Improving the Feasibility of Building Deconstruction and Adaptability

by

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ABSTRACT

Design for Adaptability and Deconstruction (DfAD) is an emerging trend in the construction industry that focuses on the end-of-life aspect of buildings. It is based on the concept that the life of a building or building component ends because it is unable to adapt to change. With proper implementation, DfAD is an important tool to achieve sustainable design for buildings, as it ideally may form a closed materials loop for construction materials by optimizing the amount of materials salvaged at the end of a building's useful life through deconstruction.

This thesis focuses on ways to improve the feasibility of deconstruction and material savings, primarily through DfAD. By implementing DfAD principles and guidelines, designing with reusable materials, and planning and implementing a project effectively, the current practical and economic barriers to deconstruction may be mitigated. This thesis presents the essential considerations for deconstruction and materials salvage and presents potential policies to improve its viability. Three case studies present the applications of DfAD approaches and the lessons learned from common challenges associated with deconstruction.

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1.0 INTRODUCTION

The construction industry contributes significantly to worldwide waste flows and carbon emissions. In order to achieve greater sustainability in the construction industry, most industry professionals focus on the initial design and use phase of a building's life, often neglecting end-of-life considerations. Design for Adaptability and Deconstruction (DfAD) addresses the end of a building's useful life, during which most construction and demolition waste is produced, by considering potential renovation, reuse, or deconstruction of a building and its components rather than complete demolition and disposal. By extending the useful life of building materials in this manner, virgin resources are conserved and the construction industry may near a sustainable closed loop material cycle.

DfAD theory reflects a new focus on simplicity, interchangeability, and repetition in building designs, making it easier to change, replace, or take apart building components. This goal requires that different layers and functions of a building be independent and accessible, grouping, instead, components of similar functions and life spans. Thus, implementation of DfAD at the beginning of a building's life cycle allows greater conservation of materials at the end of its life cycle than conventional design techniques currently allow.

Although DfAD implementation simplifies and stimulates building deconstruction, it is not a prerequisite to deconstruction, which is already taking place on older, conventional buildings, albeit with some challenges. Many practical and economic barriers prevent more widespread uptake of DfAD and deconstruction practices. It is the purpose of this thesis, therefore, to provide a comprehensive overview of current deconstruction practices and potential methods to improve their feasibility, including implementation of DfAD. The second section includes the benefits of DfAD over current construction practices. The third section highlights the goals and underlying theory of DfAD, and the fourth section provides detailed principles and design strategies. The fifth section provides an overview of common construction materials and their potential for deconstruction and reuse. The sixth section addresses the deconstruction process and potential ways to improve the feasibility of DfAD and deconstruction. Finally, the seventh section presents three case studies: a residential building prototype embodying open building and adaptability, an eco-renovation of an existing home, and the design of a retail facility using reclaimed materials from a deconstructed building.

2.0 DfAD CONTEXT

In recent years, the concept of Design for Adaptability and Deconstruction has become a growing topic within manufacturing industries, as attention is increasingly devoted to managing the end of life of products, including buildings. The need to consider the full life cycle of a product is driven by increasing difficulty disposing large amounts of waste, as well as pollution impacts and the loss of material resources and embodied energy in disposed products. Buildings are like other manufactured products in that they are composed of pre-assembled components; the major distinction, however, is that buildings are constructed with the predominance of "wet" assembly, that is, systems constructed for and at a specific site, such as cast-in-place concrete, which is generally not feasible for separation and reuse at the end of its useful life. Because of the importance of the building industry on society and culture, as well as its large impact on global resource use, the sustainable design of buildings requires the management of resource flows in the building life cycle, including extraction, manufacturing, design, construction, operation, renovation, and end of life (Guy and Ciarimboli, pp. 1-2).

DfAD, considered a relatively new practice, has its roots in many primitive structures that were built to exist in an organic relationship with their surroundings, especially when mobility and change were often necessary. For example, Native American teepees were often assembled and disassembled, and were thus designed to make the relocation process easy and efficient. In traditional Japanese culture, the wide availability of timber, mild climate, and earthquake-prone geography promoted a craft-intensive architecture based on wood joining, which allowed for easy disassembly. DfAD is also integral to modern temporary structures, such as exhibition pavilions, entertainment structures, and temporary military facilities. These structures can provide valuable concepts to be imitated for semi-permanent buildings (Guy and Ciarimboli, pp. 4-5).

2.1 ENVIRONMENTAL IMPACT OF CURRENT PRACTICES

The building industry has a substantial effect on waste and resource flows both in the United States and abroad. The US Environmental Protection Agency (EPA) estimates that material from building demolition and renovation alone account for 25-30% of all waste produced in the nation annually (Guy and Shell, p. 189). The US EPA also estimates that 92% of construction waste itself is a result of renovations and demolitions (the other 8% accounted for by new construction). The US Geological Survey estimates that 60% of the total material flow in the US economy is consumed by the construction industry (Guy and Ciarimboli, p. 2).

Europe experiences similar trends. Construction and demolition waste (CDW) accounts for about 25% of the waste flow in the EU, totaling 450 million metric tons each year. Excluding excavated material, this value is about 180 million metric tons, or 480 kg per person annually. Recycling rates vary widely by country, and range from 5-95%, with an overall average of 28% across the EU, dependent mostly on the policies and legislation implemented in individual countries. Therefore, about 50 million metric tons of CDW material is recycled annually in the EU, while 130 million are landfilled or incinerated (Giglio, pp. 63-71).

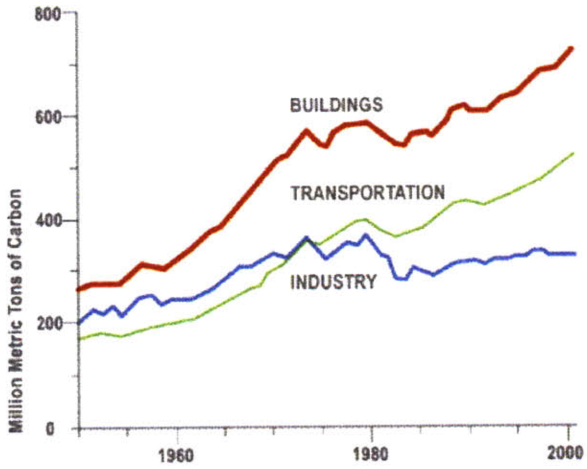


Figure 1: Sources of US Carbon Emissions (Ochsendorf, 2009)

The effect of the building industry on the environment is great, as shown by Figure 1, depicting the sources of US carbon emissions by industry. Buildings produce the greatest amount of CO_2, which includes contributions from initial construction, operation, embodied energy, renovation, and demolition. A breakdown of embodied energy by building component is displayed in Figure 2. By reducing the material usage through an extension of the useful life of each of the building systems, the embodied energy of buildings, and therefore the CO_2 emissions of buildings, can be drastically reduced.

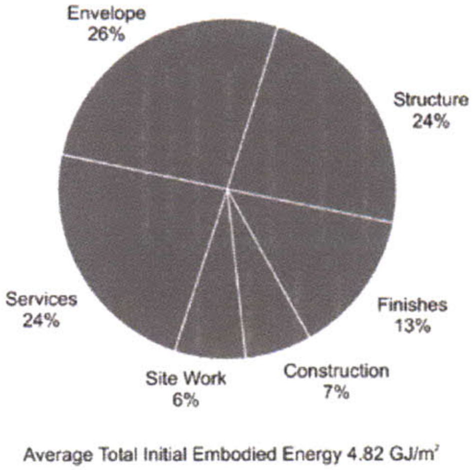


Figure 2: Breakdown of Embodied Energy by Typical Office Building Components (Ochsendorf, 2009)

One study predicts that about 27% of the existing buildings in the US in 2000 will be replaced by 2030, and that over 50% of the buildings existing in 2030 will have been built after the year 2000 (Guy and Ciarimboli, p. 2). If the current trend towards sustainable development requires greater reuse of currently developed land, likewise, trends towards reusing and rebuilding infrastructure will increase (Guy and Shell, p. 190). This trend will be facilitated and made more efficient by implementation of DfAD principles.

2.2 BENEFITS OF DfAD

The primary goal of DfAD is as follows: to reduce the impacts of pollution, to reduce resource use, and to increase economic efficiency in the adaptation and removal of buildings, as well as the recovery of building components and materials for reuse, remanufacturing, and recycling (Guy and Shell, p. 189).

The obvious environmental benefits, however, may not be enough to persuade many building owners and contractors to implement a deconstruction approach as opposed to demolition, which is generally more cost-effective and time-efficient. It is therefore useful to recognize other direct and indirect benefits of DfAD. Some economic or public-relations benefits for the building owner include accommodation for future change (and maintaining value for resale to future owners who want to make renovations); allowance of easy maintenance and repair of components; reduction of toxic materials; reduction of future liability and waste disposal cost; potential profit from the sale of salvaged materials; and US Green Building Council LEED Credit for Adaptation, Renewal, and Future Uses (Guy and Ciarimboli, p. 9).

Other aspects of DfAD implementation can benefit a local community or the public. DfAD can allow for the salvage of important structural features and quality craftsmanship to be used in other buildings. It can also allow a community to meet market demand for flexible, convertible buildings while helping said community to reach recycling and landfill diversion goals and to decrease site disturbance. By creating a widespread DfAD trend, deconstruction provides the potential to reduce the waste stream in the US from 125 million metric tons per year of CDW by 62-113 million tons (Languell, pp. 21-27). With a widespread DfAD market, the result will be a more cost-effective deconstruction industry with reduced time and labor requirements, as well as direct and associative employment through deconstruction work and material distribution, recycling, remanufacturing, and resale. A study based on nine private and four government reuse operations estimates that on a per ton basis, reuse operations generate nine times as many jobs as traditional recycling operations and thirty-eight times more than landfilling or incineration operations. The study estimates that if 25.5 million tons of CDW currently disposed of annually in the US were instead reclaimed, more than 220,000 jobs may be created (Gorgolewski, p. 3)

3.0 DfAD THEORY

3.1 DEFINITIONS

In this paper, DfAD is used as an all-encompassing term for a method to increase the life cycle of building materials through salvage, remanufacture, recycling, or reuse of materials, components, elements, or the entire building itself. This method can also be called Design for Recycling, and encompasses the following, more specific methods (te Dorsthorst and Kowalczyk, pp. 75-78):

Design for Adaptability: used when buildings have a longer life than their expected function, and must therefore adapt to other functions. Adaptability consists of structure reuse, the highest level of building reuse. This method is particularly useful for monuments and historic structures. Important parameters in design include a flexible span and frame height.

Design for Deconstruction: used when the life of individual building elements exceed the life of the building, which is most common in housing projects and shopping centers. This method is used to deconstruct building elements at the demolition stage. To reuse whole elements, one generally needs a deconstruction or rebuilding plan, and element sizes should be standardized for reuse.

Design for Dismantling: used when structures have to fulfill their function for their entire lifetime, which is as long as the technical lifetime (common in temporary buildings). With this method, construction elements are reused at the material level. Therefore, non-recyclable materials should not be used, or should be easy to recognize and separate before or after demolition.

Other useful definitions include the hierarchy of building parts. An element, here, is considered a major building part, such as a roof, wall, floor or floor system, or foundation. A component is the next level of non-structural parts, such as a window or a heating or cooling system. Components should be designed for reuse or remanufacture, whereas sub-components should be designed for remanufacture, recycling, or biodegradation (Guy and Shell, p. 202).

3.2 LIFE CYCLE ANALYSIS AND MATERIALS LOOP

The concept of closed loop material cycles (CLMCs) combines the goals of zero waste processes and resource-efficient construction. Closely related to the concept of industrial ecology, it aims to identify opportunities for waste and pollution reduction by using low-value by-products (waste) of one process as raw materials for other processes. The concept as applied to buildings consists of extracting materials from buildings at the end of their useful life and directly reintegrating or first reprocessing and then reintegrating them into buildings or other products. The ideal option is to create an infinite cycle in which the processes involved must not subject the material to significant loss of quality or mass within a limited period and without significant pollution emissions (Sassi, pp. 2-4).

Different waste management options can be arranged in a hierarchy based on environmental benefit. In general, the hierarchy is as follows: prevention and minimization of waste, reuse, recovery (through recycling or composting), energy recovery through incineration, landfill disposal. The recycling process can be similarly ranked into upcycling, in which a material is reused for a more valuable purpose (such as fly ash in concrete aggregate); recycling, in which a material is reprocessed and used again for the same purpose; and downcycling, in which a material cannot be converted back to its original form and suffers an intrinsic loss of value (such as broken masonry used as aggregate) (Sassi, p. 3).

Building materials that satisfy the general requirements for CLMC include timber, which is minimally processed, biodegradable, and part of a natural closed loop, and steel, which is homogeneous and can be industrially reprocessed without losing significant quality or mass.

Other materials can achieve a near-CLMC condition with some drawbacks. For example, virgin material must sometimes be added to recycled material to ensure proper quality, as in gypsum, which allows a maximum recycled content of 20%. Other materials lose mass during the recycling process, as in aluminum oxidation. The worst materials for achieving a CLMC are composite and compound materials, such as melamine and concrete, as well as components with adhesives or coatings. In all cases, it is necessary to limit hazards associated with the recycling process, such as emissions of dioxins, heavy metals, fluorides, and alkali fumes associated with steel recycling that are strictly regulated (Sassi, pp 2-8).

Traditional building waste management is end-of-pipe, that is, addressed at the end of its life cycle. Figure 3 traces the traditional material life cycle through various building stages. By taking into account the waste management during all building stages, it is possible to approach a CLMC. This waste reduction method is called integral chain management and consists of "the maintenance of products and processes in such a way that all materials in a chain can perform their function as long as possible" (te Dorsthorst and Kowalczyk, p. 73). By keeping building materials as long as possible in their own cycle, waste is kept at the lowest possible level. There are three general ways to reuse the material in a building: reuse the structure (corresponding to renovation and Design for Adaptability), reuse the elements (corresponding to disassembly and Design for Deconstruction), and recycle the material (corresponding to reprocessing or recycling). Thus, the waste management hierarchy can be adapted for buildings as follows: prevention, structure reuse (renovation, relocation, or adaptive reuse), element reuse, material reuse, material recycling (including upcycling and downcycling), immobilization, incineration with energy recovery, landfill (te Dorsthorst and Kowalczyk, pp. 70-75). With ideal implementation of integral chain management, a result like that shown in Figure 4 is approached, in which building materials are part of a closed loop.

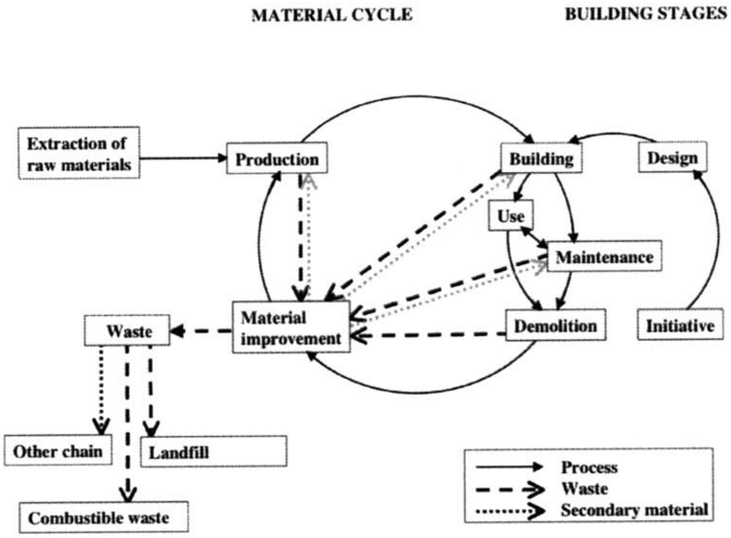


Figure 3: Traditional Building Waste Management Scheme (te Dorsthorst and Kowalczyk, p. 72)

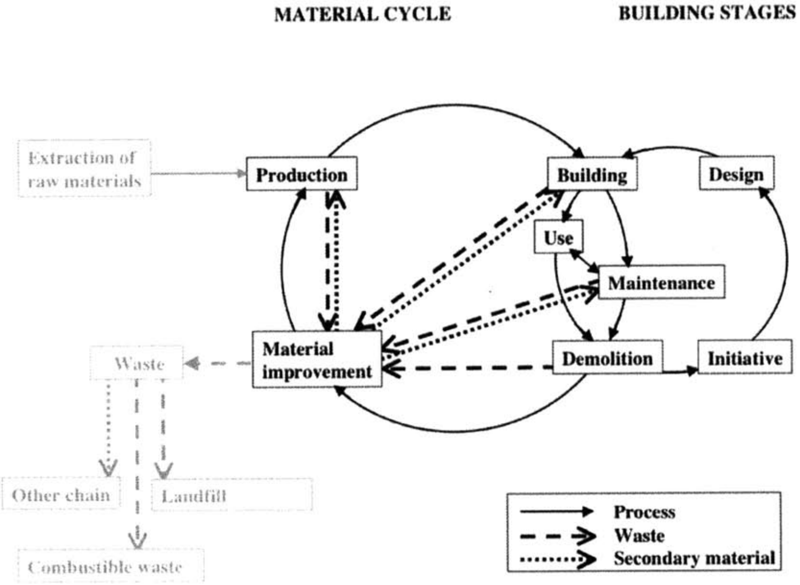


Figure 4: Closed Loop Building Material Cycle Through Integral Chain Management (te Dorsthorst and Kowalczyk, p. 74)

Chini and Balachandran identify five phases in which to apply waste prevention techniques during building design and construction through integral chain management (p. 176):

- Asset management: Ensure that existing buildings meet current needs and optimize the use of available features to meet them.
- Project planning: Set goals and formulate a waste management plan.
- Design: Design the structure so that components fulfill requirements for reusability, durability, and adaptability.
- Construction: Promote efficient procurement of materials, delivery, and storage as well as effective use of materials on the project site.
- Demolition: Encourage deconstruction and salvage of materials for reuse.

3.3 BUILDING SYSTEMS AND ELEMENTS

When considering DfAD principles, it may be useful to consider disassembly in terms of the building systems hierarchy. The building construction process consists of the assembly of materials into components, components into sub-assemblies (or elements), and sub-assemblies into buildings. Deconstruction is merely the reverse of this process. The importance of this model for DfAD is in identifying the complexity of a system that allows or disallows good buildability (and therefore good deconstructability). The design principles for DfAD can be better understood within the wider context of the systems environment (Crowther, p. 8).

3.3.1 Structural System Hierarchy

When building materials, components, systems, and spaces have dependent relationships, the structure consists of fixed spatial systems. The result is that every change within a building can have consequences for the entire structure, making it difficult to separate or change any single component. Traditional buildings have complex dependent relationships, while new structures that implement DfAD represent the conversion to simplified relationships among independent sub-assemblies. The hierarchy of material levels in a building from lowest to highest is: material, component, element, system (whose functions are bearing, finishing, insulation, etc.), and building (which is responsible for load-bearing, enclosure, partitioning, and servicing). These material levels are related to the integration of the functional and technical life cycle of building materials; life cycle coordination is essential (Durmisevic and Brouwer, pp. 82-87).

Another way to describe building layers is what is known as the Six S's, originally developed by Stewart Brand, in which the parts of a building are separated according to life cycle and function in the structural system. The Six S's, as seen in Figure 5, are as follows (Guy and Ciarimboli, pp. 25-26):

- Site: The geographical setting of the structure, which outlasts the structure itself
- Structure: The foundation and load-bearing elements, with a lifespan of 60-200 years
- Skin: The building envelope, frame, and exterior finishes, with a lifespan of 30-60 years
- Services: The utilities, HVAC system, and moving parts (like elevators), with a lifespan of 5-30 years
- Space Plan: The division of space, partitioning, cabinetry, and interior finishes, with a lifespan of 5-20 years
- Stuff: The furniture, appliances, and temporary objects, with a lifespan of 5-15 years

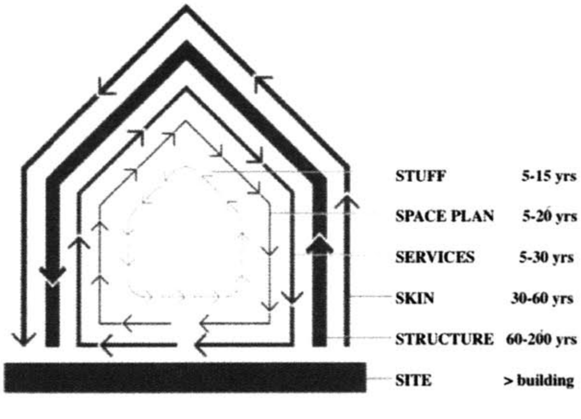


Figure 5: The Six S's According to Stewart Brand (Guy and Ciarimboli, p. 25)

3.3.2 Structural Configuration Design

Because a building is composed of the sum of systems and components, it follows that deconstruction is related to the sum of disassembly properties for each level of building integration and can be expressed as follows:

$D_{total} = D_{bl} + D_{sl} + D_{cl}$

That is, total disassembly is equal to the sum of decomposition of the building, system, and component levels. The two main criteria for allowing decomposition of a building are independence and exchangeability of components. These criteria are determined by three domains of the structural configuration: product features, structure features, and connection features. If one of these domains is not optimized on a specific level, the whole structure on that level is not deconstructable (Durmisevic and Brouwer, pp. 89-90).

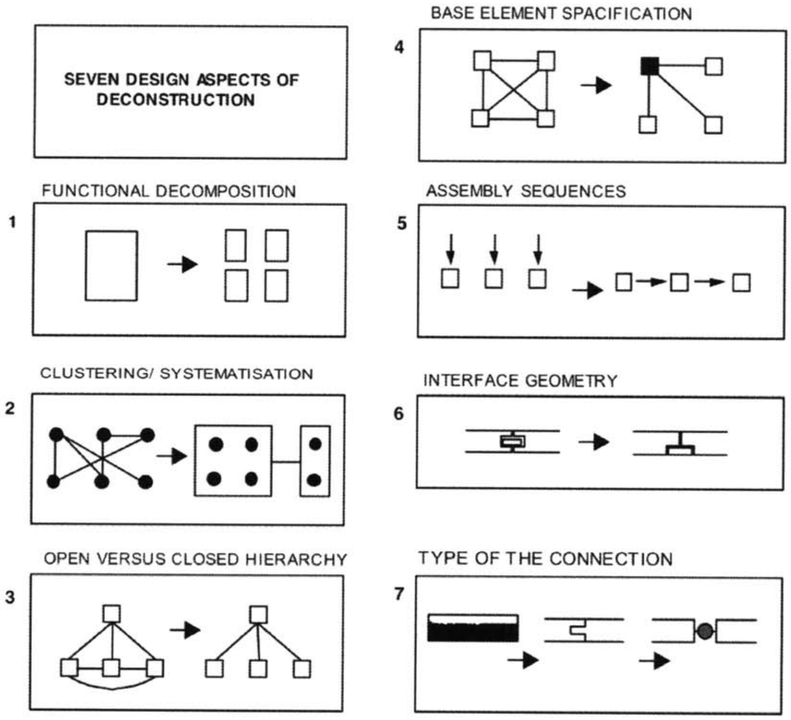


Figure 6: Design Aspects of Deconstruction (Durmisevic and Brouwer, p. 92)

Figure 6 defines seven main design aspects of structural deconstruction. These aspects determine the performance characteristics of building structures and to what level they fulfill the criteria of independence and exchangeability. The first, functional decomposition, consists in whether two or more functions are integrated into one building product or in separate products. The best option is total separation between functions at all building levels. The clustering/systematization aspect consists of subdividing the building into distinct sections that have different life cycles. A sub-system is therefore a cluster representing building elements that act as a single independent building section during both assembly and disassembly. These sub-assemblies are defined based on required performance, production flexibility, system design, and geometric and mechanical criteria. Another aspect is open versus closed hierarchy. Hierarchy implies dependency based on assembly sequence and defines the load path throughout the building. If a load is transferred directly from one element to another, then those elements are dependent. Independence is achieved instead by adding an extra part that takes over the load-bearing function, called a frame or base element, thus creating a dependent relation to only one element. The base element will integrate all surrounding elements into a cluster. Its function is to connect elements within an independent assembly and to perform as an intermediary with other clusters. The assembly sequence aspect consists of parallel or sequential sequences. A parallel assembly sequence can make a building assembly process faster, and a sequential sequence creates dependence among components and makes substitution and replacement more difficult. Disassembly sequences can also be affected by changing the geometry of the product, a decision that is closely related to the interface design and specification of connection type. The building interface and connection design defines the degree of freedom between connected components. There are three main types of connections: direct, or integral, in which the geometry of the component forms a complete connection by overlapping or interlocking; indirect, or accessory, in which an additional part is used to form a connection; and filled, in which a chemical material is used to fill the connection on site. Indirect connections are the most flexible, and chemical connections are fixed and difficult to disconnect (Durmisevic and Brouwer, pp. 91-97)

Using these seven aspects, it is therefore possible to classify all buildings from fixed to partially decomposable to completely decomposable, as shown in Figure 7. The main characteristics of decomposable structures include use of accessory joint types, application of parallel assembly and disassembly, use of mechanical connections as opposed to chemical, and creation of open hierarchy of different modules. This configuration allows for the independence and exchangeability of components (Durmisevic and Brouwer, pp. 98-100).

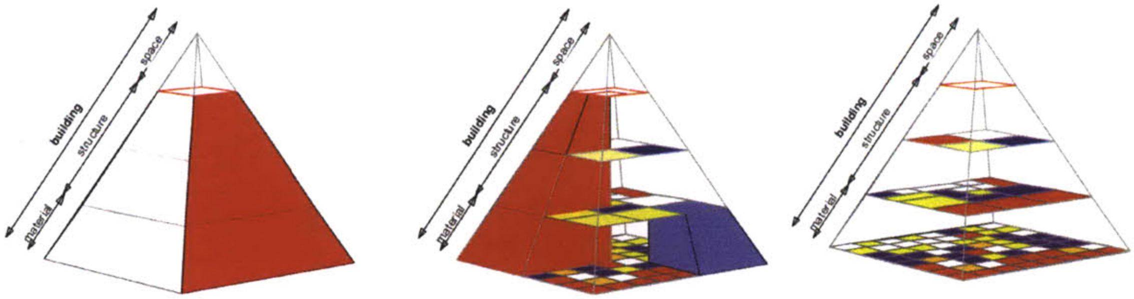


Figure 7: Integration of Material Levels in a Building (Durmisevic and Brouwer, p. 98)

4.0 DfAD DESIGN PRINCIPLES

4.1 GENERAL PRINCIPLES

The main principles for DfAD are intrinsically related to buildability and flexibility. Nearly all DfAD design rules fall under three tenets: simplicity, standardization, and clear communication. Specifically, some major DfAD principles are as follows (Crowther, pp. 10-12):

- Use an open building system, in which parts are more freely interchangeable, are less function-specific, and allow adaptability.
- Use modular design (components and pre-assembled sub-assemblies that are easily compatible with other systems).
- Use pre-fabricated sub-assemblies and mass production whenever possible to allow greater control over quality and conformity and to reduce site work.
- Use standard, accepted assembly technologies.
- Allow for parallel rather than sequential disassembly; be able to remove components without disrupting others.

In addition to these major principles, some other necessary considerations implicit in DfAD best practices include documenting materials and methods for deconstruction, selecting materials using the precautionary principle (that is, it is better not to risk uncertain negative repercussions, even if they are not verified), designing for the worker and the labor of separation, allowing for safe deconstruction, and designing for inherent simplicity and interchangeability of structure and form (Guy and Ciarimboli, p. 6). These underlying themes influence all specific DfAD design rules and guidelines.

4.2 RULES AND GUIDELINES

Based on the above principles, the following detailed strategies apply to all components and layers of a building:

- Minimize different types of components to simplify sorting on site and to make reprocessing more feasible.
- Allow ease of access to all components to minimize the need for special equipment.
- Use components sized properly for expected handling (including assembly, disassembly, transport, and reprocessing).
- Design realistic tolerances to allow for movement during disassembly (possibly greater tolerances than initial assembly requires).
- Provide spare parts in on-site storage (particularly for custom parts) to facilitate minor repairs or alterations.
- Keep and record all information about the assembly process, disassembly process, material and component life expectancy, and maintenance requirements (Crowther, pp. 11-12).
- Do not design with hazardous materials, but also minimize fibrous insulations, chemical wood treatments, and synthetic materials as sealants, coatings, or adhesives (Guy and Shell, p. 206).

Other specific strategies can be broken down according to Brand's six layers, and four in particular that are most influenced by DfAD strategies: the structure (foundation and load-bearing elements), skin (cladding and roof), services (mechanical, electrical, plumbing, or MEP, and HVAC), and space plan (interior partitions, finishes, and components that do not carry load). It is also necessary to consider connections and their influence on DfAD feasibility.

4.2.1 Structure

To allow for greater building adaptability, the foundations should be overdesigned, particularly to allow for vertical expansion (Guy and Ciarimboli, p. 8). Furthermore, so-called "thin-wall foundations" can reduce concrete usage by 20% by using a 6" foundation wall thickness instead of a conventional 8" thickness (Chini and Balachandran, p. 179). Over-designing columns and connections, especially at the perimeter of the building, also allows greater adaptability, because greater redundancy of structural elements accommodates structural changes. Designing on simple, optimized structural grids also allows for an easier change of use. Additionally, internal columns should be minimized to allow flexible open space. Beams and columns should remain as accessible as possible to allow for potential strengthening, such as welding top or bottom flanges or plates to the components (Edmonds and Gorgolewski, pp. 1-3). In general, long spans and post and beam construction reduce interior elements and allow structural stability while removing partitions and structural envelope elements. It can also be effective to choose a single material capable of providing multiple functions to reduce layering of materials (Guy and Shell, p. 207). The designer should allow for assembly technologies compatible with standard building practices to avoid the potential need for specialist labor. One common method, however, pre-stressed and post-tensioned components, can pose a danger by de-stressing the component during deconstruction (Chini and Balachandran, pp. 180-181).

4.2.2 Skin

The most important DfAD principle in the design of the structural skin is to separate the structure itself from the façade, better allowing adaptability and deconstruction. Windows and doors should be designed for maximum standardization and repetition. When designing a roof, it is generally helpful to design a roof that slopes, facilitating drainage and reducing the need for chemical sealants in the building, which can hinder reuse. Vinyl roofing membranes are an advantageous material, as it can easily be recycled into other products such as speed bumps, parking curbs, and asphalt pitching material. It is lightweight and reduces the need for steel and timber supporting members (Chini and Balachandran, pp. 183-184). To accommodate laborers and their safety, roofs should be built with a safe access, built-in edge protection, and anchor points (Languell, p. 88). Bolted roof trusses or roof-wall connector components should be attached at a point away from the roof-wall contact point to allow greater accessibility to the connection (Guy and Shell, p. 206).

4.2.3 Services

To reduce the number of light fixtures, wiring, and conduits for MEP and HVAC systems, a good design will use natural daylight, passive solar heating, and natural cooling as much as possible. In addition, electrical systems should be designed in such a way that power for the entire building can be turned off during the deconstruction process for worker safety (Chini and Balachandran, pp. 184-185). Mechanical, electrical, and plumbing systems should each be separated and their service points consolidated to reduce entanglement and element conflict (Guy and Shell, p. 207). Heating and ventilation systems should also be zoned to allow upgrades, facilitated by raised floors. This method allows for future changes in services and duct sizes (Edmonds and Gorgolewski, pp. 1-3).

4.2.4 Space Plan

An optimal space plan is one that minimizes partition walls and maximizes an open plan. Often, especially for office space, only a visual barrier is necessary to partition space. Furthermore, walls should be designed to be non-load-bearing, but rather as a membrane going in between the structural system, thus reducing the overall building weight. Modular interior wall panels allow for flexible systems, reconfiguration of space, and easy replacement of damaged sections, saving time on installation and renovation (Chini and Balachandran, pp. 182-186). If the walls are of a platform type, in which they sit on top of floor structures instead of extending through the plane, they will facilitate mechanical separation and stability during the deconstruction process. Lightweight materials such as Structural Insulated Panels, or SIPs, can reduce necessary work time and use of equipment (Guy and Shell, pp. 205-206). To increase natural daylight, a building depth of 13-17 m on plan is ideal for cellularized office space. It is also useful to increase floor to ceiling heights to both increase natural daylight and allow adaptability for other uses (Edmonds and Gorgolewski, pp. 1-3). To account for differential wear of the flooring system, one may use carpet tiles to replace small amounts of carpet instead of the entire carpet, since 10-20% of the carpet area typically bears 80-90% of the wear. Such a method can result in 80% material savings for floor covering replacement (Chini and Balachandran, p. 186).

4.2.5 Connections

The most important strategy for connections is to make them flexible rather than fixed (see Figure 8). One should avoid irreversible processes like adhesives, welding, and chemical bonds in favor of mechanical connections such as bolts, screws, and nails (Edmonds and Gorgolewski, p. 1). One should also eliminate the presence of caulking and sealants in connections, which are nearly impossible to remove, and reduce the mixture of different connection types in a single structure to minimize the changing of tools during deconstruction. It is best to consolidate both the types and sizes of connectors (Guy and Shell, pp. 205-206). If chemical bonds must be used, they should be made weaker than the components that are being connected, so that bonds break during disassembly rather than the components themselves (Chini and Balachandran, p. 182). To allow for adaptation of connectors, joints should be designed to withstand repeated assembly and disassembly (Guy and Ciarimboli, p. 7). Table 1 lists some of the most common types of connections, as well as their respective advantages and disadvantages.

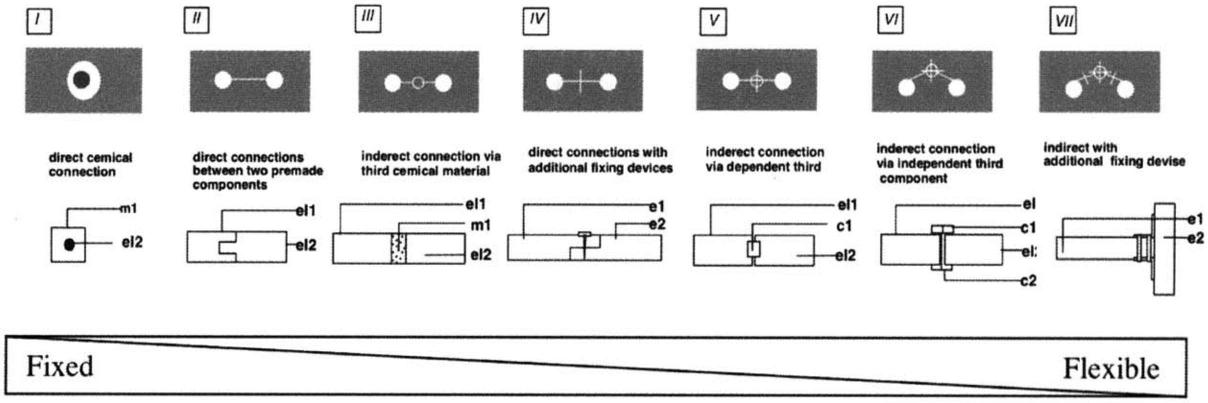


Figure 8: Seven Connection Styles; m=material, e=element, c=connection (Durmisevic and Brouwer, p. 97)

Table 1: Advantages and Disadvantages of Specific Connection Types (Adapted from Guy and Ciarimboli, p. 21)

Type of Connection	Advantages	Disadvantages
Screw	Easily removable	Limited reuse of both hole and screws Cost
Bolt	Strong Can be reused multiple times	Can seize up, making removal difficult Cost
Nail	Speed of construction Cost	Difficult to remove Removal usually damages component ends
Friction	Keeps component whole during removal	Relatively undeveloped connection type Structural weakness
Mortar	Can be made to a variety of strengths	Mostly cannot be reused Strength of mix often over-specified, difficult to separate bonded layers
Adhesives	Strong and efficient Deals easily with awkward joints Variety of strengths	Virtually impossible to separate bonded layers Not easily recycled or reused
Rivet	Speed of construction	Difficult to remove without damaging component ends

4.3 STRUCTURE TYPE

Modular buildings are structures built through industrial mass production of standardized modular components. Compared to traditional buildings, they have the advantage of being assembled on or off site, as necessary. The use of modular components increases the flexibility of a building by standardizing the processes and materials and by allowing for mass production and easy assembly. Some disadvantages of modular buildings, however, include a perceived threat to construction labor job security, particularly for low-skill labor, as well as less uniqueness in buildings. Modular buildings can be subdivided into portable, on-site assembly, and demountable buildings (Macozoma, p. 122).

Portable buildings are designed and manufactured industrially and made of pre-fabricated modular components, configured according to building specifications for the specific user needs. They can be assembled in factories and transported to the site to enable quick construction and flexible configuration. This structure type also allows easy disassembly of components and can be relocated (Macozoma, p. 122).

On-site assembly buildings, like portable buildings, are industrially designed and manufactured, composed of modularized and pre-fabricated components, and configured according to user needs. Components are all assembled on site, but the pre-fabricated system reduces the required amount of time on site, also allowing for easy component disassembly (Macozoma, p. 122).

Demountable buildings are modular buildings specifically designed for deconstruction. They are industrially manufactured and designed to adapt to changing use. They are assembled on site and suitable for a short service life. At the end of their useful life, they can be completely disassembled and stored for reassembly when needed (Macozoma, p. 122).

Table 2 shows a comparison among traditional, non-modular buildings as related to deconstruction capability. The optimal structural form is the post and beam system, combined with exposed connections and minimal partitioning elements that communicate visual data about the structure's potential for disassembly. Other desirable qualities of the structural form include a grid system, an open span of the structural frame, simple forms, and reduced overall complexity (Guy and Ciarimboli, p. 21).

Table 2: Structural System Types as Related to Deconstruction (Adapted from Guy and Ciarimboli, p. 22)

Type of Structure	Advantages	Disadvantages
Masonry	• Components break down into small, reusable units • Solid mass can be recycled if monolithic • Reuse does not dictate new design	• Reused blocks need soft binder, which reduces strength • Heavy machinery required to break down mass
Light Frame	• Structurally efficient, allows for many occupancy patterns • Easy to deconstruct into reusable elements if detailed appropriately • Can be layered separately from building envelope • Can be industrially manufactured	• Difficult to deconstruct unless framework is detailed with appropriate joints • Notching, holes, and binding with resins can reduce possibility of reuse • Can be manually or mechanically deconstructed depending on size and type
Panel System	• Structurally efficient • Industrial manufacturing gives precision • All components can be built in to minimize waste	• Requires mechanical deconstruction • Materials are bound together and hard to separate • Internal options reduced by need for cross wall bracing
Post and Beam	• Separates structure from envelope and other systems • Can provide standardization of dimensions and homogeneous materials • Can reduce mass of structure with fewer components	• Fewer larger members require mechanical deconstruction • Less-multi-functionality is possible

4.4 DECONSTRUCTION PROCESS CONSIDERATIONS

4.4.1 Sorting and Recycling

To reduce the costs of deconstruction, it is necessary to consider the sorting and recycling of building waste after dismantling. The best option is to combine the sorting of building waste with the capabilities and potential of existing recycling plants. In 2002, the French-German Institute for Environmental Research performed a study to test sorting processes, aiming to decrease the cost of dismantling, sorting, and preparation of reclaimed building materials, on which they plan to develop a computer software planning system (Seemann, et. al., pp. 15-16).

The use of construction materials in sophisticated recycling methods requires defined information about the characteristics of materials as well as strict standards for the required composition and production of those materials to ensure that they meet the same quality standards as new materials. As of 2002, some guidelines for reclaimed construction materials do exist in Germany; in general, recycled materials have to fulfill requirements for both new and recycled materials (Seemann, et. al., pp. 16-17).

Separation techniques include manual sorting and sorting at a recycling plant. Selective dismantling at the building site is the most efficient method, but drawbacks include high labor costs, which can be higher than savings from less waste disposal. Materials instead may be separated by manual sorting after traditional demolition of the building (which is still much more frequent than selective dismantling), resulting in a separation that is not as exact, but that takes less time and is cheaper compared to dismantling. This method is preferred if requirements for material purity are not very strict (Seemann, et. al., pp. 18-19).

Material sorting at a recycling plant is either water-based or airflow-based. Water-based, or density-based methods can allow the separation of lighter and heavier materials, sometimes with the use of supplementary water jets or air. The four kinds of water-based separation include thin film separation, jig separation, up current separation, and float and sink separation. Airflow-based separation techniques work by blowing away and isolating lighter, non-mineral materials from heavier materials. These systems have lower operational costs than water-based systems, but the material separation is not as exact. The two fundamental airflow system types are a reverse airflow sorting technique and cross airflow sorting technique. Cross airflow generally works better because materials are in the system for a shorter amount of time, increasing performance efficiency. In this case, the geometric form of the materials is more important, which allows for better sorting. The exhaust of foreign matter technique is a modification of the cross airflow technique; instead of a free fall system, materials are on a vibrating conveyor belt. The zig-zag separation technique uses a modified reverse airflow technique with a zig-zag machine form, allowing an increased effectiveness equal to several cross airflow devices in succession (Seemann, et. al., pp. 19-21). These schemes are illustrated in Figure 9.

The purpose of this study was to develop a computer tool to link dismantling, sorting, and recycling through an investigation of material flows. Planning starts with the predetermination of the future application of the proposed recycling materials and definition of requirements of the material quality. Next, a recycling plant with separating devices of adequate effectiveness must be chosen. Further planning is based on determining the overall material composition of the building, which requires an audit. Then, it must be verified that the requirements of the recycled material quality can be fulfilled. If so, no further separation techniques need be applied, but if not, the elements must be dismantled and sorted before the waste can be recycled. A computer-aided algorithm can then be used to determine which elements must be fully dismantled and which elements can be sorted after demolition, taking into account material characteristics and cost estimates for each element (i.e., deconstruction costs and sorting costs by weight). Building elements containing unfit materials can be either deconstructed or demolished and sorted to remove them from the material flow. Materials containing harmful substances and those that can definitely be reused without need for reprocessing must be dismantled and separated. There exist three possibilities for the other materials: dismantling, downstream sorting, or remaining among the demolition waste, which is determined by cost (Seemann, et. al., pp. 21-23). This process is summarized in the flowchart in Figure 10.

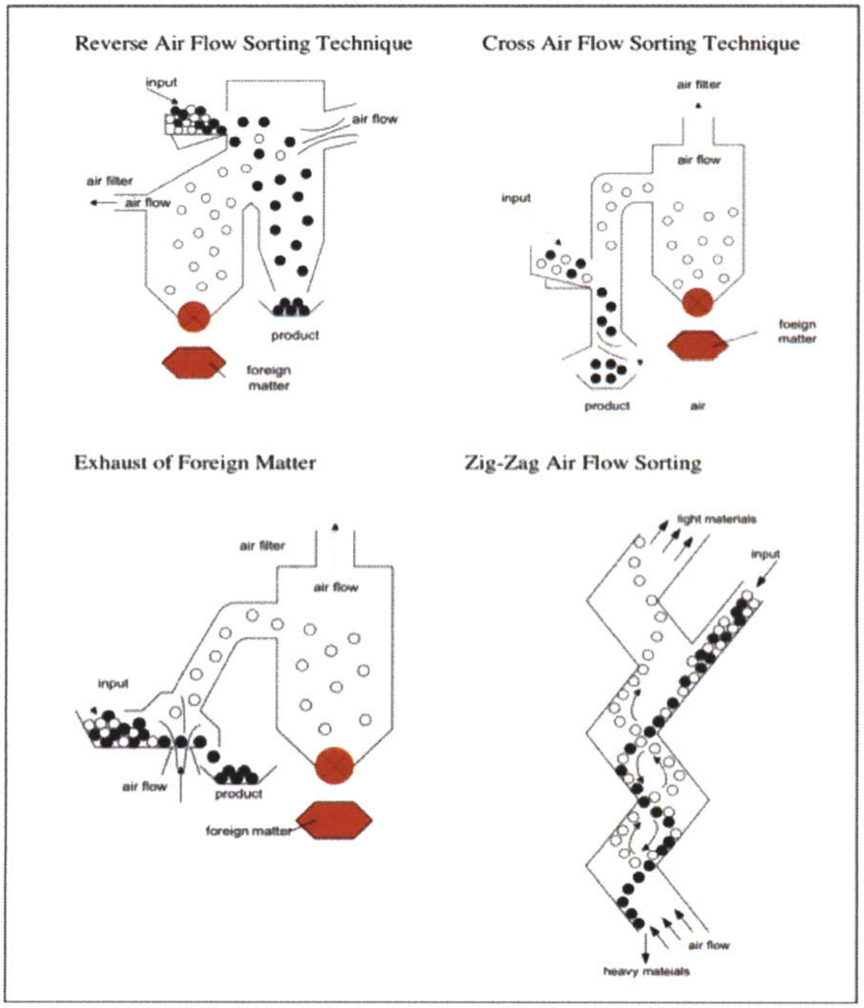


Figure 9: Airflow Separation Techniques (Seemann, et. al, p. 20)

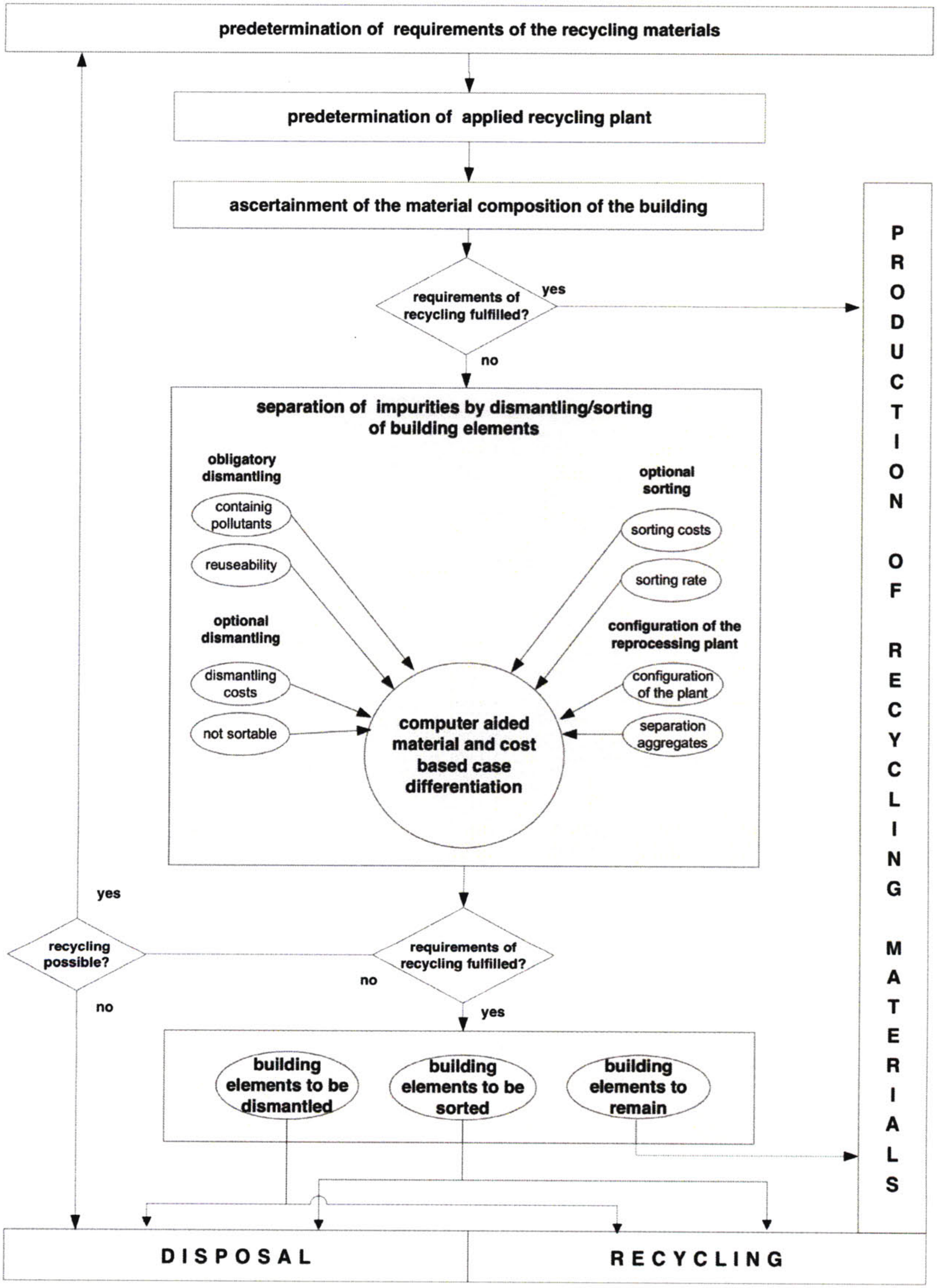


Figure 10: Planning System for Separation and Recycling of Building Materials (Seemann, et. al., p. 23)

4.4.2 Labor Considerations

The relatively new field of deconstruction brings up several job safety and training issues. In one study, the average time spent on tasks for deconstruction of residential buildings broke down as follows: deconstruction activity (26%), processing materials (24%), disposal and cleaning (17%), and demolition (10%). Many contractors are trained in conventional construction and demolition tasks, but not in the tasks required for deconstruction. Some issues specific to deconstruction include the need to stabilize weakened sections of the structure, establish removal routes for materials, and handle objects with nails or partial connections still in them, as well as the general need to understand connections and the best tools and methods for removing them, the load-bearing components, and damaged, weaker points (Guy and McLendon, pp. 3-10).

Worker safety is important to address before deconstruction, as it is a relatively new activity with little documentation of specific means or best practices of implementation. In the US, Occupational Safety and Health Administration guidelines offer only limited guidance and minimal standards for deconstruction. The first step in any deconstruction project should be the completion of a job hazard analysis to examine required work activities and to identify potential hazards for workers. This process begins with the assessment of the presence of hazardous materials, particularly asbestos (present in insulation, siding, roofing, caulking, floor tiles, and adhesives), lead (present in pipes and paint) and any others potentially located in utility services, stored or spilled on site, or in refrigerant or gas lines. The next step is an analysis of the specific tasks to be performed, including an examination of the integrity of structural components and load-bearing elements, the potential for falls and unanticipated collapse, and the potential for electric shock. Finally, a project-specific safety program should be prepared, outlining the required procedures to avoid or minimize serious hazards. Training is a key component of this program and includes a pre-task safety session for the crew to predict and reduce hazards (Hinze, pp. 211-212).

This process is necessary for all deconstruction projects regardless of the original building design, but the general process would be much safer if these issues were addressed in the original design. The greatest danger comes when load-bearing components are being dismantled. The ideal situation is to design facilities in which the shell or structure is permitted to remain intact, allowing reuse of the building for different functions (Design for Adaptability), confining deconstruction activities to removal and salvage of non-load-bearing walls and other aspects of the space plan. With a flexible design, it is possible to allow partial deconstruction that does not destroy the facility itself. When this situation is not possible, other design rules are useful for full dismantling. The structure, and especially the roof, should be composed of assemblies that may be lowered to the ground by crane in an intact unit, allowing disassembly to take place at the ground level. For roofs that must remain in place, slopes of less than 18-20 degrees are safer for workers, and a resilient roof material should be use to avoid eventual overlaying of materials for maintenance and repair. It is also helpful to incorporate anchors into the roof design to provide footholds and reduce falling risk. Bolted, mechanical connections are preferred over nailed or welded connection so that it is easier to assess when the connection is failing and ready for removal. Removal of welds also poses a potential for fire and greater uncertainty for structural support and failure. Precast concrete is preferred over cast-in-place concrete, since destroying the latter results in the emission of harmful dust (Hinze, pp. 214-216). In general, the approach that is preferable from a safety perspective usually coincides with the best option from an environmental and sustainability perspective.

5.0 DECONSTRUCTION AND REUSE POTENTIAL OF MATERIALS

As discussed in Section 3.2, certain materials, such as timber and steel, are preferable for deconstruction from a closed loop cycle perspective. However, it is necessary to consider the deconstruction and reuse potential of all the common materials of CDW: soil, ballast, concrete, asphalt, bricks, tiles, plaster, masonry, wood, metals, paper, and plastics (te Dorsthorst and Kowalczyk, p. 72). Excluding excavation waste, the most common CDW materials are concrete, ceramics (including bricks and tile), furniture, timber, metal, plastic, and electrical goods. Concrete is the largest waste stream at 53%, followed by ceramics at 22.5%. Over a third of these materials are non-inert (Hurley, et. al., p. 143). Table 3 shows a lifespan of different materials that can be used to assist in material selection and provide focus for connection detailing.

Table 3: Repair and Replacement Cycles of Building Materials (Guy and Ciarimboli, p. 20)

Building Materials Types	Repair (yrs.)	Total Replacement (yrs.)
Flat roof BUR membrane	10	20
Pitched roof, cement composite shingles	20	50
Pitched roof steel sheet	usually not required	30
Brick cladding	25	75+
Acrylic stucco	20	?
Interior gypsum board	3 to 10	25
Interior concrete or block	10 to 20	75+
Metal or vinyl windows	10 to 20	40
Clad wood windows	10 to 15	25 to 50
Solid wood interior doors	4 to 8	15
Metal doors	5 to 15	25
Terrazzo	0 to 15	60+
Ceramic floors	10 to 15	40+
Vinyl composition tile	8 to 15	20
Hardwood floors	5 to 10	40+
Carpet	3 to 8	5 to 15

There are several material qualities preferable for deconstruction that is valid for all material types. Included is flexibility within the material type, consisting of both physical flexibility and the ability to serve multiple needs and adapt to different uses. The designer should replace active service elements with passive elements to reduce material quantity and the need for mechanical servicing (i.e., double-skin facades, passive day lighting design). Designs should also minimize adhesives, resins, or coatings, which can lead to premature disposal of the material and limited possibilities for reuse. It is also helpful to anticipate differential wear and tear of certain building components, for example by allowing replacement of parts of a flooring system without replacing the entire floor, or by separating door handles from door bodies. Specification of limited, standard sizes of elements can also facilitate eventual reuse (Guy and Ciarimboli, pp. 38-39).

5.1 TIMBER

The largest market shares for timber construction materials are renovation, packaging, temporary formwork, joinery, floor and ceiling joists, and fencing. Opportunities for deconstruction of timber components include products with high-quality or high-value timber, which ensures profitability for relatively low resale volumes. The most commonly reused timber components are beams, railway sleepers, doors, flooring, and windows. Some products that require reprocessing before reuse include fencing, garden structures, cladding, fixtures, and floorboards (Hurley, et. al., pp. 162-163). Timber framing is generally desirable for reuse because it maintains large member sizes and typically uses fewer, larger connections. Wood siding also allows replacement of individual boards without impinging on adjacent boards. Painting and coatings increase its durability but also reduce reuse potential (Guy and Ciarimboli, pp. 42-44).

Various connection options are available for timber components. The most common connection types and their potential for deconstruction are as follows: nails (most common, but damages the material), screws (more easily removed with less material damage), bolts (easily deconstructable with minimal damage), staples (difficult to withdraw), glued joints and glue laminations (permanent connections that cause material damage), metal plate connectors (easily removed by hand), and mechanical bonding in masonry (easily deconstructed). The type of connection can therefore enable or hinder possible deconstruction. Another possible barrier to deconstruction for timber include thermal and UV degradation, which results in darkening and breaking down of the material, requiring treatment before reuse. The process of deconstruction requires careful manual removal of timber components to minimize damage, which may be labor intensive and uneconomical (Hurley, et. al., pp. 163-164).

The material qualities that make timber preferable for deconstruction include its non-toxicity, homogeneity, light weight, potential modularity, potential for mechanical fastening, high reusability and recyclability, and obedience to the precautionary principle (Guy and Ciarimboli, pp. 42-44). Other environmental positives is that wood carries the least embodied energy of all major structural materials, is the only truly renewable material, and is biodegradable. To ease deconstruction and reduce overall environmental impact, a designer should select wood that is certified by the Forest Stewardship Council, used panelized or modular construction to reduce waste, and use already salvaged wood whenever possible (Webster).

An alternative to solid timber, engineered wood (also known as composite wood) is a wood product that is pre-fabricated and manufactured by binding together wood particles or veneers with adhesives to form a composite structural component. Engineered wood makes efficient use of material and is generally salvageable, but has higher embodied energy than natural wood and can use toxic adhesives (Webster). Another, increasingly common wood-based material is SIPs, in which insulation is sandwiched between two pieces of oriented strand board. Thus, sheathing, structure, and insulation are combined in one composite, lightweight building component that is both modular and pre-fabricated. Because of their composite nature, SIPs are difficult to break down and separate by material, but they can be reused as a whole entity (Guy and Ciarimboli, p. 41).

5.2 STEEL

Common structural steel products include beams, columns, joists, bearing piles, hollow sections, channels, angles, and tees. Connections to hot rolled steel products are usually made with bolts or welds. Cold rolled sections have a greater range of possible connections: bolts, screws, rivets, pins, and spot welding (Hurley, et. al., pp. 165-166). Particular steel components that are amenable to deconstruction include open-web steel joists, which are lightweight, high-strength members capable of crossing long spans, with a large depth that can be used to house utilities and services with minimal entanglement. Light-gauge steel framing is a convenient alternative to conventional wood framing, as it is lighter, stronger, and more resistant to damage due to moisture and insects. Metal roofing is also useful for deconstruction because it is lightweight and usually mechanically fastened, allowing disassembly using simple tools and low-skill labor (Guy and Ciarimboli, pp. 42-45).

The qualities of steel that lend it to easy deconstruction are that it is easily recyclable through a thermal process, able to span long distances with less mass than other materials (such as concrete), and apt for post and beam construction due to its high tensile strength (Guy and Shell, p. 202). Steel is also highly reusable and already made of mostly recycled content; rolled shapes are made almost entirely out of recycled steel, and other shapes have varying recycled content, depending on the production method (Webster). Because the demolition industry already recycles most of its steel materials, an opportunity to further decrease environmental impact is to reuse entire steel components whenever it is economically viable to do so (Hurley, et. al., p. 166).

The greatest barrier to steel reuse is economic, but other barriers include uncertainties concerning in-service history (often requiring proof testing), deformation, and elongated fasteners or thread stripping. There are also health and safety implications in working close to connections, potential technical difficulties in removing composite sections, contamination due to sprayed products for fire protection, and corrosion of the metal. To improve steel deconstructability and likelihood of reuse, it is useful to design with components of standard dimensions, modular components, pre-fabricated units, and light gauge steel. Light gauge steel is generally connected with screws (instead of bolts or welds) and can therefore be removed more easily without causing significant damage to the structural member (Hurley, et. al., pp. 166-167).

5.3 CONCRETE

Common concrete products include foundations, retaining walls, pipes and drainage structures, culverts, bricks and blocks, floors, framing elements, and stair units. By market share, the most common precast concrete products are: masonry blocks, paving slabs and blocks, roof tiles, pipes, floor units, and fixtures, fittings, and joints. Some of the most commonly reused concrete components are vehicle safety barriers, paving slabs and blocks, roof tiles, garden products, and tunnel linings. Many key concrete products like slabs and blocks have no fixtures and can be easily dismantled and reused. Roof tiles and pipes can be reused only after removing connections, but it is difficult to dismantle other systems such as floor units without damaging them (Hurley, et. al., p. 156).

Most concrete products, with the exception of concrete crash barriers, are not designed for reuse. Some, however, could be reused with only slight design alterations, such as masonry blocks, paving blocks, and roof tiles (Hurley et. al., p. 158). Other pre-fabricated concrete members have potential for reuse if connections are easily removed (Guy and Ciarimboli, p. 40). The raw materials required for concrete are abundant and recycled materials can often be used for aggregate. Concrete has moderate embodied energy, is moderately recyclable, and highly durable, requiring little to no maintenance when properly designed and constructed (Webster). It can form integral floor or ceiling elements that can also multi-task as the envelope or finish. When broken down, concrete can be recycled unless it is contaminated by other building elements (Guy and Shell, p. 202).

Some drawbacks to concrete use are that cement production produces over 5% of the worldwide total of CO_2 emissions, production uses a very energy intensive process, and cast-in-place concrete is generally not salvageable (Webster). The biggest barrier to deconstruction is again economic; the cost of individual concrete units is so low that new ones are usually more cost effective. Most concrete components, such as foundations, pipes, and framing elements, cannot be reused in their original form. In addition, most orders for structural concrete units call for unique dimensions and specifically-made components, limiting their potential for reuse. Other physical barriers include mortared or glued joints, inaccessible joints, a dangerous de-stressing process, natural aging of the material, and corrosion of the reinforcement. Practical barriers include lack of skill, information, and tools for deconstruction; lack of an established market for salvaged concrete; and reluctance of manufactures, who prefer that users purchase new materials (Hurley, et. al., p. 157). Improvements to current practices include replacing cement with fly ash, rice husk ash, or other substitute materials; using larger and better aggregates to reduce the required volume of cement; using voids and air entrainment; replacing virgin aggregates with recycled materials; using precast concrete whenever possible; using non-toxic form release agents; and considering unreinforced concrete whenever possible (Webster).

5.4 MASONRY

Masonry encompasses all structural systems constructed by stacking, piling, or bonding together chunks of rock, fired clay, or concrete. The most common masonry products are bricks, stone, blocks, paving, slates, and tiles. There are four main masonry construction techniques: (1) irregular shapes and sizes chosen to achieve interlocking, (2) units cut to precise sizes and placed using a grid pattern with little or no mortar, (3) small to medium-sized bricks or blocks in few sizes assembled in a grid pattern, with inaccuracies filled with mortar, and (4) irregular shapes and sizes packed apart and bonded with mortar. Only the fourth method depends on mortar for structural stability (Hurley, et. al., pp. 159-160).

Each of the six masonry products provide different opportunities for deconstruction. There exists a large market for reclaimed traditional bricks (that is, hand made, of good quality, with lime mortar), though brick structures are expensive to deconstruct. Deconstruction of contemporary brickwork is almost impossible, as wall ties and mortar often damage the units. They can, however, be downcycled as aggregate. Stone structures can be deconstructed if lime mortar is used. It is still possible to deconstruct stone of good quality when other mortar is used, as it can be cut from the wall. Blocks provide little opportunity for deconstruction because of the use of cement mortar and the poor quality of the material itself. They can therefore be only downcycled as aggregate. The deconstructability of paving depends on what is used to fix the paving to the ground. If cement is used, the paving can only be broken up and downcycled as aggregate. Stone paving is easier to deconstruct, unless concrete is used as a base. Finally, slates and tiles may both be removed easily with the use of traditional mechanical pegged connections. There exists a market particularly for the reuse of roofing materials (Hurley, et. al., pp. 160-161).

Several recent studies have been dedicated to new technologies to attain high level recycling of crushed masonry CDW. One such technology enables the targeting of aerated concrete and crushed sand from masonry for reuse. By adding fine material such as sand and dust from brick waste to aerated concrete waste, granules may be formed, which are then consolidated into pellets through a burning treatment process. The density of the resulting material is controlled by adding expansion agents before burning, resulting in high-quality lightweight aggregates (Reinhold and Miller, p. 27). Other options for all fractions of crushed masonry include material for gardens, ornamental gravel, and concrete aggregate for coarse fractions; aggregate for mortar for sand fractions; and use as mineral admixture in concrete for fine fractions (Mueller and Stark, p. 36).

The deconstruction benefits of masonry materials include good durability and potential use as a finish material. Stone masonry also has low embodied energy from extraction and transportation (Webster). It is also readily designed for disassembly, reusable, and easily repairable when used in modular sizes. Modular block wall systems are inherently flexible and readily demountable, using mechanical connections. Brick with lime mortar is also highly durable and easily reusable, but its structural capacity can decrease over time. Mortar-less brick veneer uses screwed mechanical fasteners instead of a "wet" connection by attaching each unit to vertical strips connected to the wall sheathing. This system uses a specific brick shape that limits its reuse options, but is much easier to disassemble (Guy and Ciarimboli, pp. 40-44).

The biggest barrier to masonry deconstruction is once again economic; the labor cost to take down, stack, and clean bricks is exorbitant. It is even more difficult when modern repairs have been performed and cement mortar used, which cannot be cleaned off of bricks (Hurley, et.

al., p. 161). Thus, the manual disassembly of masonry walls requires much more labor and yields lower recovery than, say, wood framed walls (Languell, p. 88). In addition to cement mortars, the presence of steel reinforcement can make deconstruction more difficult. To make masonry more apt for deconstruction, a designer should use unreinforced masonry whenever possible, lime mortar instead of cement mortars, and already salvaged masonry if it is available (Webster).

6.0 FEASIBILITY OF DfAD

6.1 BARRIERS TO IMPLEMENTATION

6.1.1 Practical Barriers

Despite the many benefits of building deconstruction and materials recovery, the trend is still far from widespread. The recovery activity for building materials generally fluctuates according to the economy, available technology, codes, trends, and disposability of components (Gorgolewski, p. 2). Part of the lack of acceptance of DfAD practices is the current stigma that homes and buildings are semi-permanent fixtures on the landscape, precluding extensive research into the realities of the need to design for deconstruction. There is also a perception that DfAD measures imply aesthetic, safety, or economic compromises for building users and owners. Other practical barriers include worker health and safety hazards, the increased time required for deconstruction, the need for a storage site for recovered materials, lack of standards for material reuse, and lack of established supply-demand chains (Guy and Shell, pp. 191-193). These concerns, combined with the convenience of the status quo, make uptake of DfAD even more unlikely; the availability of raw materials, relatively low cost of landfilling, and wide availability of dumping sites provide little incentive to change current practices (Giglio, p. 63). Disposal of CDW is generally difficult to control because of the large number of potential sources (demolition sites) and the fact that CDW is generally inert, resulting in a high risk of illegal landfilling (te Dorsthorst and Kowalczyk, p. 71).

Current trends in the construction industry itself can create both physical and practical barriers to deconstruction as well. Building trends have moved away from renewable and fiber-based materials towards inorganic materials and caused an increase in the use of composites and chemically complex materials. The most commonly used connections are those that are most difficult to disconnect, and a trend towards loss in craft skills cause prohibitive labor costs to create exposed connections and details. It is also common to rely on coating and encapsulating building components with finish materials that inhibit reuse (Guy and Ciarimboli, p. 3). The biggest practical problem for builders and members of the construction industry is the transfer of knowledge. To facilitate widespread knowledge, it is necessary to grab the attention of industry members long enough to provide them with the appropriate tools to make an educated decision about building options (Languell, p. 46).

The biggest issue for designers is the need for an established market for reused building materials. Currently, the unsure quality and quantity of used building materials available means designers do not have a constant, consistent supply to rely on. For example, existing grade rules can be used to grade recycled lumber, but no rules or standards currently exist to specifically address recycled lumber or the qualities that distinguish it from new lumber. Another obstacle is that, due to the highly publicized niche material markets, there exists a perception that reclaimed materials are much pricier than new standard materials, which is untrue for common materials (Languell, pp. 46-59). The reuse of reclaimed components in a new building design usually requires that the designer be more flexible. Reclaimed components are not readily available from stock, and supply and demand issues may necessitate a redesign to suit the available reclaimed components, or a designer may simply need to choose whichever oversized, overdesigned components are available. A lack of clear information about procurement procedures and how to integrate reclaimed materials into new projects presents an extra challenge. Standard practice is aimed at getting things done in the fastest, easiest, and most economical way, and designing with reclaimed components adds a new level of complexity (Gorgolewski, pp. 5-6).

6.1.2 Economic Barriers

Until widespread legislation or economic restrictions on construction waste disposal take place, the biggest barrier to deconstruction will be economic. The current costs of construction waste disposal do not reflect the associated environmental externalities. As long as local landfill tipping fees are relatively cheap, and alternative markets for recovered materials are immature, deconstruction presents mostly an economic disincentive, including increased labor costs and a longer disassembly process. Another impediment is the fact that DfAD often increases the first costs of construction and does not have a near-term payback. Because of the speculative nature of building, often renovation and demolition costs are not borne by the original owner. To be effective, therefore, DfAD should not increase the first costs and should be compatible with energy efficiency. The most important criteria, however, is that the cost of final deconstruction most not exceed the cost of traditional demolition and disposal cost, minus salvage value for a building *not* designed for deconstruction (Guy and Shell, pp. 190-193).

Salvaged materials can provide some payback on a DfAD investment, but the use of salvaged materials is only feasible if lower cost, equivalent new materials do not exist. In addition, there must exist a market for such materials. Older technologies, such as salvaged windows with low energy efficiency, could have detrimental environmental effects. Salvaged materials, therefore, must be either cheaper than new materials or have unique, appealing characteristics for the buyer (Languell, p. 45). One study shows that economic and environmental benefits favor the reuse of steel components over recycled steel, but limited supply can cause bottlenecks and there may be a lack of technical feasibility for reuse and a limited market demand. Thus, an uncoordinated supply chain can lead to higher costs and even higher environmental impact (Gorgolewski, p. 3).

6.2 PROJECT IMPLEMENTATION

6.2.1 Project Team

If DfAD methods are to succeed, the entire project team, as well as the client, must agree about the project goals from the beginning of the project. The client plays a pivotal role in the direction of the construction project and is the main driver for green buildings. Through programs like contractor rating systems and registers of "green designers," a client can successfully select a construction team committed to green building (Macozoma, p. 120). Table 4 details the roles of different team members during each phase of the project.

Table 4: Role of Team Members during a DfAD Project (adapted from Guy and Ciarimboli, p. 15)

Phase	Client	Designer	Contractor
Pre-Design	Support scenario planning. Hire an architect experienced in sustainable design and DfAD. Brief the design team on critical requirements for adaptability and flexibility in use. Stipulate "as built" drawings and specification as part of the design contract.	Conduct scenario planning and programming. Demonstrate best practices of DfAD to client. Investigate DfAD relative to building type and client needs. Develop goals and priorities including which building elements are most cost-effective to DfAD.	
Concept Design	Engage contractor as expertise on design implications for DfAD.	Organize meetings with the contractor and vendors to identify reused materials and construction processes that support DfAD.	Obtain initial briefing and training on DfAD.
Schematic Design		Carry out a design check by producing an outline plan for deconstruction and ensuring that the design proposals are consistent with this form of reverse engineering.	Advise the design team on deconstruction processes, potential salvage and reuse priorities, and recycling requirements for various material types.

Design Development		Produce a detailed plan for the deconstruction of the building.	Advise the design team on implications for deconstruction in relation to design and detailing.
Construction Documents		Ensure details have been implemented to not compromise DfAD integrity. Incorporate plan for deconstruction in drawing specifications. Ensure bid documents reflect commitment to DfAD.	Advise the design team on implications for deconstruction of design and detailing. Identify good construction practice for DfAD and advise design team on deconstruction plan drawings and specifications.
Construction Administration	Ensure that all maintenance staff and contractors are fully briefed on DfAD strategies. Allow for additional time in contract period to ensure DfAD through careful construction practices.	Create or update the construction documents to created comprehensive "as built" documents.	Ensure quality of workmanship to maintain integrity of DfAD details as designed. Train subcontractors as necessary.
Facility Operation Services	Monitor the performance of the project over time and build in the evaluation into future DfAD projects.	Ensure that all maintenance staff are fully briefed on DfAD strategy, and instigate a feedback strategy on building performance from DfAD.	

6.2.2 Design Process

The goal of the design process, particularly for DfAD projects, is to ensure buildability, which applies to all stages of the building life. There are three dimensions to buildability: the participants (clients, users, financiers, designers, and contractors), buildability factors (activities used for ease of assembly and disassembly), and stages of the life cycle (feasibility study, design, documentation, construction, commissioning, and demolition or deconstruction) (Crowther, p. 8). The effectiveness of a project is significantly impacted by the timing of input from various team members. This tendency is known as the Pareto principle, in which decisions taken at early stages of a project life cycle have a greater potential to influence the final outcome of the project than those during the later stages (Chini and Balachandran, p. 177).

It is therefore best to consider design options, particularly potential reused materials, at the beginning of the design process and to design to availability of materials. This method, however, requires purchasing items at their time of availability, at the beginning of the project, presenting potential cash flow issues and management consequences when a contractor has not yet been hired. If pre-purchasing components is not a possibility, flexibility in the design is necessary to allow for alternative options. This process involves additional research by the design team at the front end of the project (Gorgolewski, p. 6).

The rest of the design process includes developing the components, materials, construction techniques, and information and management systems to achieve maximum material recovery at the building's end of life. There are five stages in traditional architectural design to consider: pre-design, in which feasibility, site analysis, and environmental goal setting take place; concept design, consisting of initial abstract formal design; schematic design, in which structural systems are selected, dimensions articulated, and building codes analyzed; design development, consisting of refinement of dimensions, materials, systems, and cost analysis; and construction documents, consisting of final permit drawings and specifications. With these stages in mind, the design team must implement special steps for DfAD. The first step requires briefing the team members on DfAD concepts and a discussion of roles, bringing the entire team on board at the beginning of the project. It is helpful to conduct a life cycle cost analysis based on anticipated building use and consideration for an appropriate period (say, 50 years). It is also necessary to evaluate the site constraints, budget, building functions, and construction delivery process when setting DfAD goals. Targeting specific components and assemblies for material recovery and reuse can help inform design decisions, as well as undertaking cost-benefit analysis for the reuse of existing materials. When drawing up plans and specifications, DfAD detailing may be necessarily more explicit than in traditional construction drawings. Before and during construction, it is necessary to audit contractors and ensure that initial briefing and training for DfAD activities takes place (Guy and Ciarimboli, pp. 3-13).

Perhaps the most important step for the design team to take, however, is the development of a comprehensive deconstruction plan early on to expedite understanding and increase feasibility of the disassembly sequence. The plan also allows for prioritizing materials, planning management, and dealing with scheduling and safety requirements (Guy and Shell, p. 202). Included in the deconstruction plan is the statement of strategy for DfAD to demonstrate the strategy behind the design and describe best practices to ensure that best methods are implemented. The plan should include a list of building components to provide an inventory of materials and components together with specifications, manufacturers' details, and contacts. The list should also describe the intended design life of each component and identify best options for reuse and reclamation. Furthermore, the plan should provide instructions on how to actually deconstruct the building elements, also adding information as necessary to the "as built" drawings to demonstrate preferred techniques as well as to describe the required equipment for dismantling, sequential processes, and health and safety implications. The plan, when completed, should be issued to all involved parties at the completion stage to allow maximum awareness, and extra copies should be placed with the building legal documents and any building commissioning or operations and maintenance files (Guy and Ciarimboli, pp. 16-17).

When the time comes to implement deconstruction activities, the following processes must be considered before deconstruction can take place. Many of these processes are facilitated by a preexisting deconstruction plan, but it is generally assumed that for deconstruction taking place today, such a plan will not exist. First, the team must acquire a deconstruction permit, which entails the same process as that for traditional demolition. It is necessary to perform a building assessment and material inventory to assess the age of a structure, type and condition of the materials and components, methods of construction, and availability of recycling options. An environmental assessment will include the identification of hazardous materials and the need to perform asbestos and lead abatement. To ensure field safety, the project site superintendent should coordinate field safety education and performance. Procurement of workers' compensation insurance is also necessary; premiums for construction and demolition workers' compensation are based on individual tasks performed throughout the workday. It is therefore necessary to explain the nature of the work involved to insurance agents to accurately reflect the risk of deconstruction activities. When scheduling, one must reconcile tight time constraints with the fact that deconstruction takes two to ten times longer than traditional demolition. Therefore, planning as far in advance as possible is the best solution. In preparing the job site, there should be clear areas for parking, a denailing station, and dumpster locations. A site map is useful to allocate space for deconstruction activities as well as storage space, processing space, and disposal space close to the structure (Languell, pp. 67-75). See Figure 11 for a sample deconstruction site map.

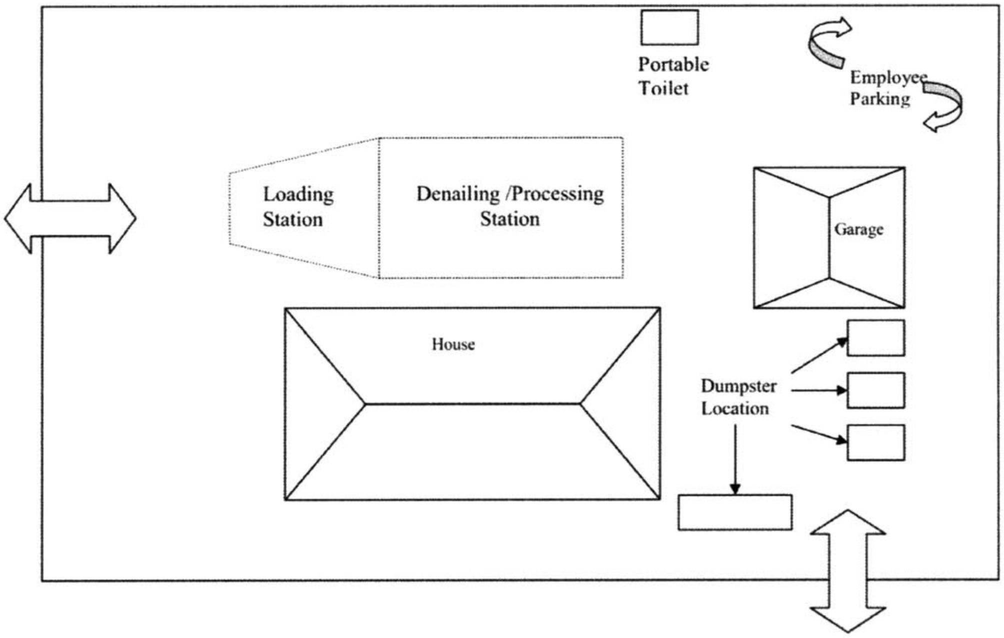
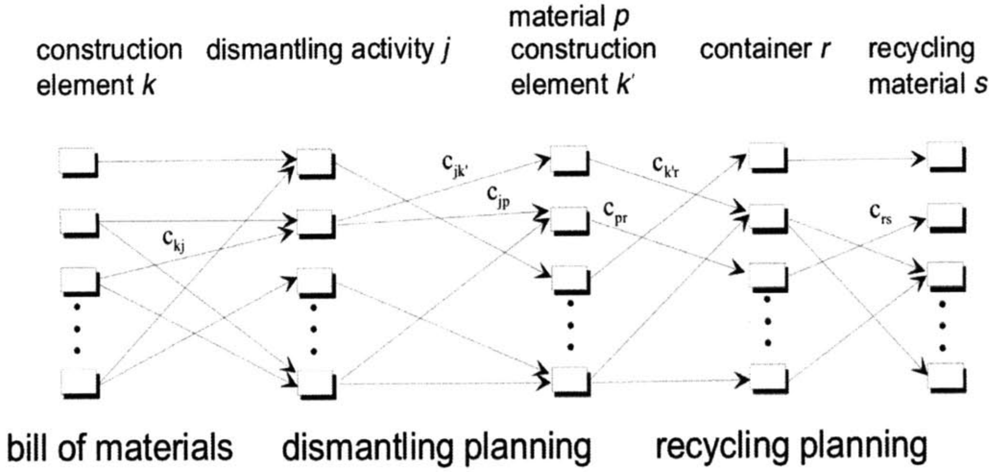


Figure 11: Diagram of Deconstruction Site Organization (Guy and McLendon, p. 74)

6.2.3 Project Scheduling

Sophisticated project scheduling methods may be applied to deconstruction projects and recycling of buildings. Such a method consists of both material-flow management (to ensure that environmental requirements are met) and resource-constrained project scheduling (to optimize processes on the construction site). The dismantling and recycling of buildings, like most construction projects, is considered a make-to-order production, in that it is a response to customer orders and no inventories are built up for future sales. Dismantling can also be considered on-site manufacturing because the resources required for dismantling must be transferred to the production/construction site rather than vice versa. The deconstruction process therefore requires more planning than other types of manufacturing. Conventional manufacturing production usually requires the use of Materials Requirements Planning, or MRP, consisting of four steps: (1) determination of gross requirements of final products, sub-assemblies and components with a bill of materials; (2) determination of net requirements based on gross requirements, scheduled receipts, and inventory; (3) lot sizing; and (4) time phasing. Make-to-order production, however, skips steps (2) and (3). The disadvantage of such a system is that resource capabilities are not explicitly considered in MRP. For example, step (4) assumes the availability of unlimited resources for the execution of activities. Usually, revisions and delays are necessary with this approach. Some unique characteristics of buildings to take into account is the fact that buildings are "meta-products" composed of multiple components of varying characteristics, as well as their long lifetime that imposes problems for construction and deconstruction planning. The unique combination of components integrated into a building requires a unique approach for each building, especially as the possibility of past modifications and renovations results in unreliable data on the building composition. An appropriate approach, therefore, is integrated time and capacity planning done with algorithms for resource-constrained scheduling, including material-flow management for environmental requirements (Schultmann and Rentz, pp. 48-49).

Problems with material flow management in construction arises from the time lag between initial construction and the end of life. In general, the composition of buildings at their end of life is mostly unknown, so the first step is usually a pre-deconstruction survey and building audit to determine how dismantling should be carried out. Figure 12 shows a material flow graph for dismantling and recycling of a building. In the diagram, construction elements (*k*) are the sources. By the application of dismantling activities (*j*), the building is dismantled into parts and, depending on the stage of dismantling, the dismantled components can either be a single construction element (*k'*) or a mix of building materials (*p*) (Schultmann and Rentz, p. 50).



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 12: Material Flow Graph for Building Dismantling and Recycling (Schultmann and Rentz, p. 50)

It is also essential to identify contaminated components before dismantling starts and isolate them. This may involve creating a pollutant balance in addition to a material balance for different dismantling steps. Figure 13 shows how the composition of demolition waste can be influenced by performing seven progressive ways of dismantling a building, with alternative (I) being no dismantling and alternative (VII) being full dismantling. For each of the alternatives, the building materials and pollutants to be dealt with may be quantified and tabulated. Increasing the level of dismantling and material separation leads to a decrease in the amount of pollutants remaining in the building waste. These balances may serve as a framework for the dismantling work necessary to guarantee a quality level of recycled materials. These results are then used for more detailed dismantling planning with resource-constrained project scheduling methods (Schultmann and Rentz, pp. 51-52).

After a material flow analysis is completed, a dismantling plan aims to first set up an activity order that is technologically and environmentally oriented. Technological and environmental precedence relations are illustrated by an activity-on-node network (AON), as shown in Figure 14. In an AON, nodes represent dismantling activities (j=1…J) and arcs represent the precedence relations between them. The AON includes one source (j=1) and one sink (j=J). After precedence relations are determined, activities must then be specified in detail by determining necessary resources and activity duration. Activities can often be executed in different ways (requiring different resources and time spans), such as by disassembling outer walls with dismantling, pneumatic hammers, a grabbing bucket, or a hydraulic excavator.

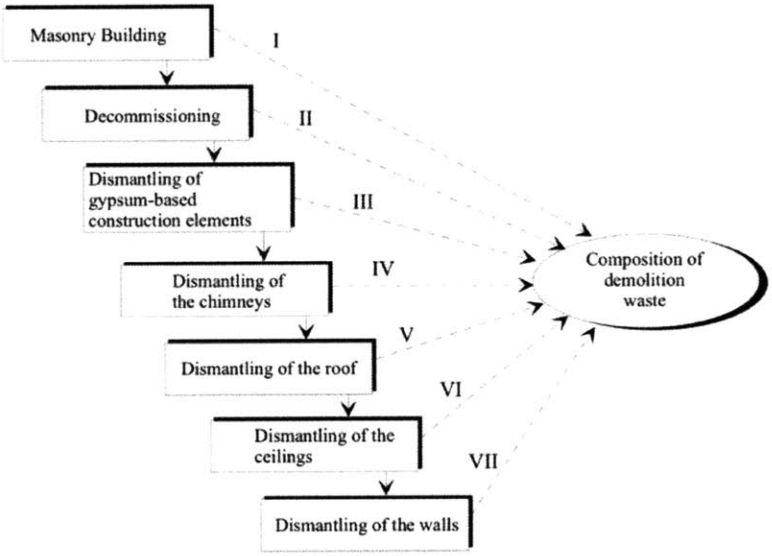


Figure 13: Dismantling Alternatives for a Residential Building (Schultmann and Rentz, p. 51)

Such alternatives may be modeled by introducing different modes (m). Performing activity j in mode m has a duration of d_{jm}, still contained in one integrated model. It is also possible to introduce resource categories; associated with activity j and mode m is the usage of renewable resources, including machines and man hours, constrained on a period basis, and nonrenewable resources, including the financial budget, that is limited on the basis of the entire duration of the project, such that consumption by activity *j* reduces its availability for the rest of the project (Schultmann and Rentz, pp. 53-55).

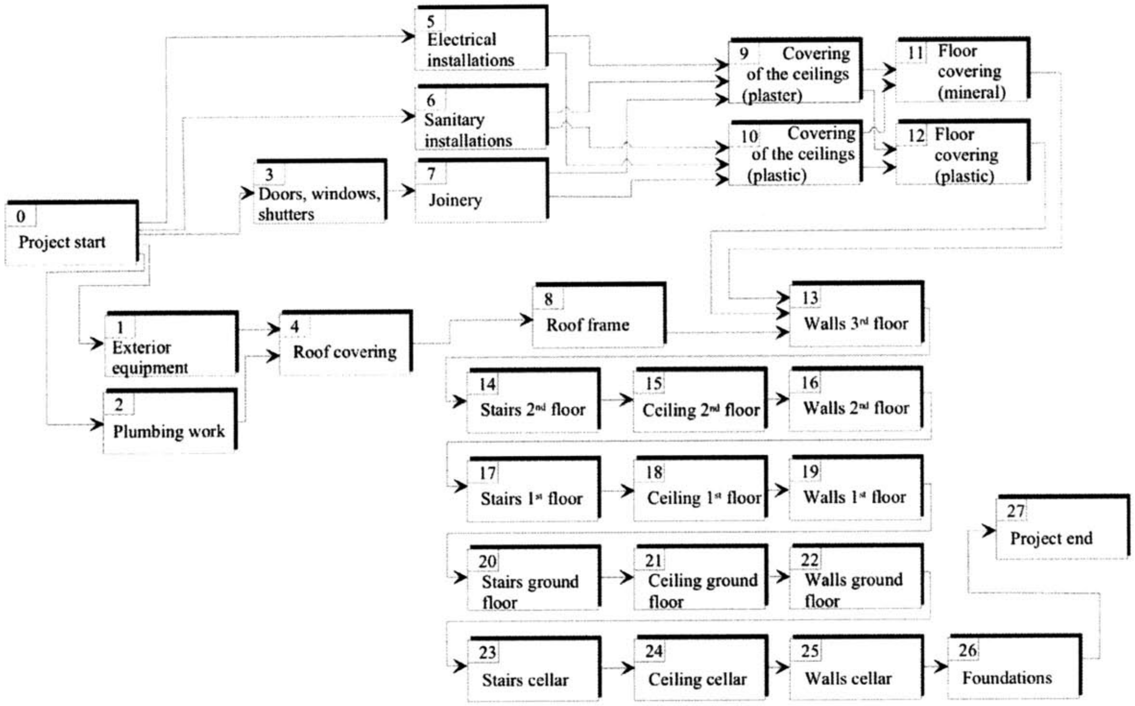


Figure 14: Dismantling Network for a Residential Building (Schultmann and Rentz, p. 53)

When the network model is built, it is then necessary to use critical path analysis using the earliest (Ef_j) and latest (Lf_j) finishing times for each activity *j*. Variables for usage, consumption, and constraints are as follows (Schultmann and Rentz, p. 55):

- q_{jmn}: capacity of nonrenewable resource *n*, consumed by dismantling activity *j* in mode *m*
- 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*
- Q_n: total capacity of nonrenewable resource *n*, $n \in N$

The decision variable is therefore x_{jmt} (dismantling activity *j*, performed in mode *m*, completed in time period *t*). The planning model is outlined below (Schultmann and Rentz, pp. 55-56):

Minimize

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

Subject to

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

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

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

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

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

Function (1) is the objective function, minimizing the completion time between the source and sink. Constraint (2) ensures that each activity *j* is processed in only one mode and with one completion time. Constraint (3) ensures compliance with dismantling precedence relations of activities. Constraint (4) takes into account capacity restrictions of renewable resources per time period. Constraint (5) ensures that the schedule is feasible with respect to nonrenewable resources (Schultmann and Rentz, p. 56).

The purpose of this model is to evaluate possible project scheduling improvement. To test the model, its creators defined three potential scenarios, designed in cooperation with demolition companies to resemble real situations. In Scenario 1, the dismantling approach typically chosen in practice is used, consisting of mainly manual dismantling techniques. In Scenario 2, the dismantling is carried out partially with automated devices, such as pneumatic hammers, mini excavators, and water jets, reflecting possible improvement of the current procedure with sophisticated machines. Scenario 3 is strictly focused on separating and recycling as many materials as is technically feasible according to material-flow analysis. These scenarios were run using the above model and compared to the present situation, that is, results typically obtained in practice, in Figure 15 (Schultmann and Rentz, pp. 56-57).

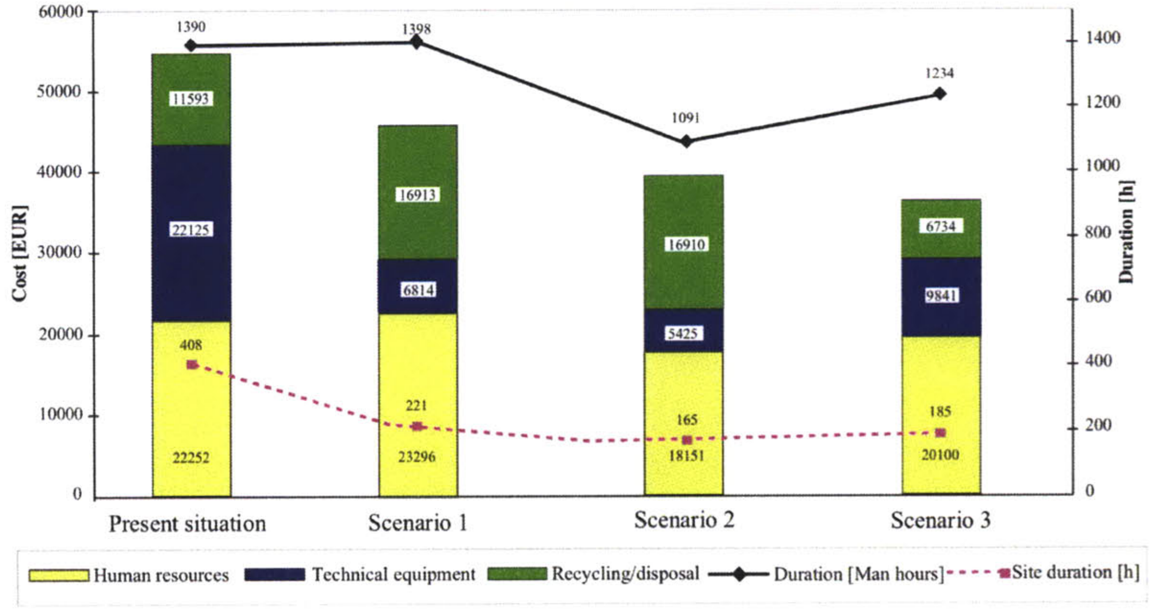


Figure 15: Cost and Duration of Dismantling Strategies for a Residential Building (Schultmann and Rentz, p. 57)

The results show that the overall project and on-site duration of activities is dramatically reduced for all scenarios. In Scenario 1, the site time and cost of machinery decreases by carrying out work simultaneously whenever possible and by reducing the duration of cost-intensive devices on the construction site. Scenario 2 shows a further reduction in duration due to possibilities of accelerating certain activities by using sophisticated machines. Scenario 3 has a slightly more prolonged duration because of additional activities required for maximum material recovery, but allows the lowest total costs due to the higher quality of materials salvaged from dismantling. Scenarios 1 and 2 guarantee a recycling rate of 95%, and Scenario 3 guarantees a rate of 98%, as well as overall higher quality recycling materials. The results of this model show that efficient planning can support deconstruction strategies that are not disadvantageous from an economic standpoint, resulting in reduction of project duration and cost when compared with current results in practice (Schultmann and Rentz, pp. 57-59).

6.3 COST ANALYSIS

Deconstruction often requires the use of a cost model to assess the financial implications of the project. The procedure for calculating the cost of deconstructing a component *a* is as follows: $DC_a = f(K_a+L_a+E_a)$. That is, deconstruction cost is a function of the capital required to deconstruct *a*, the cost of labor to deconstruct *a*, and the "entrepreneur cost," or overhead. The disposal value of *a* as an asset is: $DV_a = R_a - DC_a$. That is, the disposal value of *a* equals the residual value of *a* minus the deconstruction cost of *a* (Hurley, et. al., p. 169). In order to be financially advantageous, DV_a should be minimized.

Several factors come into play when determining the cost of deconstruction for a building. The first factor is planning. Because every structure is unique, it is necessary to evaluate each project individually to anticipate potential problems and minimize delays. Training is a process that requires finesse and coordination as well as knowledge of construction techniques for deconstruction and handling hazardous materials. Because deconstruction is a labor intensive process, the cost of manual labor, which varies by region, can greatly affect the viability of a project. It is also necessary to consider material collection, as materials must be separated as the structure is being disassembled, collected, and cared for until resale to get the highest possible salvage price. Also associated with material collection and resale is sorting according to material type and dimension, inventory of materials required for future sale, and storage, since it is unlikely that materials will be sold immediately after removal. Many of the materials may need to be graded, particularly timber. Currently, the reuse of timber is mostly limited to non-structural applications, but wood can be regraded at an additional cost, subject to recent research to establish guidelines for salvaged wood. It is also usually necessary to transport materials from the job site to a storage site, and often resale adds yet another cost, as marketing options may be necessary (Languell, pp. 63-64).

One study by the Center for Construction and Environment at the University of Florida sought to understand the potential cost effects of deconstructing wood-framed residential structures. Volunteers collected time and activity data and all associated costs for six structures and estimated revenues from salvaged materials as well as traditional demolition costs to form a valid comparison. The buildings were all between 1000 and 2000 square feet, built between 1900 and 1950, wood framed, and water damaged. By size and structure type, they represented 97% of residential wood-frame buildings. Three homes had asbestos-containing materials, and one had lead-based paint, which needed to be removed before deconstruction activities took place (Guy and McLendon, pp. 1-2).

The results of the study showed that on average, first costs for deconstruction are 21% more than those for demolition, but there was an overall 37% savings estimated using a conservative salvage value. To make these estimates, disposal cost data was normalized to a weight-based disposal cost of $34/ton. Comparative volume-based disposal was $154/cu.yd., or $120/haul. On average, the demolition cost of the houses was $5.36/sq. ft. and disposal was an average of 40% of these total costs. The average "gross" deconstruction cost was $6.47/sq. ft., not considering salvage values. Of this amount, asbestos and lead surveys and remediation accounts for $0.97/sq. ft. The average salvage value for deconstructed materials was $3.28/sq. ft., making net deconstruction costs $3.19/sq. ft. This study, however, did not include the operating costs of a redistribution business (Guy and McLendon, pp. 18-20). Other studies corroborate the potential savings that comes with deconstruction. According to one developer in the Mid-Atlantic region, it costs $14,000 to deconstruct a small abandoned house and $16,000 to demolish it (Languell, p. 60).

Factors affecting the salvage value of reclaimed materials include the material type (which determines quantities they are generally used in, finishings, typical dimensions, and uses), time of year (construction firms may be more interested during non-winter months), condition of the local economy, retail building material prices, and the condition of the material. The options to consider when determining outlets for materials include whether the material will be salvaged and immediately resold, salvaged and donated (for those with little resale value), salvaged for recycling (for those that require further processing), or disposed as waste materials. Some potential marketing approaches include direct marketing to retailers and end users, brokers, auctions, and site sales (Languell, pp. 89-90). In general, the price of salvaged lumber is 25-50% the cost of new lumber (Guy and McLendon, p. 20) and reused steel beams cost 60-80% of the cost of new members. This difference in price can offset design fees when implementing salvaged materials in new designs (Gorgolewski, p. 13).

There are multiple options for contracts to distribute costs and revenues from deconstruction to the building owner and deconstruction contractor. One option is deconstruction as a paid service to the owner, who retains the salvaged materials. Another possibility is shared ownership of materials accompanied by a reduction in contract cost, using materials as an in-kind payment to the contractor. The contractor could instead retain all materials and charge an internally calculated price based on projected revenues from the resale of salvaged materials. A final option is a non-profit deconstruction, which the contractor performs for a fee, and after which the owner donates salvaged materials as a tax write-off (Guy and McLendon, p. 5).

6.4 ANALYSIS TOOLS

Recent years have seen a plethora of DfAD computing tools that have been developed in both the private and public sectors. Some examples include BDI Design for Environment by Boothroyd and Dewhurst, Inc; Ametide by the University of California at Berkeley; DFR-Recy by Helsinki University of Technology; EUROMAT by Technical University Berlin; LASeR by Stanford University; MoTech by Technion University in Israel; and ReStar by the Green Engineering Corporation (Guy and Shell, p. 195). Many of these products are still in the development phase, but present great potential to increase the efficiency and feasibility of deconstruction. Two such products, SMARTWaste and BELCANTO, are examined in the following sections.

6.4.1 SMARTWaste for Pre-demolition Audits

SMARTWaste stands for Site Methodology to Audit, Reduce, and Target Waste. It was developed by the UK Building Research Establishment to provide a robust and accurate mechanism by which wastes may be measured and categorized by source, type, amount, cause, and cost. SMARTWaste is currently a web-based auditing tool, www.smartwaste.co.uk, that provides the UK construction industry with benchmark data for waste targets, environmental performance indicators, and practical advice on waste reduction (Hurley, et. al., p. 146).

SMARTWaste developers used data available from audits of construction, demolition, refurbishment, manufacturing and pre-fabrication as a starting point to identify and prioritize methods to reduce waste, reuse at the source whenever possible, and maximize recovery to extend a material's life cycle. The software identifies potential cost savings of projects and ways to maximize reduction and recovery options for materials. Features include an overall quantity report, cause report, Environmental Performance Indicators for different waste groups, key waste products for the project, project trend reports, waste rates of key products, interactive action plans for targeted waste, and weekly and monthly reports (Hurley, et. al., pp. 146-147). Use of this software can make a designer's job easier and the deconstruction process more efficient and closer to a CLMC.

6.4.2 BELCANTO for End of Life Cycle Analysis

BELCANTO, which stands for Building End of Life Cycle ANalaysis TOol, is a software tool for architects, building developers, or researchers to support decisions between designing a building for structure reuse (Design for Adaptability), for element reuse (Design for Deconstruction), or material recycling (Design for Dismantling). The program input is the building product information, including materials, dimensions, production energy and waste, assembly and disassembly techniques, service life, and maintenance. The user can choose to input some or all of this information. Based on this input, the program then produces an output consisting of the environmental load of the building, life cycle costs of various end of life scenarios, and the predicted ease of dismantling (a qualitative assessment) (te Dorsthorst and Kowalczyk, pp. 78-79). Figure 16 shows a schematic of the BELCANTO program.

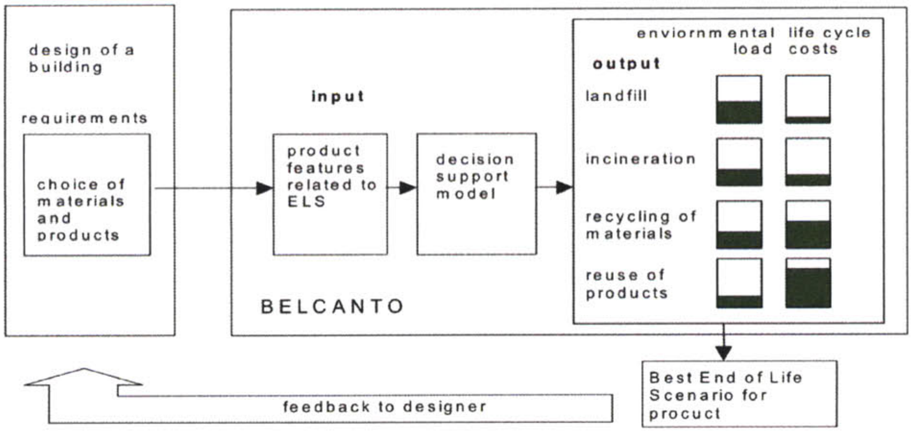


Figure 16: Diagram of BELCANTO Program Process (te Dorsthorst and Kowalczyk, p. 79)

6.5 INCENTIVES AND POLICIES TO IMPROVE FEASIBILITY

Some constraining factors for DfAD designers include fear of change (dependence on the norm, misconceptions), motivation (regulatory and financial incentives), integrity (acceptance and certification of salvaged materials), true versus hidden costs (life cycle costs and environmental effects), and recognition (rewarding resource efficiency) (Macozoma, pp. 120-121). These constraints are essential to consider when attempting to improve the appeal of deconstruction. Given the relatively low profit margins in the construction industry, a leaner approach to resource use and reuse will demonstrate that reduction and recovery strategies can increase profits and reduce the environmental impact of construction and demolition processes. The industry is also highly responsive to increasing legislation and guidance at the national and community levels (Hurley, et. al., p. 142).

Deconstruction and material reuse is already becoming more attractive as environmental concerns become more influential and as material costs begin reflecting externalities and true environmental costs of the construction industry. Another incentive to consider deconstruction is the increasing difficulties and limitations with disposal and landfilling, as well as the possibility of regarding waste as a lost resource and potential source of profit. The issue of limited supply of salvaged materials due to limited deconstruction is slowly being addressed by the development of standards for deconstruction as well as the increasing costs and difficulty of traditional methods of CDW disposal. In addition, due to the impact of green building rating systems such as LEED and construction waste legislation becoming more widespread, more designers are being encouraged to consider deconstruction strategies. Because of a new focus on contractors to manage waste on site, more members of the construction industry are becoming more aware of the value of extracted components (Gorgolewski, pp. 2-13).

In spite of these natural incentives, businesses will continue to operate in the least costly manner, regardless of environmental impacts, unless there are legal or economic incentives. There are three major approaches to encourage deconstruction: increasing education and awareness of builders, designers, and clients; creating economic incentives for owners and occupiers; and passing legislation to limit CDW, such as tax incentives, elevated disposal cost depending on material, or a take-back scheme in which manufacturers must dispose of the material in an environmentally friendly way (Sassi, p. 9). Although there is a variety of approaches, rules, and regulations by country, very few have specific waste management legislation. Denmark and the Netherlands are among the few that have attained high CDW recycling levels. The Danish government passed a law in 1996 prohibiting the dumping of reusable building waste (Languell, p. 29), including specific regulations for sorting waste to reuse material. As a result, Denmark has achieved 81% recycling in the early 2000's. The Netherlands recycles 95% of its CDW after drawing up a building site waste plan for 1990-2000. Since 2001, it is forbidden to dump reusable, combustible CDW in a landfill. The Netherlands has also launched a program for industrial, flexible, and demountable building, aimed at increasing DfAD (te Dorsthorst and Kowalczyk, pp. 72-77). In the rest of Europe, current and proposed policies affecting the construction and demolition industry include the following: a European waste catalogue, community-wide waste management plans, national waste and sustainability strategies, and proposed European lists and tests that would assist in developing a waste management system in the EU. Current and proposed fiscal measures include a landfill tax and credit scheme, aggregate tax, sustainability fund, and funds for research and development from both public and private sources (Hurley, et. al., p. 143).

In the US, the EPA started a program in 1992 called Design for the Environment, forming voluntary partnerships with industry, universities, research institutions, public interest groups, and other government agencies. With this program, they attempted to change current business practices and reach industries and people that have the power to make major engineering and design changes in construction. Since then, two major changes in federal policy have created major opportunities for deconstruction: the demolition of public housing under the so-called Hope VI programs, and the conversion of closed military bases across the US (Languell, pp. 39-40).

One study analyzing the demolition industry in Ankara, Turkey, sheds light on the marketing techniques and types of buyers for recovered materials that can be extrapolated to other regions. In Turkey, buildings are generally made of a reinforced concrete structure, plastered and painted masonry walls, and timber window framing. Floor finishes are made of terrazzo or ceramic tiles, and plumbing pipes and electric conduits are embedded in masonry walls. Such materials are not easy to deconstruct, and therefore the type and amount of recoverable materials is limited. In this region (and elsewhere), it is necessary to promote DfAD through raising public awareness, with greater responsibility falling on institutes of higher learning. There already exists a market for recovered building materials in all major cities in Turkey, but public opinion would support design for deconstruction to greatly increase and improve this already profitable market, particularly by improving the quality of the merchandise and attracting more sophisticated clients. Cooperatives, which play a major role in supporting many rural and industrial sectors in Turkey, could also benefit the demolition and deconstruction industry. These associations could help members maintain a catalogue of available materials at each salvage yard, promote specialization of yards in certain components or fixtures, and step in to collect and distribute the building material from demolished buildings. Currently, all but one yard in the city sell al types of recovered material, with little specialization. A cooperative could make purchase both more convenient and accessible to the buyer by putting an inventory and itinerary online (Elias-Özkan, pp. 132-133).

In the US, the biggest obstacles to deconstruction are money and time. One possible incentive is to increase landfill tipping fees and to impose volume-based fees to encourage deconstruction. Enforcement of hazardous materials regulations for asbestos and lead would ensure that small-scale demolition projects do not benefit from an economic advantage by avoiding costs associated with management of hazardous materials. Because deconstruction takes more time than demolition, permitting for deconstruction should allow for more time delay than for demolition permitting. Another option is to impose a mandatory waiting period on demolition permits to make it more comparable to deconstruction. In addition, permit fees should be waived for deconstruction, and demolition fees should be based not on the value of work or the number of stories (which is an arbitrary measure), but on the projected volume of waste. These fees can then be rebated upon proof of the diversion of waste materials to recycling or reuse (Guy and McLendon, pp. 21-22). Other disincentives for demolition and waste disposal may include a mandate that all demolition company employees attend deconstruction seminars, required before the issuing a demolition permit. Contractors, who are required to attend continuing education courses to maintain their licenses, could take similar courses (Languell, p. 41).

Besides encouraging deconstruction over demolition, it is also necessary to encourage the market for reclaimed materials. On-site sales of salvaged materials can drastically reduce overhead due to off-site handling costs and reduce on-site time for deconstruction, because less time will be spent processing materials (Guy and McLendon, p. 21). To induce a greater disparity in the price between new and salvaged materials, such as timber, it is possible to make manufacturers responsible for end-of-life disposal costs of all new materials. This responsibility would be reflected in higher new material costs, providing a greater incentive to purchase reclaimed timber (Languell, p. 46). To help markets become less volatile, a network of storage and distribution centers, as well as product demand, is required. Such a network has already proven successful for reuse and recycling of architectural and ornamental components, bricks and blocks, second-hand furniture, and recycled aggregates (Hurley, et. al., p. 145).

Other potential incentives and policies that merit further thought include: identifying good structural candidates for deconstruction and making a database of this information available to the public; requiring deconstruction to be considered before demolition; converting public housing demolition programs to deconstruction programs; requiring minimum content of used building materials in public construction and renovation projects; allowing preference to project bids that achieve deconstruction targets; and developing a network for deconstruction service providers and advocating known "green" builders (Languell, p. 86).

7.0 CASE STUDIES

7.1 OPEN_1: AN ADAPTABLE HOME SYSTEM

An open building approach is one that recognizes both stability and change as realities in the current built environment. Key concepts of open building include acknowledging that the built environment undergoes constant transformation and an ongoing design process, and that users, inhabitants, and multiple other participants can make design decisions as well as professionals (Edmonds and Gorgolewski, p. 2). Based on the open building approach, Bensonwood Homes in New Hampshire, a design-build residential building company, has developed a system called Open-Built, which was created as a reaction to the low standards of the status-quo in the design-build process. The goals of the Open-Built system is to improve consistency, quality, and efficiency in home building; to reduce the cost and complexity of custom architecture; and to reduce on-site construction time and waste of materials. Since 2000, Bensonwood homes has been building Open-Built homes using a library of hundreds of standard components. A standard package includes a timber frame, roof system, exterior wall system, and ceiling system using Open-Built components ("Open-Built: The New Foundation for Construction," p. 2).

The ten major principles used in designing these homes are as follows ("Open-Built: The New Foundation for Construction," pp. 2-4):

1. Homes should be unique and adaptable.
2. Disentangle: a well-organized design and separation of components of different life expectancy allows easier alterations and replacements.
3. Precise positioning: well-defined three-dimensional measurements and a positioning system allows for efficient decision-making and waste reduction.

4. Build it twice: a routine part of the design process should be the creation of a three-dimensional "virtual construction" of the building to resolve potential issues in the computer space first.
5. Design assemblies and assemble designs: An Open-Built home is assembled from pre-designed components, assuring quality, variety, cost, and fit. A component library eliminates the need for standardized home plans, and the client still gets a custom home for a "standard home" price.
6. Involve everyone: the design process involves the clients, architects, engineers, and builders, each with respective roles in the design process.
7. Build systems, don't supply raw materials: factory-built systems ensure quality and consistency in the final product.
8. Modular components, not modular homes: use manufacturing expertise for modular components such as SIPs, plumbing systems, and electrical systems.
9. Build in the factory, assemble on site: the shop is the best place to achieve quality control, and shipping components is equally efficient as shipping raw materials, allowing reduction of on-site construction time as well as construction waste.
10. Non-proprietary: Open-Built is the equivalent of open-source software, that is, an open-access system designed to be shared with architects, builders, and manufacturers.

Bensonwood took open building a step further when it decided to collaborate with MIT to build a prototype of an open building based on Stewart Brand's six layers of building separation, called OPEN_1, encompassing the concept of layers, disentanglement, and flexibility (Dey, p. 58). The design focuses on each sub-system, physically separating it from the others. For example, if wiring and piping is embedded in the walls, access is provided in the wall surface to allow upgrades and repairs without the need to alter the building structure. The design is based on pre-assembled components and as much off-site pre-fabrication as possible for each system (Guy and Ciarimboli, p. 29). The home design is organized into a virtual three-dimensional grid that is expressed in the computer-based catalogue of standardized components and underlies the floor plan, allowing the ability to create custom floor plans based on an organizing grid (Dey, p. 60). See Figure 17 for an exploded view of the OPEN_1 model.

Figure 17: Exploded Axonometric View of the OPEN_1 House (Guy and Ciarimboli, p. 29)

Each layer of the home was designed for maximum adaptability and deconstructability, based on each of the six S's. Regarding the site, the prototype was constructed on a slope with a concrete basement foundation, allowing better access to MEP systems. The structure itself is based on the use of pre-fabricated wood-framed panels with sheathing and finishes within the timber frame support. Panels were constructed in modular units with cellulose insulation and sheathing applied in the factory, with final building assembly taking place on site. Both the exterior and interior were designed on the structural grid system. The first floor was constructed with open-web steel trusses, and upper floors were built with the Open-Built Spacer, which creates a space between the floor structure and the ceiling below for ductwork and utilities. The roof system used pre-fabricated SIPs, which can be cut into panels again when disassembled (Guy and Ciarimboli, pp. 29-30). See Figure 18.

Figure 18: Assembly of Interior Walls and Ceiling Panels (Dey, pp. 60-61)

For the structural skin, windows were designed with installation details that allow easy removal and replacement while retaining the surrounding framing. Wall panels are "furred out" with a furring element that allows wiring to run vertically and horizontally beside the wall framing (rather than within a cavity). To accommodate the building services, an open raceway, accessible by a removable cover, was built into the base of the interior walls of the first floor, allowing placement of wiring without entanglement or exposure (Guy and Ciarimboli, p. 30). In higher floors, access is through the removable wood ceiling panels. The services are allocated into specific zones to allow for parallel, rather than sequential, installation of systems. The services make later modifications easier with so-called "plug-and-play" components, such as crimpable plumbing unions, PEX plumbing lines, and quick-connect electrical unions (Dey, pp. 59-63).

7.2 ECO-RENOVATION OF AN EXISTING HOME IN NEW ZEALAND

An example of renovating a residence using DfAD principles is the major redesign and "eco-renovation" of a home in Wellington, New Zealand in 1998. Renovation of the home incorporated deconstruction and waste reduction practices in the redesign approach, using components and materials recovered from the original house whenever possible. The clients' goal was a home that was at once environmentally responsible, aesthetically pleasing, comfortable, and life-enhancing, but that was also built within the standard budgetary constraints of a normal home. The existing home was originally built in the 1950's under traditional construction practices. It was built with quality materials, but poorly planned and crudely built (Storey, p. 105).

The most difficult aspect of this project was finding a building contractor who shared the same goals of sustainability while still working at an affordable price. The builder ultimately employed had a good history with conventional building work. The designers used carefully prepared contract documents as well as verbal dialogue with the contractor to ensure his compliance with the design intentions. Despite spending extra time and effort for this communication, they only met with limited success. The contractor sought to avoid extra work or costs associated with the sustainable aspects of the project and did not instruct his workmen or subcontractors of the contractual requirements. It was up to the architects and the clients to inspect the work and identify deviations from the specifications. This process required extra time and effort from the architect until near the end of the project, when the contractor realized it was easier to comply and allowed a slight improvement. Overall, however, it was difficult to obtain this compliance due to a constantly changing workforce, numerous subcontractors, and an uncommitted main contractor (Storey, p. 106).

The major design strategy was to use as many of the existing building components as possible while still complying to the New Zealand Building Code requirement of ensuring a 50-year minimum life expectancy for a remodeled house (the New Zealand Building Code is one of the few building codes that has such a stringent durability clause). All structural building materials, whether they are new or reused, must comply with this requirement in the context of their specific use. Cladding materials must have a lifespan of 15 years and all other non-structural materials must last for 5 years. To ensure compliance with these requirements, a structural engineer examined all reused structural members and an architect examined all other components (Storey, p. 106).

The design strategy when reusing doors and windows was challenging, but not overly restrictive. Doors and windows have a major impact on the visual coherence of the building, so great care was taken to integrate old with new to form a unified appearance for each of the spaces while still seeking to appear modern. External painted timber framing components were the obvious unifying factor, but it was also necessary to retain a similar scale and proportion for new components to achieve a cohesive integration. The result was three different conditions for doors and windows: original elements retained in place, existing elements reused, and new elements used (see Figure 19). Each condition is distinguishable in the final home, but only one category is used within any given space for visual unity. All existing windows except one, all existing external doors except one, and all interior doors except three were reused. New windows and external doors were only necessary in a few spaces. All interior windows, door sills, linings, and architraves had to be replaced due to damage of the original components during extraction. Interior doors were paneled to visually unify them with the new doors. Financially, the reuse of the existing window and door components generated significant cost savings, but interior door reuse only allowed marginal savings (Storey, pp. 107-108).

Figure 19: (From Left to Right) Reused, Retained, and New Windows (Storey, p. 108)

The roof design was dominated by the clients' concern with the lack of headroom of the existing ceiling. Existing conditions were a minimally angled monopitch with bituminous felt finish on timber beams and flat ceiling below. Architects wished to retain the existing sound structure and add a new weather skin above and supported by the existing roof. This strategy meant pivoting the roof structure on the external walls and building up the central structure wall. Contractors expressed hesitation due to potential damage to the roof during pivoting, and none would provide a quote for this part of the work. Architects had to redesign the roof, as the original design would have resulted in a significant cost premium. Instead, the existing roof was left in place with a new metal weather skin on top of battens. The flat ceiling was removed and a sloping ceiling incorporated to follow the underside of the existing beams. During this process, the existing ceiling battens were acceptable to reuse for one-third of the building. The benefits of this redesign include cost savings, an increased ceiling height satisfactory to the clients, main living spaces that were more open to the sun, a system that muffles noise on the metal roof, increased internal insulation value of the roof, and mitigation of roof overheating by a double roof and ventilated cavity (Storey, pp. 109-111).

None of the existing fittings and fixtures were reintegrated in the renovated house. Instead, they were removed and given to the clients, who tried to reuse or resell them. For example, the previous kitchen countertop now serves as a study desktop, and old cupboards and worktops serve as workshop benches and shelving in the garage. Other fittings were disassembled and the resulting timber stored for future use. Designers planned to remove cedar weatherboard siding on one side of the house to allow for the extension and then reincorporate it into the new wall. They had predicted a 70% recovery rate, but only 40% was achieved, mostly because the builder did not use best practices to maximize recovery. To prevent this issue, the architect should have emphasized best practices at the beginning of the operation. It was also difficult to recover existing gypsum wallboard linings due to damage incurred during construction. Most was sent to a landfill, along with small amounts of concrete, asbestos-containing tiles, preservative-treated timber, and general rubbish. Most of the excavated material was redistributed on site, consisting of 100-120 m^3 used on site and 20 m^3 removed off site. The builder's attitude for this task was generally unhelpful, as he neglected careful placement, resulting in arguments with the architect and clients (Storey, pp. 111-113). A summary of the material and component reuse and disposal for this project is shown in Table 5.

Table 5: Disposal Methods Employed in Eco-Renovation (Adapted from Storey, pp. 115-116)

Material or 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 low grade fill
Timber	100% exterior wall framing reused 50% interior wall framing recovered and reused 40% of ceiling battens recovered and reused All timber not reused or stored was used for fuel in wood stove	High grade timber with little sign of deterioration after 50 years of use Significant amount of lower grade timber used in interior walls or as ceiling battens had warped badly and could not be reused

External timber doors and screens	100% recovery: 66% in house 33% retained for future use	Likely that unwanted door will eventually be sold to a building recycler
External timber windows	100% recovery, of which: 92% reuse 8% retained for future reuse	Likely that unwanted window will be eventually sold to a building recycler
Asbestos roof lining board, interior floor and exterior decking tiles	Bagged in two layers of polythene and landfilled	Currently the only approved method of treatment available
Kitchen cabinets and workshops	Recovered, adapted, and reused as work benches in garage One section of worktop adapted and reused as desktop	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 much higher recovery rate should have been possible
Timber floorboards	95% recovery of removed material, of which: 90% reused on site 10% damaged during recovery, but retained for future use	Flooring is high quality native timber 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
Hardware	Sent to metal recycler	Low quality items in poor condition after 50 years of service No market other than metal salvage
Concrete	Landfilled	Small quantities remained No recovery program in Wellington
Preservative treated timber	Landfilled	Small quantities remained No other method of disposal available
Timber cabinets	Given to owners, who disassembled and retained timber for future use	Timber is valuable native hardwood

7.3 MEC OTTAWA: REUSE OF DISASSEMBLED MATERIALS

An example of designing a new building from reclaimed materials is the Mountain Equipment Co-op (MEC) store in Ottawa, Canada (see Figure 20). MEC is an established retail company supplying outdoor equipment in several locations in Canada, many of which address green building issues. The company prides itself on its reputation for sustainability by integrating environmental and social considerations in its activities. Examples in other store locations include green roofs, composting toilets, day lighting systems, recycled and reused materials, efficient heating and cooling, and other energy-saving measures unusual to retail buildings in the regain (Gorgolewski, p. 6). The MEC vision statement is as follows: "Mountain Equipment Co-op is an innovative, thriving cooperative that inspires excellence in products and services, passion for wilderness experiences, leadership for a just world, and action for a healthy planet," ("Mountain Equipment Co-op's Green Building Approach," p. 1). MEC's members and stakeholders, therefore, expect the company to take a consistent approach to sustainability issues and to live up to its environmental ethic ("Mountain Equipment Co-op's Green Building Approach," p. 2).

Figure 20: MEC Ottawa Store (Gorgolewski, p. 7)

The goals for the Ottawa store was set by these preexisting standards. Performance targets for the new building were set by the client (MEC), and other goals were dictated by the design teams goal of achieving a LEED gold rating. Selection of materials was driven by the goal of using the maximum possible amount of reclaimed materials (Gorgolewski, p. 7). Designers were also driven by an effort to make MEC stores C-2000 compliant. The C-2000 Program for Advanced Commercial Buildings supports the development of advanced energy efficient and sustainable building practices in Canada. C-2000 buildings are at least 50% more energy efficient than traditional buildings. Through assistance from the C-2000 program, the design team for the Ottawa store used an integrated design process (IDP) for a more comprehensive approach to sustainable building, as opposed to an item-by-item approach used in the construction of previous stores. IDP brings forward sustainable building expertise at the concept development stage and encompasses the whole design team, including architects, structural and mechanical engineers, landscape architects, HVAC experts, and contractors. Each element of the design is developed with the other aspects in mind, since the elements of the building are interdependent and it is necessary to think of them as a system rather than a collection of elements. During the design process, members of the design team would typically meet for a series of five or six meetings during the first phase of design, examining each major building system in half day segments before later reconvening to share models and go through rounds of iterations. This method is different from the traditional design process, in which each team member works in near isolation. This system instead allows collaboration and sharing of expertise. As a result of implementing IDP, MEC's Winnipeg and Ottawa stores were the first two retail buildings in Canada to comply with the C-2000 Green Building Standard ("Mountain Equipment Co-op's Green Building Approach," pp. 3-4).

In general, MEC design teams consider four main categories when considering construction initiatives: reduce, reuse, recycle, and rethink. In particular, when considering each aspect of a new building, they ask themselves the following ten questions ("Mountain Equipment Co-op's Green Building Approach," p. 5):

1. Can we do without it?
2. Does it have less embodied energy than a traditional component?
3. Does it have less embodied pollution than a traditional component?
4. Is it more energy efficient than a traditional building?
5. Is the component locally manufactured?
6. Does it have a longer life cycle than a traditional component?
7. Can it be recycled, and does it contain recycled content?
8. Does it reduce the amount of waste to be landfilled?
9. Is the material a naturally occurring, renewable, and sustainable resource?
10. Does it raise awareness about environmental issues?

The MEC Ottawa store, a 2600 m^2 facility, was completed in June 2001. It is a heavy timber structure on the ground floor and a steel structure on the second floor, with open-web steel joists supporting a screw-fastened steel roof with mineral wood insulation. The building has wall cladding composed of wooden I-joists clad with locally salvaged plywood sheathing with recycled cellulose insulation. Various materials were used for exterior cladding for aesthetic reasons, including corrugated steel panels for durability, fiber cement boards in areas where vines would grow, and rock excavated from on site (Gorgolewski, p. 6).

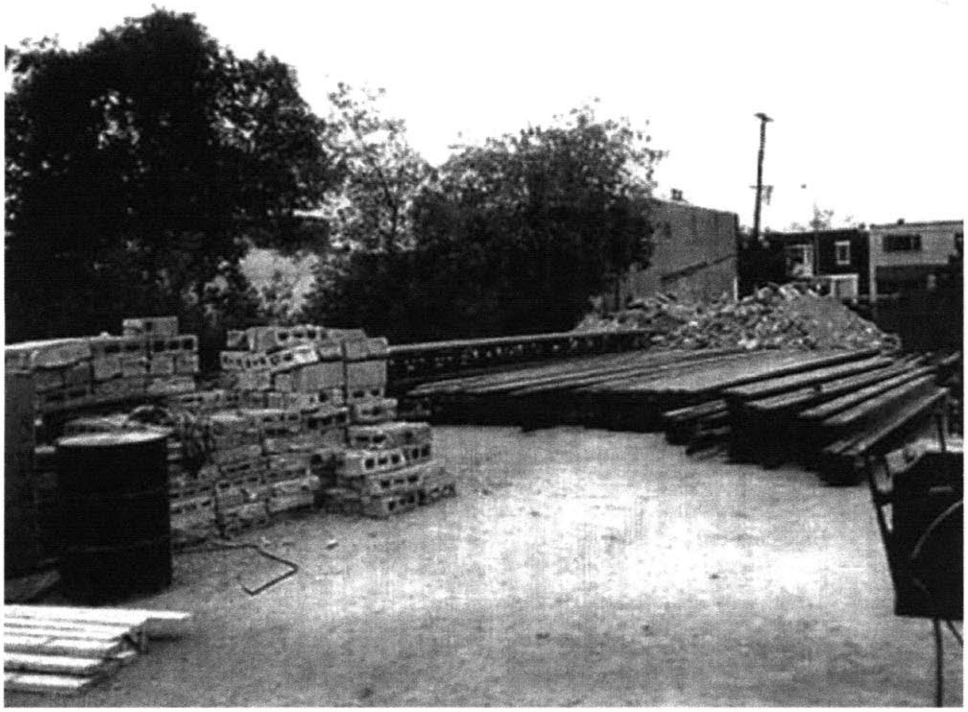


Figure 21: Materials Storage for the MEC Ottawa Store After Deconstruction (Gorgolewski, p.7)

The most relevant aspect to DfAD is the use of key structural components from an old building for a new building on the same site, resulting in reduced consumption of new materials, as well as other economic and environmental benefits. The previous building on the site of the MEC Ottawa store was a 40-year-old, one-story, 1000 m^2 former grocery store with steel columns, beams, and open-web joists. The challenge was how to integrate these components functionally and efficiently into a new, two-story building in a way that is best suited to its intended purpose. It was not possible to reuse the original structure in place, so it was therefore carefully deconstructed to reuse any salvageable components. The original frame was not damaged, though some open-web steel joists were distorted and the steel roof deck damaged beyond repair from removing welded connections; these components were instead recycled as raw steel. The salvaged components were labeled and stored off site (as there was no room on site for stockpiling, see Figure 21), and required modifications were made in the shop. In total, 75% of the structure and shell (by weight) of the old building was incorporated into the new building, including steel columns, beams, and most open-web steel joists. The remains were sorted and sent for reuse at other sites when appropriate, or for recycling. Builders held an open house for demolition contractors and end-market users to view, identify, and buy some of the unused salvaged materials (Gorgolewski, p. 7).

To reuse these components, it was necessary for the designers to establish their structural characteristics. The design team and contractor had access to the original specifications and drawings, which they used to label all the steel components as they were dismantled. All structural members were inspected for damage and assessed by a structural engineer to confirm their capabilities. The designers decided to integrate the components into the new building in such a way as to support similar loads to their original use; thus, engineers were able to demonstrate compliance with building code. For example, the original building was designed only to withstand a snow load on the roof (not another floor), so these materials were used on the top floor, above a new first floor. Structural gridlines and columns were located to accommodate the existing foundations. The existing concrete floor slab and terrazzo finish were also retained. The elements of the new structure were made of locally reclaimed Douglas fir columns and beams, which were chosen for aesthetic reasons, their low embodied energy, and high reclaimed content. This reclaimed timber was sized, inspected, and graded to fit well with the steel structure above it. The final structure included a two-story atrium space and interior climbing wall feature. The main elements of the primary structure, including columns, beams, and 50% of the open-web steel roof joists were reused components, which were supplemented by new steel joists and a new roof deck. The load requirements for the new roof were virtually unchanged (Gorgolewski, pp. 7-8).

The MEC team encountered some resistance from three or four bidding contractors because of the lack of familiarity and challenges associated with building with reclaimed components, resulting in a natural inclination to big higher. The lowest bidder, however, was interested in the concept and eager to undertake the challenge. To assist the contractors, an open house was held where builders could view materials before bidding. The MEC team expected about 10% additional costs over a traditional building to achieve their environmental goals. The total building and site development costs were $2.9 million (CA), including consulting fees. This cost was about $\$1100/\mathrm{m}^2$ of the building, about 13% higher than typical "big box retail" building costs in Ottawa, mostly due to higher thermal and environmental standards, and not necessarily the material reuse, which may have actually saved money (Gorgolewski, p. 8). Table 6 summarizes the reused elements of the building.

Table 6: Reused Elements for the MEC Ottawa Store (Gorgolewski, p. 8)

Element	**Reused from existing building on-site**	**Reused from other locations**
Substructure	Existing foundations were reused by using the same structural grid; concrete removed from the site was crushed and used as backfill, slab underlay and parking lot fill	
Primary structure	Primary steel structure from the original building was reused on the second level of the new building	300 mm square Douglas fir structural components salvaged from old log booms from the St Lawrence River were used in the ground floor structure
Roof	Open-web steel joists from the original building were reused in the new roof structure	
Wall	Rock salvaged from the site was used for cladding on the north face; blocks from the original building were used to create a two-hour fire-rated party wall on the east side of the building	Salvaged plywood was specified for external sheathing of walls, but was not available at the time of construction
Floor	Existing floor slab with terrazzo floor was used for the new building	Floor finish for the second storey was a structural wood deck using salvaged Douglas fir
Other		Office and staff rooms were furnished with used or recovered furniture; salvaged wood was used for sun shades and other details

The major indicators that MEC uses to measure results of its green building endeavors are energy efficiency, embodied energy, landfill diversion rates, and CO_2 emissions. The business itself benefits greatly from implementing green building design, starting with lower operating costs. As a proportion of total operating costs, the MEC green buildings spend 15% on mechanical systems as opposed to 25% for other buildings. They also benefit from enhanced public image and reputation, generating positive customer and member response, strengthening relations with members, and provoking extensive media coverage. In addition, employee morale in newer, greener stores is especially high, provoking fewer complaints regarding health and safety. The green stores provide an improved shopping environment for consumers, including improved indoor air quality and natural lighting. Finally, MEC enjoys easy market access, as city representatives are generally very receptive when MEC approaches them about establishing a nearby business. Thanks to their reputation as a green company, it is much easier to obtain permitting for new buildings and to expand the business ("Mountain Equipment Co-op's Green Building Approach," pp. 6-7).

7.4 LESSONS LEARNED

From these three cases, project teams learned valuable lessons about the challenges and best practices for putting DfAD principles into action. The OPEN_1 team learned the most effective way to assemble a home using modular units. They found that a shop is the most appropriate place to build components, and often an appropriate place to assemble them as well, as opposed to on site. This method of pre-assembly and pre-finishing in the shop worked well and saved time on the site. Some time constraints, however, kept them from completing certain components in the shop and resulted in inefficient work on site, with subcontractors getting in each other's way. In the future, they would allow more time to finish component assembly in the shop. They also learned the benefit of designing all construction details virtually in a computer model before starting fabrication, because elements with detailed shop drawings went together quickly and smoothly. They also realized that in the future they should allow more "wiggle room" in the design tolerances for intersections between components. These lessons are going into use for the second prototype, OPEN_2, currently under construction (www.openprototype.com/projects/open1/blog.html).

In the eco-renovation of the home in New Zealand, the team learned that the attitude of both the client and the contractors is key to success with deconstruction and reuse recovery. Most of the difficulties in the project, such as the low recovery of cedar siding and resistance to the roof design, were attributed to the indifference of the contractors to the environmental goals and an unwillingness to try new methods. The work was of relatively high quality once the contractor was committed to the course of action, and diligent observation by the architect and clients encouraged the contractor to adhere closely to the specifications than he would have liked. The lesson learned here is to employ contractors sympathetic to the DfAD objectives of the clients and architects. The design team also suggests that Wellington, NZ introduce a "Green Builder" program like that in Austin, Texas in 1992. In this free program sponsored by the City of Austin, builders were encouraged to learn about and adopt sustainable construction practices. Registered Green Builders could then rate the houses they build under a rating system controlled by the city and obtain a marketing edge over their rivals, thus providing education support and business incentives for DfAD and green design (Storey, pp. 114-115).

The design team for the MEC Ottawa store also learned several valuable lessons about designing with reclaimed structural components. Deconstructing can be economically viable for the client, but adds a new level of complexity and changes the design and construction process. Reclaimed materials do not necessarily arrive at the right time, in the right amounts, or in the right dimensions. Using materials available from the same site, however, eliminates some of the unknowns and allows for the development of a design based on availability, such as reusing foundations based on the spans of the original structural components. A willingness to adapt the design throughout the process is necessary; for example, some elements of the steel roof and timber floor system were redesigned three times to accommodate available materials, increasing the design fees. It is also important to analyze and establish the structural characteristics of reclaimed materials, using the original drawings and specifications, structural tests, or professional graders. In general, it is easier and safer to reuse components for the same original purpose. In particular, hot rolled steel and large timber components are easier to reuse than lightweight open-web steel joists which are more susceptible to damage and less cost effective. Though many contractors are nervous about bidding for unusual projects, the role of the clients is crucial in such a project—they must be committed and willing to adapt the process and accept risk. Reusing materials is site-specific and time-dependent, subject to space and time constraints and design requirements that can influence the overall project feasibility (Gorgolewski, pp. 11-12).

Several important factors contributed to the success of the MEC Ottawa project. The green changes required little behavioral change of the managers and employees of the store, who thus embraced the sustainable aspects. The project had an internal champion in the project manager, as well as receptive Board members who made the project possible. They also benefited from financial assistance through the C-2000 program and the sharing of knowledge and information between MEC and various other local organizations. Their continued success is attributed to public acceptance, which is increasingly favoring green and sustainable projects ("Mountain Equipment Co-op's Green Building Approach," p. 8).

8.0 CONCLUSION

Deconstruction and reuse of buildings has the potential to provide substantial environmental benefits through material savings at building end of life. The best way to facilitate this is through Design for Adaptability and Deconstruction, which embodies separation of building layers (structure, skin, services, space plan, and stuff), accessibility of components and connections, and modular forms, while increasing worker safety during deconstruction procedures. Although it is possible to reuse most common building materials, timber and steel are preferable because of their ability to form part of a closed loop material cycle. Implementation of best design practices, however, can improve the potential of most materials for salvage and reuse.

Although deconstruction is steadily increasing in popularity, practical and economic limitations still pose barriers to implementation, such as a lack of an established market, increased time and cost to deconstruct, and hesitance of builders to try new methods. Likely methods of improving feasibility include general education and awareness, legislation requiring greener construction, economic incentives for deconstruction, and disincentives and penalties for traditional demolition. Deconstruction and DfAD are a promising market with the potential to restructure the way buildings are made and demolished.

REFERENCES

Chini, Abdol R., and Shailesh Balachandran, "Anticipating and Responding to Deconstruction through Building Design," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 175-188.

Crowther, Philip, "Design for Buildability and the Deconstruction Consequences," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 6-14.

Dey, Andrew, "Reinventing the House," *Fine Homebuilding*, October/November 2006, pp. 58-63.

Durmisevic, Elma, and Jan Brouwer, "Design Aspects of Decomposable Building Structures," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 81-103.

Edmonds, Jordan, and Dr. Mark Gorgolewski, "Design for Adaptability in Steel," Department of Architectural Science, Ryerson University.

Elias-Özkan, Soofia Tahira, "An Overview of Demolition, Recovery, Reuse, and Recycling Practices in Turkey," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 128-138.

Giglio, Francesca, "Controlling Environmental Impacts in the Dismantling Phase," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 62-69.

Gorgolewski, Mark, "Designing with Reused Building Components: Some Challenges," *Building Research & Information*, Vol. 36, No. 2, 2008, pp. 175-188.

Guy, Bradley, and Sean McLendon, "Building Deconstruction: Reuse and Recycling of Building Materials," Center for Construction and the Environment, University of Florida, 2000.

Guy, Bradley, and Scott Shell, "Design for Deconstruction and Materials Reuse," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 189-209.

Guy, Bradley, and Nicholas Ciarimboli, "Design for Disassembly in the Built Environment; A

Guide to Closed-Loop Design and Building," http://your.kingcounty.gov/solidwaste/greenbuilding/documents/Design_for_Disassembly-guide.pdf, accessed on April 22, 2010, Hamer Center for Community Design, Pennsylvania State University, 2007.

Hinze, Jimmie, "Designing for Deconstruction Safety," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 210-217.

Hurley, James, et. al., "Design for Deconstruction – Tools and Practices," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 139-174.

Languell, Jennifer L., "Implementing Deconstruction in Florida: Materials Reuse Issues, Disassembly Techniques, Economics and Policy," Florida Center for Solid and Hazardous Waste Management, 2000.

Macozoma, Dennis S., "Understanding the Concept of Flexibility in Design for Deconstruction," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 118-127.

"Mountain Equipment Co-op's Green Building Approach," Five Winds International, April 8, 2003.

Mueller, A., and U. Stark, "Recycling of Clay Brick Debris," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 36-46.

Ochsendorf, John (MIT Department of Civil and Environmental Engineering), "Sustainable Design: The Construction Industry," presented at 1.819J *Design for Sustainability*, Massachusetts Institute of Technology, September 17, 2009.

"Open-Built: The New Foundation for Construction," Bensonwood, http://bensonwood.com/innovation/obbrochure.pdf, accessed on April 22, 2010.

Reinhold, M., and A. Mueller, "Lightweight Aggregate Produced from Fine Fractions of Construction and Demolition Waste," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 27-35.

Sassi, Paola, "Defining Closed-Loop Material Cycle Construction," *Building Research & Information*, Vol. 36, No. 5, 2008, pp. 509-519.

Schultmann, Frank, and Otto Rentz, "Resource-Constraint Project Scheduling for Deconstruction

Projects," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 47-61.

Seemann, A., et. al., "Cost-Effective Deconstruction by a Combination of Dismantling, Sorting, and Recycling Processes," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 15-26.

Storey, John, "Reconstructing Deconstruction," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 105-117.

te Dorsthorst, Bart J.H., and Ton Kowalczyk, "Design for Recycling," in Abdol Chini and Frank Schultmann (eds.), *Design for Deconstruction and Materials Reuse*, International Council for Research and Innovation in Building Construction, Karlsruhe, Germany, 2002, pp. 70-80.

Webster, Mark D. (Simpson Gumpertz & Heger), "Sustainability," presented at 1.819J *Design for Sustainability*, Massachusetts Institute of Technology, November 12, 2009.