

Design for Deconstruction and Materials Reuse

Authors: Bradley Guy, Center for Construction and Environment, Gainesville, Florida;
Scott Shell, Esherick, Homsey, Dodge & Davis Architecture, San Francisco, CA

SUMMARY

The building legacy of the 20th century has been one of waste and toxicity. The US EPA has estimated that the materials debris from building renovation and demolition comprise 25 to 30% of all waste produced in the US each year. Aesthetic conventions and economic factors that influence land use and buildings over long periods of time are not predictable by the building designer, but nonetheless, buildings can be built with the intention of adaptation and/or eventual removal. Design for deconstruction (DfD) can make use of the lessons learned from product design for environment, and from the obstacles encountered in the deconstruction of modern buildings. This paper will discuss principles of design for disassembly and lessons learned from deconstruction practice to propose guidelines for design for deconstruction as a form of environmentally responsible architecture. Although there are three fundamental building types - residential, commercial and industrial, this paper will focus on the generic levels of: whole-building, elements, components, sub-components, and materials.

KEYWORDS: building disassembly; deconstruction; design for deconstruction

INTRODUCTION

Design for deconstruction (DfD) is an emerging concept that borrows from the fields of design for disassembly, reuse, remanufacturing and recycling in the consumer products industries. Its overall goal is to reduce pollution impacts and increase resource and economic efficiency in the adaptation and eventual removal of buildings, and recovery of components and materials for reuse, re-manufacturing and recycling.

While the term is new, the foundation of DfD in the latter 20th century includes the work of N. J. Habakren on housing “support” systems, the Open Building movement, and the writings of Stewart Brand on adaptive architecture (Habraken, 1981; Kendall and Teicher, 2000; Brand, 1994). The International Style of the 1940’s, 50’s, and 60’s had attributes that are compatible with DfD such as modular construction, open floor plans, exposed structural and mechanical systems, and the use of concrete, stone, steel, and glass, i.e. recyclable materials. The dynamic technological and economic forces on commercial buildings in general have driven the development of modular and self-contained workstations, raised flooring systems, passive building integrated heating and cooling systems, and finish products reclamation programs. By these means, commercial building design has facilitated buildings that enable the disassembly of non-structural components. Whether there is reuse and recycling of the materials and components is a separate matter.

DfD expands upon these commercial building adaptive strategies to consider the whole life-cycle of the building, not just construction and operation, and maintenance and repair, but major adaptations, and eventual whole-building removal from the building's site. If overall "sustainable development" necessitates an increase in the reuse and recycling of urban land and first generation suburbs, the trends towards renovation and rebuilding to use existing land and infrastructure will only increase. It is clearly important to address the decisions made in the design and construction of buildings that will mitigate the "waste" that will be generated from building removals in the 21st century and beyond.

The economics of building-related debris disposal or recovery are driven by the relative and highly externalized costs of local debris landfill tipping fees and the presence of alternative markets for recovered materials. Two other very important factors are the labor costs and speed of the disassembly process itself. The efficiency of the deconstruction affects the direct costs of labor and equipment and also affects the time costs of a project where building removals are integral to new construction on the same site. Herein lie the opportunities and challenge for DfD. Of all of these factors, the efficiency of the deconstruction process and the cost-effectiveness of materials recovery with highest reuse or recycling value are most influenced by the designer. The choices and specific uses of materials, the connections between individual materials or components, the inter-relationships of building elements, the designs of spaces and whole-building structure, and even the ability to "read" the building are within the designer's control.

Lessons learned from the deconstruction of older buildings – well-known to practitioners in the field – include: the prevalence of materials that later became regulated environmental hazards; the entanglement of HVAC, electrical and plumbing systems within walls, floors and ceilings, that in turn cause damage during the construction process or impedes the separation of building components; the use of connectors that are inaccessible and cause damage in the process of separating materials; the weakening and de-stabilization of a building during the deconstruction process; matching the scale of the capabilities of a human laborer to the scale of building components; and how the building assembly process may render materials un-reusable or un-recyclable via drilling, nailing, and use of binders, adhesives, and coatings - especially hazardous materials.

Buildings designed for deconstruction will include the dis-entanglement of systems, and reductions in chemically disparate binders, adhesives or coatings - or thermal / chemical / mechanical means to better separate constituent materials. They will include a construction blueprint and also a deconstruction blueprint. They will have bar codes for materials so that the deconstruction contractor will have "handling" instructions for the material or component upon removal. These buildings will have self-supporting and self-stabilizing components, component accessibility designed in, and built-in tie-offs and connection points for workers and machinery. Most importantly, buildings that facilitate reuse and recycling will use non-hazardous materials, bio-based materials, high quality and highly recyclable materials. Design for deconstruction offers possibilities for the

design of buildings that will close the loop of materials-use in building, and help make the transition towards a zero-waste building industry. Two notable examples of recently constructed commercial buildings in North America that relied heavily on recovered materials and were also designed to facilitate future materials recovery are the Phillips Eco-Enterprise Center, Minneapolis, MN, and the C.K. Choi Building at the University of British Columbia, Vancouver, BC.

STATEMENT OF THE PROBLEM

The current state of deconstruction is severely limited by numerous factors. The main obstacles can be categorized as costs and time, with these being interrelated. The main opportunity factors for deconstruction are the prohibitive aspects of building materials disposal and the value of recovered materials in environmental and economic terms. Related to the economic costs/benefits of recovered materials are the quality of materials, either high-quality reuse, economically recyclable, or hazardous materials and materials and systems that become obsolete or are difficult to separate. Last but not least, buildings in modern society are typically not *designed* to be deconstructed.

There are many efforts to redefine production and achieve “eco-efficiencies” for consumer products through dematerialization, environmental management, design for environment, design for disassembly, and design for recycling. The design, construction, and maintenance characteristics of buildings are much different than consumable goods. Buildings are expected to have much longer lives, are greater capital investments, and involve a multiplicity of actors in design, construction, regulation, financing, insurance, maintenance, repair, occupancy, and ownership over time. Housing is often seen as a psychologically and culturally more significant artifact than an automobile for instance, although some automobiles might cost more than a modest home. The perception that housing should be malleable for adaptation and disassembly carries the perception of instability, incongruent with the notion of “home as castle.” Housing in fact does share many characteristics of consumable products depending upon the culture and urban location. According to Nakajima and Futaki, the average design life of wooden residential houses in Japan is about twenty five to thirty five years and the average actual life cycle is fourteen to seventeen years (Nakajima and Futaki, 2001). Changing cultural expectations, economic conditions regarding land use, and technological obsolescence, especially in regard to the energy-efficiency, are key functional and environmental stresses that cause the removal of buildings from use.

Buildings also have public impacts by their influence of urban form as the walls of urban streets and squares. The realization that these urban forms can be radically altered by the removal of buildings inevitably comes as a visceral shock when it occurs. Yet it does occur, and the lack of acceptance of the economics and fluidity of land uses in modern society has precluded extensive research into the realities of the need for design for deconstruction. While sustainable buildings should be designed for longevity and durability, this does not preclude the need for urban land-use diversification and flexibility via adaptation and deconstruction as well. On a global basis, transportation energy use impacts, sprawl patterns of land development, and the energy expenditure to

operate buildings all have a much greater environmental impact than the use of the materials in construction and resultant waste. Therefore design for deconstruction should be thought of as an important means to facilitate the resolution of these problems as much or more than solely to reduce building-related materials waste. If a sustainable built environment maximizes the ability to operate in a hierarchical and flexible manner, buildings will need to be multi-faceted storages of energy and materials, able to work within temporal and cultural currents of economic, social and natural environmental conditions.

A principle consideration for building adaptation is the spatial and temporal shearing inherent between the systems and materials in the building (Brand, 1994). This includes accessibility of components without conflicts between shorter-lived and longer-lived components. A key consideration for the end-of-life deconstruction of buildings is the connections between components, separation of materials into their base form, and the removal of nails, staples, paints. The contamination of base materials by the connecting devices, coatings, treatments, and the time requirements and damage resulting from the re-separation for salvage and reuse often make deconstruction extremely un-economic in a high-labor rate market.

One of the impediments for design for deconstruction is if the addition of elements that facilitate deconstruction cause an increase in first-costs of construction and clearly do not result in any near-term payback for the resultant future avoided costs or recovered value. In order for design for deconstruction to be effective, it will optimally not cause an increase in first costs and will be compatible with energy-use and other operational efficiencies. An example of an individual element that costs more than traditional practice but facilitates adaptation and energy-efficiency is raised flooring systems. Deconstruction is facilitated with this system by eliminating ductwork and placing wiring in a more accessible location in the floor plenum rather than an overhead plenum.

The single greatest criteria of design for deconstruction is that the cost of the final deconstruction does not exceed the avoided disposal costs plus the reuse or recycling value of the components and materials compared to a building not designed for deconstruction, (Billatos and Basaly, 1997). The economic feasibility of deconstruction in low disposal costs regions is therefore dependent upon the highest and best reuse or recycling value of the recovered materials and the efficiency of the deconstruction process.

GOALS OF DECONSTRUCTION

Deconstruction is a means to an end, it exists for the purposes of the appropriate recovery of building elements, components, sub-components, and materials for either reuse or recycling in the most cost-effective manner. Within the theme of design for deconstruction there is a distinction between designing for reuse and designing for recycling based upon components and types of materials used in a building. Deconstruction per se implies a high degree of refinement in the separation of building components. If a building were deconstructed to some hypothetical maximum it would

result in materials and components down to the level of their original form before construction. It is not practical to approach design for deconstruction at the whole-building level in this manner as some components, such as a window for instance, may be obsolete by the time the building is deconstructed and undesirable for reuse as exterior windows. The cost-effectiveness of recovering varied and small materials such as wiring, nails and bolts might also be negative. It is practical to consider that some materials are not readily reusable but can be recycled in a cost-effective manner. Based upon this perspective, it is possible to approach design for deconstruction as “hierarchical design” including; 1) design for reuse, 2) design for remanufacturing, and 3) design for recycling, with the intent to work within a series of constraints. These constraints are based upon the scale of buildings and components, temporal forces between differing building elements, functional and service requirements of the building, relative importance of building elements in terms of both first costs and life-cycle costs, the physical forces at work in a building, the chronology of construction and hence deconstruction of the building, and the components and raw materials of the building.

If one were to say that design for deconstruction dictates that the fewer number of parts to the building, the better, this criteria alone is insufficient. A very few pieces that required expensive and large equipment to maneuver and were not compatible to reuse as it, due to the difficulty in matching the component to the most viable new use, might not necessarily be cost-effective. If a material such as steel is used which is highly and effectively recycled, a highly refined deconstruction process is relative in this case since a building largely comprised of steel could be traditionally demolished and the steel separated from the heterogeneous debris through the use of magnets. The separation technology supersedes any special requirements to facilitate separation in the demolition phase. Since the energy costs of operating a building are a high proportion of the total costs of the building over its life, including construction and deconstruction, then designing for deconstruction in a manner that compromises the energy-efficiency of the building would not result in an environmentally or economically effective building overall. An example of this situation might be eliminating moisture and air filtration sealants to facilitate mechanical disassembly but not designing a substitute means to reduce moisture and air penetration through the building envelope. A substitute can be as simple as eliminating so called “flat roofs” which by their nature require highly sealed membranes to overcome the loss of gravitational force to facilitate rainwater runoff afforded by high-slope roofs. Therefore, the mechanical properties of gravity are substituted for chemical sealants.

The design for deconstruction problem can be described by asking certain questions such as:

- What parts of the building support other parts ?
- What parts of the building are self-supporting ?
- Where do specialized service inputs and outputs (telecommunications, electricity, water, gas, wastewater, supply and exhaust air) occur and how are these flow mechanisms constructed ?
- What parts of the building are subject to the most stresses from climate?

- What parts of the building are most subject to wear from human use and change from aesthetic preference ?
- What parts of the building are most subject to alteration based upon functional, economic, life-expectancy, or technological requirements?
- What parts of the building are comprised of components and sub-components based upon a complex set of functional requirements and what parts serve only one function and hence are comprised of relatively homogenous materials ?
- What parts of a building pose the greatest worker hazards in disassembly?
- What are the functional sizes of the principle elements and components of a building?
- What are the most expensive elements of a building, which have the highest reuse and recycling value and which impact the life-cycle efficiency of a building the most?

The goals of deconstruction will inevitably not be purely environmental and will most likely (until widespread legislation or economic restrictions on the disposal of construction-related debris) be heavily based on economic considerations. If manufacturer responsibility regulations expand to the building industry and associated products, design for deconstruction will serve the interest of recovering these elements on less economic terms. Deconstruction in the current state of the building industry has both opportunities and constraints as illustrated in Table 1.

Table 1 - Opportunities and Constraints of Deconstruction

| Opportunities | Constraints |
|---|---|
| Management of hazardous materials | Increase worker safety/health hazard |
| Reduction in landfill debris | More time required |
| Economic activity via reused materials | Site/storage for recovered materials |
| Preservation of virgin resources | Lack of standards for certain recovered materials reuse |
| Removal of inefficient/obsolete structures | Lack of established supply-demand chains |
| Reduction in site nuisance compared to demolition | |

Based upon possible conflicts between these factors it is important to consider the goal(s) of deconstruction when adding design for deconstruction to the many other aspects of sustainable building design and construction. Some goals for design for deconstruction might be:

- Rapid removal of building from building site.
- Reduction in environmental, health and safety stresses for workers.
- Easy access to components and materials, preventing damage in the deconstruction process.
- Reducing the costs of tools and equipment, which would include the variety of tools, and use of specialized operators.
- Eliminating the wastes by-products from the process.

- Materials recovery with high utility for reuse and recycling, i.e. require minimal additional processing for the highest return on investment in the deconstruction process.
- Eliminating toxicity in building materials which impacts responsible reuse and disposal and reduces reuse/recycling opportunities
- Increasing the longevity of a building such that deconstruction is actually less likely to occur via the inherent adaptability that design for deconstruction will convey upon the building.

PRODUCT DESIGN FOR DISASSEMBLY

Design for disassembly has been well-studied in the so-called consumer products industry, for example, for automobiles and computers. The automotive industry has been engaged in design for environmental activities for some time, for example General Motors, Chrysler and Ford formed the Vehicle Recycling Partnership in 1994 to develop the means to recover materials from automobiles for reuse and recycling (Billatos and Basaly, 1997).

Examples of design for disassembly tools for products that have been recently developed include: BDI Design for Environment, Boothroyd and Dewhurst, Inc.; Ametide, University of California at Berkeley; DFR-Recy, Helsinki University of Technology; EUROMAT, Technical University Berlin; LAsER, Stanford University; MoTech, Technion University, Israel; ReStar, Green Engineering Corporation (Otto and Wood, 2001). The number of tools and disparate locations of their development indicate a widespread interest in solving the problems of consumer products designed for disassembly.

Buildings have the distinction of being fixed in a bio-climatic location, unlike other consumer products. For any given location and type of building there are inherent functional, cultural, climatic, geographic and ecological forces that suggest certain forms, structure, envelop designs, and materials. Design for deconstruction should not look the same for all buildings even of the same types if there is any consideration for sustainable design and cultural appropriateness.

The Manufacturing Modeling Laboratory at Stanford University developed an end-of-life categorization tool called the End of Life Design Advisor (ELDA) which is meant to inform the design of products based upon their end-of-life (Rose, 1999). The tool is also meant to help determine the paths of materials upon disassembly, either for reuse, recycling, disposal or hazardous materials management.

A list of key characteristics used in the ELDA to determine a product's disassembly and materials reuse/recycling potential provides generic guidelines for design for deconstruction as a form of design for disassembly. The key characteristics used to measure disassembly potential are noted below:

- Functional complexity - high level of dependence between parts with multiple functions
- Number of materials
- Number of modules
- Number of parts
- Cleanliness of the product - amount of dirt accumulated by product
- Hazards and hazardous materials - components that need to be removed before further recycling
- Size
- Design cycle - time between new designs
- Technology cycle - time that product will be cutting edge before new technology makes it obsolete
- Replacement life - time that average user upgrades product
- Reason for obsolescence
- Wear-out life (Rose, 1999)

By testing the ELDA on a series of consumer products it was found that the number of parts, number of materials, level of cleanliness, design cycle, technology cycle and replacement cycle are important factors for end-of-life. Size, number of modules, hazards, wear-out life, reason for obsolescence, and functional complexity were not found to be critical to prediction of end-of-life strategies (Rose, 1999).

Because buildings have such a long life compared to many consumer products, and are considerably larger, heavier and more complex than consumer products, the design for disassembly principles that apply to products have to be modified. Buildings are also subject to the deprecations of weather and to the stresses of repair, maintenance and alterations that occur over time with differing ownership or functional needs. A key philosophical question is whether buildings should be intentionally designed for deconstruction in order to reduce the waste and inefficiency that occurs from depreciation in the performance of the building especially regarding energy use and technology-related components. Designing to allow a more rapid life-cycle for components that tend to become obsolete faster is one strategy proposed to maintain the quality and efficiency of products (Sindjou, 1999). While the remanufacturability and recyclability of components and materials would remain high with a rapid turnover it is not clear whether this would be the most environmentally sustainable strategy overall, except for those elements that directly impact the energy-efficiency of a building. Components such as mechanical and electrical equipment that are designed for deconstruction would possibly increase the efficacy of maintaining a building's structure and envelope as long as they do not require extensive modification of the structure and envelope when they are upgraded. In any case, the point of diminishing returns will be reached by upgrading HVAC equipment for instance when the efficiency of the building envelope - as a fixed element - is low, and does not also continue to contribute to increasing the efficiency of the building operation. As illustrated in Figure 4.1, over the 30 years of the projected energy costs for the reference "bad existing" building, the lowest total energy costs will be for an immediate new high efficiency retrofit. A new low-energy replacement building will require more energy initially, but over the next 25 years it will begin to recoup that

additional energy by lower operating costs overall. Beyond 30 years the new low-energy replacement building becomes more and more cost-effective. The retrofit option will be much less initial investment but at the 25-year mark begins to become less efficient on a yearly basis. Extending the projections it might be seen that at 50 years, it is appropriate for total life-cycle costs - construction, materials and operation - to completely replace this new low energy-use replacement building, and again at 50-year intervals.

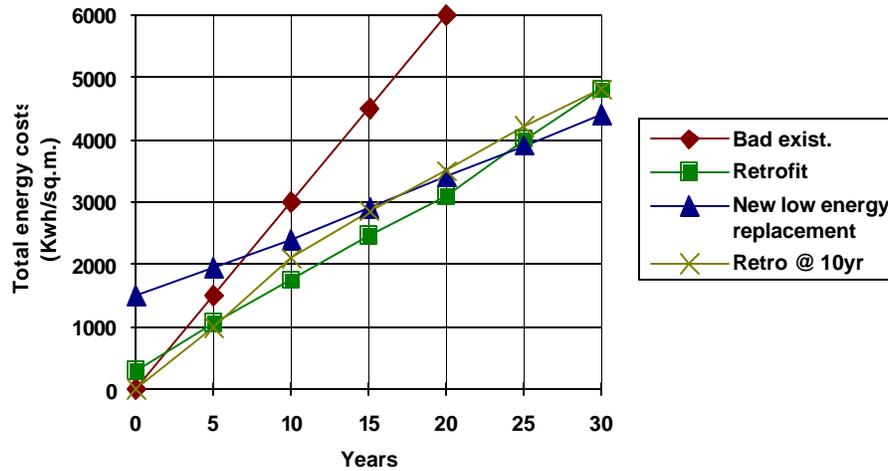


Figure 1 - Life-Cycle Costs Scenarios for an Existing Building (UNCHS, 1991).

This hypothetical replacement cycle of 50 years for an average building is very long relative to any other consumer product but could be confirmed for a specific type of construction through extensive modeling. Some assumptions would have to be made about the increasing speed of technological innovation for cutting-edge building systems such as building-integrated photovoltaics and hydrogen fuel cells. If it is presumed that overall sustainable construction requires maximizing resource-efficiency, then designing for building life-cycles, and achieving near zero-waste in the deconstruction of buildings at the end of this life will be one method for achieving this goal.

LESSONS LEARNED FROM BUILDING DECONSTRUCTION

Product analysis of design for assembly can be accomplished by disassembling products and putting them back together. This method also establishes baseline for the time and difficulty to disassemble a product (Otto and Wood, 2001). Deconstruction can be used in a similar way with the intent to heuristically analyze the critical elements necessary to design for deconstruction.

The approach to design for deconstruction suggested herein is to use the basic concepts of design for disassembly from the product industry combined with a categorization of the generic qualities of a building and its major elements, and lastly to learn from the deconstruction of buildings built in the 20th century. The author has been involved in the demolition and deconstruction of buildings ranging from large multi-story

commercial/institutional buildings, to heavy timber buildings, to light wood-frame residential buildings both pre- and post-WW II. Many themes related to future design for deconstruction were discovered from this field-based research.

Concrete and Masonry Institutional Building

Hume Hall was a 1950's, 133,000 square foot, 4-story institutional building constructed of a concrete floor and column system with a flat concrete roof and built-up tar and gravel roof finish. The exterior and interior walls were infill concrete masonry units and the exterior was a double-wythe brick veneer. Windows and glazing were comprised of casement metal frames and aluminum storefront and fixed glazing, respectively. Mechanical and electrical systems were run principally in ceiling plenums formed by suspended acoustic tile ceilings. Interior finishes were comprised of resilient floor coverings, painted concrete masonry, and drywall.

The non-structural process of removal consisted of the recovery of all reusable fixtures and hardware, and the removal and disposal of windows as part of the abatement of asbestos containing caulking materials. The major elements and structural removal was comprised of a partial "stripping" of the brick veneer to separate it from the concrete structure and masonry exterior walls and the mechanical reduction of the predominantly concrete, masonry and steel reinforced structure. The only cost-effective reuse or recycling occurred from the soft-stripping of hardware and fixtures before the demolition process took place. Although the brick veneer was readily separated from the building façade for additional de-mortaring, the mortar itself was cement-based and did not lend itself to hand separation. Considerable costs were avoided by the mechanical reduction of the masonry and concrete materials and removal of reinforcing steel for recycling. Asbestos abatement was a large proportion of removal costs with no reuse or recycling potential.

Design for Deconstruction Opportunities

Masonry construction must use a system that allows either de-panelization for reuse of large areas or mortar that facilitates the separation of the masonry back into individual units, i.e. the mortar has different strength or other properties that can be utilized in a separation process.

Large concrete and steel structures are constructed using mechanical equipment and therefore lend themselves to deconstruction using similar equipment. Mechanical equipment has the capacity to reduce concrete to recyclable form as long as contaminants of interior components, finishes, and thermal and moisture protection systems can be removed cost-effectively. Post and beam and/or flat plate concrete systems allow for maximum flexibility in separating all non-cementitious materials from the concrete and steel reinforcing mass of the building. Concrete is inflexible for reuse but readily recyclable, therefore the ability to recycle concrete should be prioritized over the concept of large concrete components' reuse.

Light Wood-Framed Residential Structures

More than nine residential structures have been deconstructed by the Center for Construction and Environment in the past four years. These structures were light wood construction on wood floor structures raised on piers. Walls were light-wood framing with drywall, wood lath and plaster, wood interior finish, wood exterior finish and combinations of asphalt shingle and metal roofing. Light wood framing is also known as “stick-framing” which indicates the method of construction and hence most appropriate method of deconstruction, i.e. stick by stick. As wood has considerably more value in reuse than in recycling and mechanical equipment is difficult to use at a “stick-by-stick” level of disassembly, this type of structure lends itself to hand deconstruction.

These structures were typically deconstructed by removing all interior non-structural elements, layer by layer, removing the structural elements starting with the roofs, then the load bearing walls, then the floor structure and foundation. Because workers are within the building at every step of the process, the building must be structurally sound at every stage of the deconstruction. Structure versus non-structure, sizes and weights of components and materials, and the height of exterior and interior elements relative to human scale, are key elements that control the deconstruction effort.

One of the most onerous aspects of modern architecture and construction readily found in most US buildings built before 1970 or so is the presence of lead-based paint (LBP) and asbestos containing materials (ACM). At a secondary level, PCBs, mercury, and ozone depleting chemicals are also hazardous materials that greatly complicate the recovery of building materials for reuse and recycling while not endangering workers and/or expending large sums to separate these materials from potentially reusable or recyclable base materials or sub-components. The regulatory requirements for worker protection and disposal of hazardous materials were a large cost for the deconstruction of older wood-framed residential structures, and the presence of lead-based paint is an impediment to wood reuse.

Design for Deconstruction Opportunities

High-slope roofs are problematic for deconstruction working platforms, therefore the use of ridge caps that are easily removable and allow access to the roof structure for tie off, or are designed to support the requisite load for a worker lifeline would facilitate both roof repair and ultimate deconstruction.

Panelized roofs that allow the mechanical removal of large sections of roofs for processing on the ground would preclude the need for fall protection and risks and added time involved from working at heights.

Light wood frame construction and the properties of wood allow for drilling and cutting small sections from walls and roof structural members to run electrical conduit and plumbing fixtures. This has the unfortunate consequence of creating a layer of materials that can be embedded throughout wall cavities. In order to remove the materials, they must be cut, unscrewed, pulled and collected together. Ceiling mounted HVAC and electrical systems require ladders, scaffolding and considerable mobility to access and

remove. The less of these interstitial components the better, therefore designing to consolidate mechanical and plumbing systems into fewer locations, surface mounting of electrical and telecommunications systems, and sectionalized gang units of electrical and telecommunications wiring with snap fitting or other screw-in connector would allow for adaptation and removal.

A notable impediment for deconstruction was often damage to components by water leakage and wood-boring organisms over time. This damage weakens the building structure and reduces the value of the recoverable materials. If nothing else design for deconstruction would also add impetus to design for durability and solve the problem that it is of little utility to efficiently disassemble a building if the materials themselves have not been protected from decay.

Although chemical sealants, coatings and adhesives add water protection and strength to building materials, they are significant prohibitions to hand deconstruction. From an environmental perspective, these types of additives should be eliminated with the recognition that mechanical methods of water protection and connections will require additional design and construction effort. The resulting reduction in performance, if one occurs, can be overcome by the ease of disassembly (by using screws and bolts for instance) for replacement and repair of components and sub-components.

Large Wood Post and Beam Structure

The Unitarian Church was a 5,000 square foot structure with slab-on-grade foundation and floor, large glu-lam arch structural frame with structural 2"x 6" tongue and groove roof planking, built-up tar and gravel and asphalt shingle roofing. The building wings' roof structures were long span glu-lam beams supported by steel columns at one end and the sides of the glu-lam arches at the other end. Bolts were used at the connections between columns and slab, between beam and column, beam and arch, and between arch and slab and between the arch members at the ridge point. Glazing was large sliding glass doors or fixed glass, and non-structural exterior and interior partitions were comprised of light wood framing and either wood paneling or drywall. Wiring and ductwork was placed into framed ceiling cavities or interior partitions.

Upon hand removal of interior finishes and partitions and ductwork, the roof structural planking was removed by hand as well. The side wings' glu-lam beams were unbolted and removed by a crane as were the structural glu-lam arches. The remaining debris and the concrete slab was removed by machine labor and crushed for disposal and recycling, respectively.

Opportunities for Design for Deconstruction

This building exemplified many concepts of design for deconstruction. The structural arch frame integrated both post and beam into one member that in turn was bolted at the floor structure and to each other. The horizontal beams were also bolted, as were the steel columns. The central arched section of the building was self-supporting and allowed the wings to be removed as separate elements. Structural roof planking combined structure with roof exterior sheathing and interior finish on the underside, greatly reducing

materials used and layers of additional materials removal to separate the wood members. The mounting of mechanical and electrical ductwork and wiring within only non-structural wall or ceiling cavities allowed for selective demolition of these low-value components. A flat roof system on the wings of the building acted as a working platform to great effect for roof removal, whereas the high-slope roof portion presented greater difficulty. Conversely, the flat roof system used a built-up tar and gravel roof membrane over rigid insulation which was the epitome of heterogeneous, chemically bonded and heavy-weight materials that do not facilitate removal or cost-effective separation and recycling. Given the overall time and effort for each type of roof, the high-slope roof was a better option for deconstruction. A monolithic slab-on-grade foundation integrated foundation and floor structure at the grade level, facilitating ease of mechanical scraping to remove contaminating debris and then crushing the homogenous concrete element for recycling.

PRINCIPLES OF DESIGN FOR DECONSTRUCTION

According to Rose, et al, two of the most critical factors in predicting the end-of-life path of products are wear-out life and technology cycle (Rose, 1998). According to Billatos and Basaly, the main criteria for examining a product for increasing its assembly efficiency is to reduce the number of parts and to reduce the amount of time required for assembly (Billatos and Basaly, 1997) According to Otto and Wood, critical factors in design for disassembly are the number of tasks, number of tools, and the time or degree of difficulty of the tasks (Otto and Wood, 2001). Each of these factors also has relevance for building disassembly.

Time is the single most important factor for building disassembly, unless the entire building can be removed to a separate location for disassembly, but this relocation can cost as much or more than the entire deconstruction. Time is a factor of the number of tasks, and difficulty of tasks. Difficulty includes the number of tools, height, safety precautions, etc. Wear-out life and technology cycle conflicts between faster and slower cycling components also count as critical concerns over the adaptive life of the building, but less of a concern for a whole-building removal.

Based upon generic elements of structure, building envelope, and services - including roofs and walls, and service systems such as the provision of electricity, conditioned-air, water, telecommunications, and gas, and the removal of wastewater and exhaust air - a building could be designed first to isolate these major elements from one another. A building designed for deconstruction for the purposes of first removing a building from a site might separate these major elements, i.e. roof, walls and floor/foundation as modular and pre-fabricated construction techniques do in the construction phase. Dealing with the material types and a sub-level of design for reuse, remanufacturing, or recycling, and other sustainability concerns such as human health and environmental impacts from materials and building energy-efficiency become mitigating factors to this level of building element separation.

On a fundamental level wood is a highly preferable material in design for deconstruction since it is flexible for both reuse and recycling, a “natural” material, and can be readily connected using interstitial connecting devices such as bolts. Steel is also a material with great utility for design for deconstruction due to its ease of recycling through a thermal process and ability to span large distances with less mass of material than concrete for instance. Steel also lends itself to post and beam construction via its high tensile strength. Of the other major material, concrete, its greatest utility in design for deconstruction is its durability as a structural material and its ability to act in both compression and tension, with reinforcing, for forming integral floor and ceiling elements that can also act as building envelope and finish. Concrete already is a relatively highly recycled material but is not easy to recycle when it is contaminated by other building components. Unless these components and sub-components have their own inherent value apart from allowing the concrete components to be recycled, it is not cost-effective to remove them for the purpose of recycling concrete components, unless mechanical means are used.

One means to design for disassembly is to expedite the understanding and viability of a disassembly sequence for either parts or the entire building. The simultaneous creation of a deconstruction plan along with the construction plan and labeling of components for their constituent materials, similar to plastic products label numeric codes to indicate the type of plastic will provide directions to the deconstruction contractor for the disposition of materials. The ability to pre-market materials for reuse and recycling based upon known types and quantities provides an economic incentive for the deconstruction process. It also allows for prioritizing materials disposition in the order of reuse, remanufacturing, recycling or disposal, depending upon local materials, reuse, remanufacturing and recycling infrastructure, with a better ability to calculate costs and benefits. An upfront deconstruction plan also allows for planning the management, scheduling and safety requirements of the deconstruction process. Borrowing from Fletcher’s hierarchy of System, Product and Materials for DfD, this hierarchy can include process as well as physical elements (Fletcher, 2000). Within each level of the building design and element hierarchy, the deconstruction process is the first step in the materials disposition process, and therefore sub-levels have an appropriate path depending upon a materials management hierarchy.

An element is defined as a major building part such as roof, vertical structure, wall, floor or foundation. A component is defined as the next level of non-structural building part such as thermal or moisture protection systems, windows and other systems such as the heating and cooling systems. A sub-component is a breakdown of a component into its smaller pieces such as the duct system of a heating and cooling system, the hardware for a door unit, or the sash of a window unit. A material is the constituent material from which all other parts are made, such as plastics, metals, wood, and masonry. Added to these physical definitions is the process of design and construction as independent levels of information that not only dictate the types of materials or connections, but can facilitate deconstruction through information management and major architectural decisions such as the slope of a roof.

An illustration of a design for deconstruction hierarchy is illustrated below.

- **Design**
 - Minimize building depreciation from poor energy-use, climatic and materials performance by performance-based materials selection
 - Substitute mechanical/gravity-based design for chemical-based design
- **Construction**
 - Record as-built conditions
 - Create deconstruction plan based upon construction process
 - Record adaptations to building over its life
- **Elements** - design for modular and panelized elements that are readily fit into common dimensional standards and possible de-panelization
 - Principle DfD sub-goal - Reuse
- **Components** - design for ease of separation from the next higher building level, i.e. elements
 - Reuse
 - Remanufacture
- **Sub-components** - design for separation from component level
 - Reuse
 - Remanufacture
- **Materials** - design for separation from sub-component level and as homogenous materials
 - Remanufacture
 - Recycle
 - Bio-degrade

As a basic principle, matching a level of complexity and invested energy, components are designed for reuse and remanufacture, sub-components are designed for reuse and remanufacture, and materials are designed for remanufacture, recycling and bio-degradation. These hierarchies would be driven primarily by the constituent materials at each level, but a high embodied energy component should require as little additional energy and costs as possible for its continued utility.

Table 2 Relative Percent of Building Components by Different Measurement Systems (Adapted from Marshall Valuation Service, Marshall and Swift Publication Co., Los Angeles, CA. 1995 and *UNCHS, 1991)

| Category | Percent of completion total | Percent of cost total | Percent of embodied energy* |
|--|-----------------------------|-----------------------|-----------------------------|
| Sitework, masonry, and concrete | 12 | 7.0 | 14.6 |
| Wood | 21 | 17.7 | 9.8 |
| Windows and doors | 2 | 4.0 | 6.4 |
| Thermal and moisture protection | 10 | 12.8 | 20.0 |
| Plumbing, electrical, and mechanical equipment | 23 | 18.0 | 27.3 |
| Interior finishes, hardware, and cabinetry | 30 | 22.9 | 9.3 |

Table 2 is meant to illustrate well-known considerations of the cost-effectiveness of deconstruction based upon considerations of mass and embodied energy of typical building elements, components and materials. Non-structural “soft-stripping” greatly reduces the worker safety and equipment considerations and increases the cost-effectiveness of deconstruction. Wood is a high proportion of the percent of completion and cost of an “average” new building but has low embodied energy. Thermal and moisture production is a relatively low percentage of completion of a building but much higher in terms of embodied energy due to the types of materials used. Plumbing, electrical and mechanical equipment are a high percentage of completion and also a high percentage of embodied energy. Interior finishes, hardware and cabinetry are the single greatest percentage of completion and costs and yet relatively very low in embodied energy principally due to the much lower mass of these types of components in a typical building. At the whole-building level, high embodied energy components such as thermal and moisture protection and mechanical, electrical and plumbing systems would not only be subject to more rapid functional, climatic and technology life-cycle stresses but inherently are environmentally and economically valuable components to be targeted for design for deconstruction. Interior finishes also have a high value to mass ratio making them an obvious target for non-mechanized, i.e. high labor rate, removal for remanufacturing and recycling. A confirmation of this type of analysis, looking at major elements of the building and deconstruction constraints is presented below in Table 3.

Table 3 Design for Deconstruction Analysis of Wood-Framed Residential Building

Assuming wood windows and doors, wood light-frame construction, drywall interior finish, asphalt shingle roofing, wood floor structure and masonry or concrete foundation, wood floors, H = high, M = medium, L = Low, Y = yes, N = no, Value = potential revenue from reuse or recycling, Mass = higher mass avoidance of disposal, Ease of removal = relative less time, equipment

| Element | Internal cycling rate | Value | Embodied Energy | Mass | Ease of removal | Structure |
|-------------------------|-----------------------|----------|-----------------|----------|-----------------|-----------|
| Windows/Doors | L | H | H | L | M | N |
| Appliances | H | L | H | L | H | N |
| M, E, P Equipment | M | M | H | L | M | N |
| Cabinetry | H | H | H | L | H | N |
| Int Finish | H | M | M | L | H | N |
| Duct, Pipe, Wire | L | L | H | L | L | N |
| Int Wall/Ceiling | L | L | L | L | M | Y |
| Roof | L | H | L | M | L | Y |
| Ext Wall/Structure | L | L | L | H | M | Y |
| Floor/Structure | L | H | L | M | M | Y |
| Foundation | L | L | L | L | H | Y |

Based on this simple residential building analysis, the inherent deconstructability of most non-structural elements indicates fewer impediments to deconstruction for these components in traditional design and construction methods. The clear exception is duct,

pipe and wiring. The low mass of a very dispersed elements with a high degree of entanglement and low reuse value all combine to make these components an impediment for selective disassembly and whole-building deconstruction. For this type of building, exterior and bearing walls have a high mass but low reuse value and medium level of effort required for removal within a sequence requiring the removal of the roof element first. One indicator from this analysis is that bearing wall construction is not conducive to cost-effective deconstruction. The roof element is relatively independent, yet requires additional time and equipment due to height

General Design Concepts

A list of design concepts for facilitating deconstruction of buildings is provided below:

- Compressed wheat-straw interior partition panels with integral paper facing are an example of self-supporting elements that can be disassembled as a unit and have the additional benefit of being a homogeneous and natural/recyclable material as a substitute for drywall and light wood 2"x 4" framing.
- Bolted roof trusses and offset tie-downs or roof to wall connectors that are attached at a point away from the actual point of contact of the roof structure to the wall. This would require an additional element such as a knee-brace to bridge between the two elements and increase the distance between the points of connection to roof and wall, but allows for ease of access to the connectors.
- Platform-type wall construction whereby the walls sit on top of the floor structure and do not extend through the horizontal plane of the floor structure and the floor above rests on top of the wall element. Separating the plane of the top and bottom of the wall from the plane of the floor structure facilitates mechanical separation and structural stability during the deconstruction process. Pre-cast concrete floor panels act in this manner.
- Light-weight materials for instance integral and modular elements combining finish, thermal and moisture protection, and structure, for roof structure, sub-structure and finishes to reduce the stresses on the lower portions of the building and reduce work at height and use of equipment. These impediments of height can be somewhat mitigated by integral worker stations and point of connections for equipment and handling. An example of this principle would be structural insulated panels (SIP). Substituting a glued and heterogeneous SIP system for individual wood roofing members must be weighed against the potential for reuse and recycling of the panels.
- Simple consolidation of plumbing service points within a building has the benefit of reducing the length of lines, but also reduces the points of entanglement and conflict with other elements such as walls and ceilings/roofs.
- A separation of structure from enclosure, will greatly facilitate adaptation and deconstruction however it is important to remember regional climatic forces, whereby a building in a temperate climate will not be as penalized by a possible variety of enclosures and loose-fit as will a building in a high heating load climate.
- Hazardous materials such as asbestos and lead-based paint have been outlawed. The next generation of these materials will include fibrous insulations, chemical

treatments for wood, and many synthetic materials used as sealants, caulking, coatings, binders, and adhesives. All materials should be examined using a precautionary approach to eliminate possible toxicity or future regulatory constraints to their use and disposition.

- Nails and bolts have appropriate uses as per the type of connection and size of the members. A variety of nails in one building causes the requirement for multiple tools for removal. A mix of bolts, screws, nails requires constant shifting from one tool to the next. Fewer connectors and consolidation of the types and sizes of connectors will reduce the need for multiple tools and constant change from one tool to the next.
- Long spans and post and beam construction reduce interior structural elements and allow for structural stability when removing partitions and envelope elements.
- Doubling and tripling the functions that a component provides will help “de-materialize” the building in general and reduce the problem of layering of materials.
- Separating long-lived components from short-lived components will facilitate adaptation and reduce the complexity of deconstruction, whereby types of materials can be removed one at a time, facilitating the collection process for recycling.
- The requirement for access to connectors is a functional requirement that in turn dictates a building aesthetic. Access areas for maintenance are well-understood but little dealt with even in conventional design, due to the need to maximize habitable and income-producing square footage, and maintain a highly refined aesthetic. The design for deconstruction aesthetic is modeled in the “high-tech” architecture aesthetic.
- Elimination of caulking and sealants and high-tolerances in the connections can be offset by the ease of removing components for repair and replacement, and designing in durability, using mechanical instead of chemical-based water protection.

CONCLUSION

Design for deconstruction has much to learn from product design for disassembly. It also has unique qualities based on buildings as significantly different artifacts than consumer products. Buildings have much greater life cycles than consumer products and engage a larger number of actors over their lives than consumer products. It is not well-understood whether design to facilitate a more rapid turnover, if not for whole buildings, then for major energy-use and technology-oriented components of buildings will inherently make them more efficient to operate and therefore assist in maintaining their long term value. The commercial building industry has already adopted many techniques to allow for internal adaptations with reduced waste and costs in order to meet service sector demands for technological and economic flexibility. Design for deconstruction can be studied from the perspective of deconstruction of existing buildings and the lessons learned from this research can be used to design for deconstruction in the future.

REFERENCES

Billatos, S., Basaly, N. Green Technology and Design for the Environment, Washington DC: Taylor and Francis, 1997.

Brand, S. How Buildings Learn: What Happens After They're Built, New York: Penguin Group, 1994.

Building Research Establishment, Deconstruction: Closing the Loop, Conference Proceedings, May 18, 2000, Watford, England.

Catelli, V., Designing for Disassembly, Ottawa, Ontario, CA: Canada Mortgage and Housing Corporation, 1998.

Fiksel, J. Design for Environment, New York: McGraw-Hill, 1996.

Fletcher, S., Buildings Designed for Disassembly, <http://www.shef.ac.uk/uni/academic>, visited December 22, 2000.

Franklin Associates, Characterization of Building-Related Construction and Demolition Debris in the United States, Washington, DC: US EPA, 1998.

Friedman, A., et al, The Next Home, Ottawa, Ontario, CA: Canda Mortgage and Housing Corporation, 1996.

Friedman, A., The Adaptable House, New York, NY: McGraw-Hill, 2002.

Giamberdine, R., et al, Guiding Principles of Sustainable Design, Denver, CO: The National Park Service, 1993.

Gungor, A., Gupta, S.M., Disassembly Sequence Planning for Products with Defective Parts in Product Recovery, Boston: Northeastern University, 2001.

Habraken, N. J., et al, Variations: The Systematic Design of Supports, Cambridge, MA: MIT Press, 1981.

Hoke, J.R., Architectural Graphics Standards, 10th Ed., New York, NY: John Wiley & Sons, Inc., 2000.

Kendall, S., Teicher, J., Residential Open Building, London: E & FN Spon, 2000.

Leroux, K., and Seldman, N., Deconstruction: Salvaging Yesterday's Buildings for Tomorrow's Sustainable Communities, Institute for Local Self-Reliance, 1999.

Mendler, S., Odell, W., The HOK Guidebook to Sustainable Design, New York, NY: John Wiley & Sons, Inc., 2000.

NAHB Research Center, Deconstruction - Building Disassembly and Material Salvage: The Riverdale Case Study, Upper Marlboro, MD: prepared for US Environmental Protection Agency, June 1997.

Nakajima, S., Futaki, M., National R&D Project To Promote Recycle And Reuse Of Timber Constructions In Japan, Building Research Institute, Tsukuba, Ibaraki, Japan, Paper presented to CIB Task Group 39 Meeting April 6, 2001, Wellington, NZ.

Otto, K.N., Wood, K.L., Product Design: Techniques in Reverse Engineering and New Product Development, Upper Saddle, NY: Prentice Hall, 2001

Rose, C., Ishii, K., Product End of Life Categorization Design Tool, Manufacturing Modeling Laboratory Design Division, Mechanical Engineering Department, Stanford, CA: Stanford University, 1999.

Sindjou, G., Effect of waste on end of product life cycle, Special Scientific Report #99-19, November 17, 1999, Tokyo, JA: National Science Foundation, <http://www.twics.com/~nsftokyo/ssr99-19.html> visited May 1, 2001.

United Nations Centre for Human Settlements (Habitat), Energy for Building, Nairobi, Kenya: UNCHS, 1991.

Watson, D., Environmental Design Charrette Workbook, Washington, DC: American Institute of Architects, 1996.

Webster, M., The Use of Salvaged Structural Materials in New Construction, The Austin Papers, Brattleboro, VT: BuildingGreen, Inc., 2002

WRITAR, et al, Resource Efficient Building, Minneapolis, MN: Minnesota Office of Environmental Assistance, 1995.

Yashiro, T., Relevant Factors and Possible Indicators to Resource-Reuse-Efficiency in Construction, Presentation to OECD-IEA Joint Workshop, Paris, November 2-3, 1999.