling deserves more attention from state and county authorities in charge of city cleaning and conservation. The main elements of the proposal are: the education of participants in the process, the collection and transportation procedures of waste and recycled products, the technological solution involved, and the need of a feasibility study. It involves the commitment of the county to supply the land and initial investment for the recycling facilities, while a private company should operate the plant and commercialize its production.

KEYWORDS: Aggregate, Recycled, Mortar, Concrete, Stucco, Blocks

INTRODUCTION

The reutilization of C&D waste is an application developed from the necessity of rebuilding of cities after wars or natural disasters. In addition, this process has been encouraged by new approaches on environment protection and clean technology development. The worldwide importance reached by the use of C&D waste has motivated the creation of a RILEM [1] committee to unify standardization criteria about these materials. Physical and mechanical properties such as durability of recycled concrete have been successfully investigated. However, one of the recommendations of Morel et al [2] is to use concrete made out of recycled aggregates in elements of minor importance, such as: masonry mortars, sidewalks, pavements, and stucco works. There are two main reasons for this: firstly, the lack of standards and specifications; secondly, use of recycled products is still restricted by psychological barriers of builders. Furthermore, there are plenty of natural aggregate sites in Venezuela as well as waste disposal sites, therefore the recycling of C&D waste has not received yet enough attention in the country. This situation should change if a significant reduction in cost of housing construction is obtained from the use of recycled aggregates, and the extraction of natural aggregates is reduced to minimize environmental impact.

With this background and justification, this paper presents a technological and financing proposal for the installation of a recycling plant and the commercialization of recycled products, based on results of research works carried out in the Department of Civil Engineering, Central Western University "Lisandro Alvarado". These results are summarized as follows:

The amount of construction waste generated in the city (0.06 cubic meter per square meter of new construction in town) and the recyclable percentage of it (40%) is enough to allow the industrialization of the recycling process (Hau et al) [3]

The cost of recycled aggregates is about 35% less expensive when compared to natural aggregates (Cortez et al) [4]

The recycled aggregates are useable in the production of masonry mortars, concrete blocks and low-strength concrete (120 Kg/cm2 - 150 Kg/cm2, Cortez et al [4] and Molleja et al [5])

The industrialization of the recycling processes is technically feasible either with conventional crushing and screening equipment or with specific recycling equipment (Pemía et al) [6]

The environmental impact of construction waste production and disposition deserves more attention from state and county authorities in charge of city conservation and health (Hau et al) [3]

EXPERIMENTS

With the purpose of fulfilling the objectives of this research, the following materials were used: Portland cement Type 1, natural aggregate, and aggregate from C&D waste recycled in a conventional aggregate plant. For all cases, a minimum of five tests were conducted for each sample. Test were performed following ASTM and ACI specifications.

Aggregates

Aggregates used in this research were classified as follows:
Natural fine aggregate from mines and river beds, traditionally used in the region for stucco works
Standard coarse aggregate from river beds, processed in crushing plants installed in the area, and commonly used for concrete production
Recycled aggregate obtained through standard crushing, screening, and washing processes applied to five samples of building construction waste and one sample of building demolition waste mixed all together, including non-reinforced concrete, mortar, clay blocks, concrete blocks, and ceramic.

Selected waste was cleaned and undesirable materials such as timber, paper bags, nails, wire, other metal pieces and plastic elements were removed. Then, waste materials were taken to local aggregate plants.

Crushing and screening of C&D waste were accomplished in two different plants. In one case, washing equipment was used to eliminate the excess of #200-sieve passing fraction in the fine aggregate. In the other case, the plant allowed the production of recycled aggregates through both wet and dry processes separately.

In both cases, crushing was performed by means of a primary jaw crusher set for 3”-maximum size resulting particle. The crushed material was passed through a screening machine where products were classified as follows: 1 ¼”-3” fraction went to a secondary crusher (hammer crusher), smaller fractions plus products from the secondary crusher were sent to a secondary screening machine. From this, 9/16”-1 ¼” fraction was selected as coarse aggregate for concrete, 3/8”-9/16” fraction was selected as gravel, and fraction finer than 3/8” was selected as sand or fine aggregate for concrete. In this stage of the process, a sand washing machine could be used to eliminate the excess of #200-sieve passing fraction thus obtaining the industrialized recycled wet process (IRWP) aggregate. Otherwise, the industrialized recycled dry process (IRDP) aggregate was obtained.

Standard quarter procedure was applied to the resulting aggregates in order to get the necessary samples for characterization. Standard ASTM testing for concrete and mortar aggregates were applied, including the following: gradation, loose unit weight, compacted unit weight, fine content, chloride content, sulphate content, and organic matter content.

Mortars

The resulting industrialized aggregates were screened separately in a 4 mm sieve to get aggregate for rough stucco works or block laying. Using a 2 mm sieve, finer aggregate was obtained suitable for finishing stucco works, commonly specified for building construction in Venezuela. The passing fraction from each sieve is considered the useable percentage for the specific purpose. Mortar mix for rough stucco work was proportioned as for normal practical use: 1 volume of cement and 3 volume of 4 mm-maximum size particle aggregate. Finishing mortar mix was proportioned as is usually done in Venezuela: 1 volume of cement, 1 volume of lime, and 6 volume of 2 mm-maximum size particle aggregate.

Bonding of fresh mix was determined by throwing the mortar against a vertical surface and checking that it is able to support its own weight without detaching from the vertical surface. For set mix, bonding was determined by applying compressive tests to specimens formed by two blocks connected with 1.5 cm-wide mortar, at the age of 28 days. Retraction of set mix was determined by comparing cracking of recycled aggregate mortar, thus measuring the amount of cracks as well as their length and width by square meter of surface. This test was performed at 28 days on stucco work areas of 60 cm x 60 cm and 1.5 cm average thickness.
Compressive strength of mortar was tested on 5 cm cube specimens at the age of 7 and 28 days.

Concrete Blocks

Concrete blocks with dimensions 40 cm x 15 cm x 20 cm were fabricated in local specialized block factories. Six types of mixes were prepared, using aggregates from both natural and recycled origin. Proportion was kept 1 volume of cement and 10 volumes of aggregate for the first four types of mixes: Mix 1 was an unknown mix corresponding to that used in 7 concrete factories located in the area which produce the average concrete block or control sample; Mix 2 was prepared with standard fine aggregate for concrete; Mix 3 was prepared with industrialized recycled wet process (IRWP) aggregate; and, Mix 4 was prepared with industrialized recycled dry process (IRDP) aggregate.

Two more mixes were prepared using gravel (4-10 mm fraction) in addition to both standard and recycled aggregates. Mix 5 was proportioned 1 volume of cement, 7 volumes of standard fine aggregate, and 3 volumes of standard gravel; and, Mix 6 was proportioned 1 volume off cement, 7 volumes of average industrialized recycled (AIR) aggregate, and 3 volumes of gravel obtained in the recycling process.

Concrete blocks were produced with these mixes and mechanical properties were tested and compared with the control sample. Evaluated properties included compressive strength, water absorption, porosity, and weight.

Low-Strength Concrete

Concrete cylinders with standard dimensions (15 cm in diameter x 30 cm high) were tested for design mixes of 150 kg/cm² and 180 kg/cm² using both standard and recycled aggregates. Mix designs were made following ACI standards. Aggregates were kept wet before the mixing process as recycled aggregates present greater absorption than standard ones. The purpose of this test was to determine the possibility of producing non-reinforced concrete to be used in floor leveling, sidewalks, gutters, and other non-structural applications. Compressive strength at the ages of 7 and 28 days, and porosity were the variables evaluated for these samples.

RESULTS

Aggregates

The recycling of materials from the construction and demolition of concrete and masonry elements through an industrialized wet process (IRWP) generates 7.50% less particles smaller than 4 mm, 15.24% less particles smaller than 2 mm, and 2.88% less particles passing the #200-sieve, when compared to the average natural or standard aggregate. Due to the coarse gradation of the resulting aggregate from the wet crushing and screening process, it is suitable for concrete block production and for very thick stucco layers but not suitable for stucco finishing works. The dry crushing and screening process (IRDP) instead, produces up to 80.25% of useable material to perform stucco works with standard finishing quality. Table 1 shows these aggregate properties. Retained material in the 4 mm sieve (4-10 mm fraction) can be used as coarse aggregate in the production of filling mortar for reinforced masonry building and floor leveling. In general, other aggregate properties such as unit weight, chloride, sulphate, and organic matter contents met the ASTM and ACI requirements.

TABLE 1: Percentage of Usable Aggregates for Stucco Mixes

Aggregate type	Passing 4 mm sieve %	Passing 2 mm sieve %	Passing #200 sieve %	Max. particle size mm
Average natural	79.25	59.53	8.43	10
Average recycled in laboratory	69.70	41.61	7.65	10
Industrialized recycled wet process (IRWP)	71.75	44.29	5.55	10
Industrialized recycled dry process (IRDP)	80.25	55.69	12.21	10

Mortars

Using a skilled mason, mixes from recycled construction waste proved to dry faster and be lighter than mixes with natural aggregates. This improves work efficiency. Mixes prepared with recycled aggregates showed good bonding behavior and acceptable cracking pattern. Fine mortar showed bonding and finishing properties as well.

Compared to a control minimum value of 1.36 kg/cm^2 from the Office State Architect of California [7], mixes from both wet and dry recycling processes of construction waste showed higher bonding capacities: 3.03 kg/cm^2 and 2.86 kg/cm^2, respectively.

Tests also showed higher 28-day compressive strengths for mortar prepared with recycled material in both wet and dry processes (198 kg/cm^2 and 163 kg/cm^2, respectively) compared to mortar from natural aggregate of common use for stucco work which developed 153 kg/cm^2. Bonding and compressive strength of mortar are given in Table 2.

TABLE 2: Bonding and Compressive Strength of Mortar 1:3

Aggregate type	Bonding kg/cm²	7-day Compressive Strength kg/cm²	28-day Compressive Strength kg/cm²
Average natural	2.05 ± 0.41	109 ± 10	153 ± 15
Average recycled in laboratory	2.29 ± 0.32	173 ± 12	233 ± 13
Industrialized recycled wet process (IRWP)	3.02 ± 0.21	141 ± 13	198 ± 18
Industrialized recycled dry process (IRDP)	2.86 ± 021	116 ± 8	163 ± 11

Concrete Blocks

Blocks made with aggregates from both IRWP and IRDP reached, in average, 30.88 kg/cm² which corresponded to 75.82% of the average compressive strength measured for standard concrete blocks produced by seven different local factories (40.73 kg/cm²). Nevertheless, blocks from recycling showed higher compressive strength than two of the seven factories considered. With the addition to the mix of 27% in volume of gravel (4-10 mm fraction) from the crushing and screening process, blocks showed a significant increase in compressive strength: 40% higher than the average for locally available standard blocks and only 10% lower than blocks fabricated with natural aggregate including 27% of gravel.

Blocks from recycled aggregates absorb 65% more water than average standard blocks, however, when adding to the mix 27% in volume of gravel, the amount of water absorbed became only 27% greater compared to the average standard block.

In average, blocks from recycled aggregates are 15% lighter than average standard blocks. When adding to the mix 27% in volume of gravel, the weight of recycled block is about the same of that for standard concrete block.

The average block from IRWP and IRDP is 75% more porous than the average standard block. However, when adding 27% in volume of gravel to the recycled material, porosity values reduced to those measured for standard blocks. Table 3 shows recycled and standard concrete block properties.

TABLE 3: Mechanical Properties of Concrete Blocks

Production Process	Compressive Strength kg/cm²	Absorption %	Weight kg	Porosity %
Average local factory	40.73 ± 10.00	6.81 ± 0.51	10.77	16.32 ± 1.52
With natural aggregate proportion 1:10	56.05	5.27	11.00	12.26
With IRWP aggregate proportion 1:10	31.06	11. 45	9.30	28.15
With IRDP aggregate proportion 1:10	30.70	11.02	9.10	28.93
With natural aggregate proportion 1:3:7	62.85	5.96	10.75	13.06
With IRWP or IRDP aggregate proportion 1:3:7	57.01	8.68	10.50	16.15

Low-Strength Concrete

For constant water-cement ratio, concrete made with IRWP aggregates developed a 28-day compressive strength that resulted 76.48% of the design compressive strength 150 kg/cm², measured for control concrete cylinders prepared with standard aggregates and 85.50% of the design compressive strength 180 kg/cm². For IRDP aggregates, maximum 28-day compressive strength resulted 78.84% of the 150 kg/cm² design concrete strength and 66.57% of the 180 kg/cm² design concrete strength.

Porosity results showed to be 67.24% higher for concrete from recycled aggregates, for design compressive strength of 150 kg/cm² and 76.1% higher for design compressive strength of 180 kg/cm², irrespective of whether the recycled aggregates come from IRWP or IRDP. Low-strength concrete properties are given in Table 4.

Table 4: Low-Strength Concrete Properties

Aggregate Type in Concrete Specimen	Design Compressive Strength 150 kg/cm²		Design Compressive Strength 180 kg/cm²	
	Strength kg/cm²	Porosity %	Strength kg/cm²	Porosity %
Standard aggregate	150 ± 3	6.38	181 ± 1	4.07
IRWP aggregate	117 ± 9	10.67	155 ± 5	7.13
IRDP aggregate	120 ± 8	10.63	120 ± 3	7.17

PROPOSAL

Based on the results presented above, a technological and financial proposal can be done for the installation of a recycling plant for reuse of C&D waste. The elements of this proposal are as follows:
To educate the participants in the construction industry about the waste recycling technology and its economical and environmental advantages
To establish the procedure for recyclable waste selection and storage in the construction sites
To define the loading and transportation system of recyclable C&D waste
To select a suitable place in the city for storage and processing of C&D waste
To install a waste crushing plant to produce aggregates in combination with a concrete block plant
To commercialize the production of concrete blocks, mortar aggregates and low strength concrete aggregates obtained from the C&D waste recycling process
To demonstrate the technical and economic feasibility of the proposal to state and county authorities in charge of environment conservation and city cleaning, as well as the Construction Chamber and the Dump Truck Owner Association

EDUCATION

To motivate for this economical-environmental process, the participation of local authorities, the construction chamber, and housing developers, as well as builders, subcontractors, and dump truck owners is required, in order to:
Teach them about the environmental impact of construction wastes
Inform them about the waste recycling technology and the alternatives of recycled aggregates used in mortar preparation for rough and finishing stucco works, mortar for block wall construction, concrete block production, and concrete for floor grading, pavements, masonry works, and other non-structural elements
Educate them on the identification at the job site of recyclable waste and how to handle them properly
Inform them about the proposal for the establishment of C&D waste recycling

SELECTION AND STORAGE OF RECYCLABLE WASTE

From previous research works, the recyclable fraction of construction waste may contain one or several of the following materials:
Remaining elements of hardened concrete without reinforcing steel
Pieces of ceramic products
Coarse fraction of natural aggregates
Some amount of soil from the job site without organic material
Remaining parts of very fine fraction of natural aggregates which becomes dust during handling of above mentioned materials

The following items, non-recyclable for the proposed used, can be present among C&D waste:
Pieces of reinforcing steel, structural steel, nails or galvanized wire
Pieces of plastic or galvanized iron pipes
Pieces of timber
Pieces of plastic or metal buckets
Cement, plaster, or lime bags, and other papers
Plastic bags
Cardboard boxes
Used cloth, shoes, and helmets worn by workers
Pieces of electricity cables
Fragments of glass and bottles
Pieces of aluminum or other metal tubes
Organic soil from the job site
Food leftovers

Workers must be informed about the selection and storage procedures when handling construction waste. Recyclable waste can be placed in metal or plastic containers to be manipulated by two workers. They can also be piled up on a clean surface closed to the street where they can be loaded to a dump truck.

COLLECTION AND TRANSPORTATION

This process will not differ from the traditional system used by builders in combination with dump truck owners. There are two ways of doing this: one is by hand with labor supplied by the dump truck owner; the other is with shovel equipment owned by the builder. Whichever the case, the deal will be arranged on the price to pay for waste disposal. Another option is that the builder uses his own truck to ship the waste. As usually accepted, the builder assumes the costs of collection and shipping of the construction waste to a site disposed by the county authority.

The collection and transportation procedure of recyclable waste would be the following:
The builder makes a deal with the dump truck owner, or uses his own truck. Whichever the case, the trucks will have a sticker and the drivers will have an identity card certifying that they have been informed about the environmental recovery plan and know the requirements to be fulfilled by the recyclable waste
The loading is made by hand or with shovel machine depending on the builder
Recyclable wastes are shipped to the selected recycling site provided by the county for storage and processing. This site must be properly located, somehow remote and oriented in such a way that the dust generated does not cause damages to surrounding communities

The cost of this waste disposal service will not increase builder's expenses unless the traveling distance becomes larger than the traditionally traveled to other disposal sites. If so, a compensation could be established to the associated builders by reducing their county contributions or taxes applied to vehicle use, industry operation or land property

PROCESSING OF RECYCLABLE WASTE

According to Pernía et al [6], the industrialized processing of construction waste can be performed in a conventional crushing and screening plant combined with a concrete block plant. These industrial facilities must be located in the site selected and provided by the county to disposed the collected waste.

Fabrication of concrete blocks with recycled aggregates from construction waste is done in a conventional plant for concrete block production. A minimum amount of water is added to the mix to make it workable to be poured into molds using conventional concrete block production equipment. The resulting block has proven to be of better quality than the average block produced by four plants investigated in the area.

Tests results were based on the following standards:

Minimum compressive strength must be 50 Kg/cm2 for heavy blocks, and 30 Kg/cm2 for medium-heavy blocks (COVENIN 42-82)
Maximum absorption must be 14% for heavy blocks and 16% for medium-heavy blocks (COVENIN 42-82)
Suction must vary between 10 g and 40 g according to Gallegos (1989)

FINANCIAL ISSUES

Currently, it is unlikely that private sectors of construction industry in Venezuela will assume the total investment required for the installation and operation of a waste recycling plant. The proposal would be the participation of the state or county government to provide the site for waste collection and installation of the plant plus the operation of the facilities and commercialization of recycled products by a private firm.

As for required investment in equipment, the following would have to be supplied by state or county authorities:
Aggregate processing plant including two crushing and two screening levels, one sand washing machine and all belt conveyors required
Concrete block production plant including molds for 10 cm and 15 cm-thick blocks
Water and electricity supplies

Equipment and facilities that can be provided by the operating private firm are:
Two pay-loaders for waste and recycled aggregate handling and loading
One mini-shovel to handle recycled aggregates in concrete block plant
Office and workshop facilities including furniture and tools

COMMERCIALIZATION OF PRODUCTS

Products from recycled construction waste that can be placed in the local construction market are the following:
Concrete blocks for walls of thickness 10 cm and 15 cm
Sand for masonry mixes and finishing stucco works
Sand for rough stucco works and concrete mixes
Coarse aggregate (size 9/16" - 1 1/4") and gravel (size 3/8" - 9/16") for low-strength concrete used in grading floors, sidewalks, benches, and other non-structural elements

All these products have a wide demand particularly in low-cost housing construction. Their acceptance by the market will depend basically on the prices offered, even if other issues will need to be examined, including the legislative environment, public perception, and government support, among others.

Definitely, a feasibility study must be carried out before the installation of a recycling plant in Barquisimeto. Funding availability, supply and demand chains, market dynamics, and involving of all actors will have to be evaluated. It is clear that the use of recycled aggregates will preserve the city from uncontrolled disposal of C&D waste. Costs of recycled aggregates will allow the production of recycled concrete blocks at a lower price than the standard concrete blocks. Obviously, shipping of blocks or recycled aggregates back to the construction site will influence the total costs. So, the location of the recycling plant must not be too far away from consumption centers compared to already installed aggregate producers and concrete block plants.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be made from the results, analysis, and actions suggested in this paper:
Previous research work has shown that construction waste processing is technically feasible as well as the use of resulting recycled aggregates
As for economic feasibility, the recycling plant requires an initial investment in land and equipment that, currently, makes the proposal not attractive for private investors alone

The feasible proposal involves the government through the state or county office in charge of urban cleanliness and environment protection. As for domestic garbage, this office should assume the costs of recycling equipment, providing a convenient site for plant location, and open a bidding process to select the private firm for plant operation and product commercialization
As a recommendation, once this proposal has received attention by the state and county authorities, a complete economic feasibility analysis must be conducted to introduce the figures showing the benefits of the proposal as a business.

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