FRAMEWORK FOR BUILDING DESIGN RECYCLABILITY

BY

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Abstract

Recycling of building materials is an important aspect of sustainable construction, while sustainable construction is a critical issue to fulfill overall sustainable development. Researchers have proved that building materials recycling is technically feasible and facilities for recycling are available, too. They have identified many obstacles of building materials recycling, but most of them are derived from experience. Researchers suggested many ways to maximize building materials recycling, but they are not powerful enough. This thesis will summarize the obstacles and put them into categories. After that, a case study will be used to testify that these are real obstacles. This thesis will focus on developing the concept of building design recyclability by giving the definition of design recyclability, describing the principles that make a design recyclable, generating drives of design recyclability, and testifying these drives. At the end, some suggestions will be given for future research directions.

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Chapter 1 Introduction

During the past few decades, human beings have had a great effect on the natural environment which supports our lives. The consumption of non-renewable resources and the creation of wastes have been identified as the most significant issues that our society must pay attention to (Lave, et al., 1999; Lingard, Gilbert and Graham, 2001). If we continue consuming and polluting at the current rate, the earth's ability to provide resources and absorb pollution will be very limited.

To solve these problems and make sure our next generation will still have a healthy environment to live in, the concept of sustainable development has been brought out. As sustainable development draws more and more attention from the public, sustainable construction, the implementation of sustainability in the construction industry, has become a popular subject for the researches who are interested in construction. As an important part of sustainable construction, material recycling has become a hot topic, because the current material recycling rate is far from satisfying and there are a lot of untouched issues in this area.

1.1 Sustainable Development

People began to look for ways to save the earth and human beings themselves two decades ago. They have made some progress. The inventing of the phrase sustainable development can be viewed as the starting point when people began to pay attention to the natural environment that they have relied on.

Sustainable development is a very complex concept, and there are over 200 definitions of it (Parkin et al., 2003). The initiation of this concept was from the Brundtland Commission report for the United Nations in 1987. Brundtland described sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). These could be interpreted as minimizing the negative impacts to ensure a good quality of life for current and future generations (Leiper, et al., 2003).

The Brundtland report highlighted the need to balance economic development, environmental protection, and social preservation to achieve sustainable development, which is known as the three pillars of sustainability: social, economic, and environmental issues. These three aspects are often symbolized as three overlapping circles, and have been characterized by business in particular as the “triple bottom line” (Fig. 1.1).

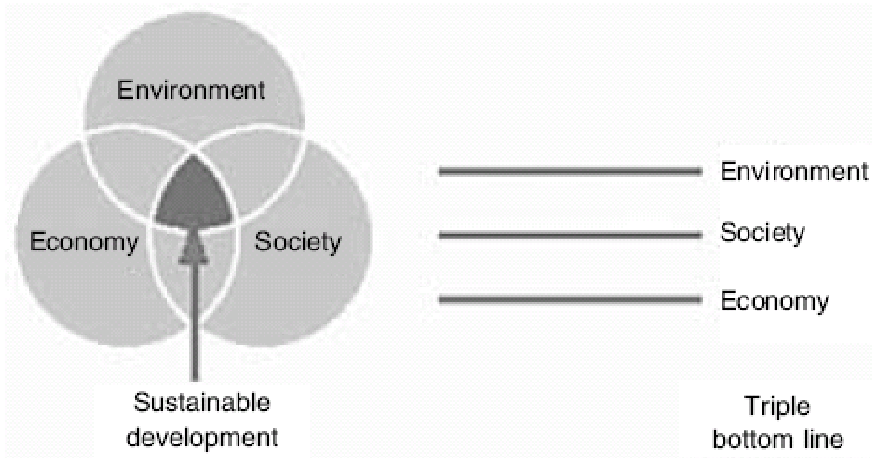

Figure 1.1: Sustainable Development and The Triple Bottom Line
(Source: Parkin et al., 2003)

Many researchers have tried to explain this concept using their own ways. Forum for the Future, a UK sustainable development charity, used a five capitals framework to illustrate sustainability (Parkin et al., 2003). These five capitals, natural capital, human capital, social capital, manufactured capital, and financial capital, represent all the resources available to a society. The relationship between the triple bottom line and the five capitals are shown in Figure 1.2.

Venn diagram/ triple bottom line	Type of capital	Stock	Flow of benefits
Environment →	NATURAL	Soil, sea, air ecological systems	Energy, food, water climate, waste disposal
	HUMAN	Health, knowledge motivation, spiritual ease	Energy, work, creativity, innovation, love, happiness
Society →	SOCIAL	Governance systems, families, communities, oganisations	Security, shared goods (e.g. culture, education), inclusion
Economy →	MANUFACTURED	Existing tools, infrastructure, buildings	Living/work/leisure places, access, material resources
	FINANCIAL	Money, stock, bonds	Means of valuing, owning, exchanging other four capitals

Figure 1.2: Capital Stock and Flows of Benefits: A Modernised Economic Model for Sustainable Development
(Source: Parkin et al., 2003)

In this model, each capital is represented by stocks. By investing in different types of stocks, we will get the expected benefits. From this point of view, sustainable development can be interpreted as the process by which we manage capitals and flows successfully. This is a good way to understand sustainable development, but it is just for understanding not for measurement. It is impossible to calculate the net contribution because it is hard to give comparable quantity to each item. However, it is still helpful to know that having a building constructed costs not only money and labors, but also our ecological systems and human health.

1.2 Sustainable Construction

All activities of industry and individuals will have impacts on the environment, which are often negative (Griffiths, Smith and Kersey, 2003). The construction industry plays an important role by providing the building environment and infrastructure, generating economic wealth, providing employment, utilizing resources and influencing the environment (Boyle, 2005; Head, 2003; Hendrickson and Horvath, 2000).

1.2.1 Interpreting Sustainable Construction

Sustainable construction is applying the principle of sustainability to construction industry (Hill and Bowen, 1997). There are a lot of explanations for sustainable construction. The Conseil International du Batiment (CIB), an international construction research networking organization, defined the goal of sustainable construction as creating and operating a healthily built environment based on resource efficiency and ecological design. The CIB also addressed seven principles for sustainable construction. They were:

1. Reduce resource consumption
2. Reuse resources
3. Use recyclable resources
4. Protect nature
5. Eliminate toxics
6. Apply lifecycle costing
7. Focus on quality

Construction industry has tremendous impact on every aspect of people's lives (McDonald and Smithers 1998). Globally, the construction industry is worth approximately US$ 3.2 trillion (Mustow, 2006). In the United States, construction is a US$1 trillion industry that employed over 6.4 million people in 2004 alone, according to the 2007 EPA report. Furthermore, construction and its products also consume large amount of energy and resources, and release pollution to the air, ground, and aquatic environments (Mustow, 2006; Miyatake, 1996; Peng, et al., 1997). The construction industry is the dominant user of most minerals. The World Watch Institute estimates that by 2030 the world will have run out of many raw materials for buildings, and we will have to recycle and mine landfills (Gorgolewski, 2006). Therefore, realizing sustainable construction is the key for us to fulfill sustainable development.

1.2.2 Reduce, Reuse, and Recycling of Building Materials

Construction industry consumes plenty of raw materials and generates huge amount of waste (Bossink, 2002; Poon, et al., 2004). Since the United States is a "throwaway" society, most of the wastes go to landfill. But the landfill is a really a bad thing. Modern landfills require mandating daily cover, clay and rubber liners, clay caps and leachate collection systems to avoid bad smells and to control pests growth. However, even with these requirements, landfills are still unpopular. The traffic and other problems make it a bother to nearby residents. Methane emissions from landfills can pose a safety hazard to nearby buildings and contribute to urban ozone problems and global warning. In most communities, groups attempt to close current landfills and have made it extremely difficult to open new ones. The closing of many landfills in the last decade and the opposition to opening new ones has led to the concern that we are running out of landfills. As a sequence, the cost of landfill is and will be increasing along with the time.

Construction industry is a big contributor to landfill. Most of the construction and demolition wastes (C&D wastes) go to landfill. To minimize construction wastes and save raw materials, there are three ways: reduce, reuse, and recycle, which are commonly known as three Rs (Poon, et al., 2004; Poon, Yu and Jaillon, 2004). The environmental impact is increasing from the first to the last.

Reduce, also called source reduction, is trying to save materials by using less, which prevents the generation of waste from the first stage. It requires proper design and construction practices. Reuse is to use a component again with some treatment. Recycle means taking a product or material at the end of its useful life and turning it into a usable raw material to make another product (Cameron, 2003). This needs reprocessing materials and remanufacturing. Reduce is the most preferred method of waste management because it has minimal environmental impact and save materials at the very beginning. Greater environmental benefits result from reuse than recycle because reuse requires little reprocessing.

1.3 Building-related Materials Recycling

It is recommended that as many components of a building as possible be extracted from the waste stream for reuse at the end of their useful life. However, reuse is not usually possible for buildings materials, and at that time, recycle will be a good choice. Reuse or recycling C&D materials can reduce the environmental effects of extraction, transportation, and processing of raw materials, and sometimes can reduce project costs through avoided disposal costs, avoided purchases of new materials, revenue earned from materials sales and tax breaks gained for donations (Inyang, 2003). It can conserve space in landfills, too.

1.3.1 Characterization of Building-related C&D Wastes

US Environmental Protection Agency (EPA) estimates that more than 160 million tons of building-related construction and demolition waste was generated in the United States in 2003, while in 1996 the number is 136 million (Franklin Associates, 1998). The majority of this waste comes from building demolition and renovation, and the rest comes from new construction. Figure 1.3 shows the percentage of wastes generated from each stage.

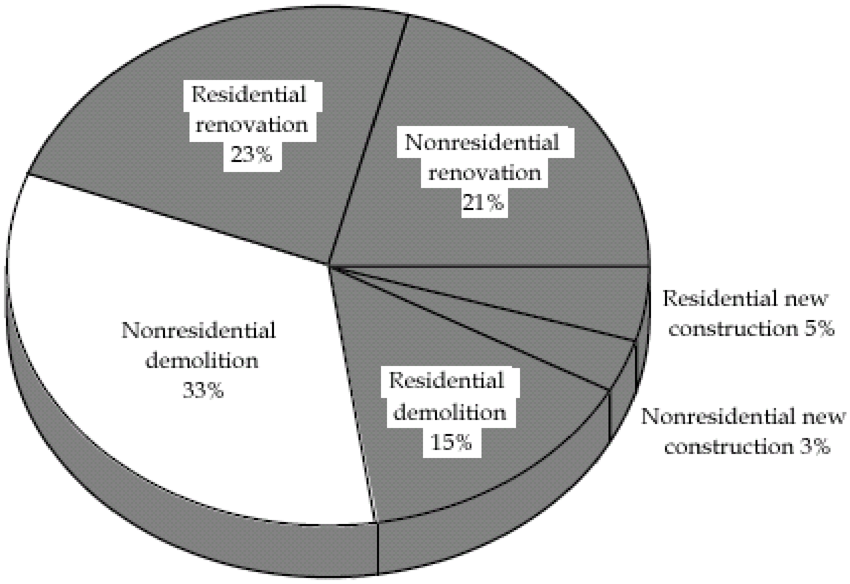

Figure 1.3: Generation of Construction and Demolition Debris from Buildings
(Source: EPA report, 1998)

The composition of construction and demolition waste varies significantly, depending on the type of project form which it is being generated (Gavilan and Bernold, 1994). Wastes from older buildings is likely to contain plaster and lead piping, while new construction waste may contain significant amount of drywall, laminates and plastics (Franklin Associates, 1998). EPA estimates the overall percentage of debris in construction and demolition wastes falls within the following rages (Table 1.1):

Table 1.1: The Percentage of Typical C&D Debris
(Source: Modified form EPA Website, 2008)

Concrete and mixed rubble	40-50%
Wood	20-30%
Drywall	5-15%
Asphalt roofing	1-10%
Metals	1-5%
Bricks	1-5%
plastics	1-5%

1.3.2 Building-related Materials Recycling Rates

Of the total building-related C&D materials generated, EPA estimates that only 40 percent were reused, recycled, or sent to waste-to-energy facilities, while the remaining 60 percent of the materials were sent to landfills (Kim and Rigdon, 1998). However, if we plan properly, most of the C&D materials can be recovered through reuse and recycling.

There are some successful stories. One project is located in Richmond, VA. It is the former Lucent Richmond Works facility, which was fenced off and left idle, leaving behind over 700,000 square feet of old and dilapidated manufacturing buildings. After demolishing the existing onsite buildings, the developer diverted 84,500 tons of material from landfills, achieving a 93 percent overall recycling rate. Cost-saving associated with recycling and reuse of demolition materials is estimated to be approximately $ 3.6 million. Another example in Emeryville, CA, got an even higher rate, which is 94.6 percent.

Comparing to these high rate, the average 40 percent is really unfavorable. It is important to find out the obstacles for building materials recycling, and figure out how to conquer them to achieve higher rate. These will be valuable endeavors.

Chapter 2 Literature Review

As building materials recycling has become a hot subject, a lot of organizations put funding into this area. US EPA has funded many projects about building demolition. US Air Force, US Army Corps of Engineers, US Department of Housing and Urban Development, US Department of Transportation, etc., they all have made some effort on construction materials recycling. Some European countries and Japan have gone even further than the US on building materials recycling (Allen, et al., 2002; Bartlett, et al., 2004).

The average building materials recycling rate is 40%, which is quite low comparing to automobile and electronic industries. What are the reasons for that? Is it because we do not have the ability to recycle building materials or we just do not want to? Many researchers have tried to develop the technologies and facilities for building materials recycling. Reviewing and summarizing them will give us a clear view of preconditions for materials recycling. Based on their findings, we can figure out what we still need to do.

2.1 Technologies for Building Materials Recycling

Technology feasibility is the foundation of building materials recycling. Fortunately, current technologies can support most of the materials recycling. Some components can be reused with proper treatment, while some must be remanufactured. Sometimes the remanufacturing process is complicated due to the contaminations.

2.1.1 Concrete

Concrete is the most commonly used material in construction. The estimated recycling rate for concrete is about 50 to 57 percent (EPA, 1998). As the largest component of C&D wastes, concrete is in tune with the environment (Environmental Council of Concrete Organizations, 2000). Concrete is environmentally friendly in a variety of ways, shown in table 2.1

Table 2.1: Environmental Benefits of Concrete

1.	Ingredients are abundant in supply.
2.	Many recycled materials can be used to make new concrete.
3.	Local concrete is available.
4.	Energy saving
5.	Long lifespan

First of all, the ingredients of concrete, water, aggregate, and cement, are abundant in supply and take a less toll in their extraction than other construction materials.

Secondly, as a nearly inert material, concrete is ideal for recycling. Moreover, many materials that would end up in landfills can be used to make concrete. Blast furnace slag, recycled polystyrene, and fly ash are among materials that can be included in the recipe for concrete and further enhance its appeal (Environmental Council of Concrete Organizations, 2000). Recycled concrete can be used as aggregate for new concrete mixtures, too.

Another environmental plus for concrete is energy efficiency. Since the materials for concrete are so readily available, concrete products and ready-mixed concrete can be made from local resources and processed near a jobsite. Local shipping minimizes fuel requirements for handling and transportation.

Once in place, concrete offers significant energy savings over the lifetime of a building. In homes and buildings concrete's thermal mass, bolstered by insulating materials, affords high R-factors and moderates temperature swings by storing and releasing energy needed for heating and cooling (Environmental Council of Concrete Organizations, 2000).

Further commendable characteristics of concrete are waste minimization and long life. Whether cast-in-place or precast, concrete is used on an as-needed basis. Leftovers are easily reused or recycled. And concrete is a durable material that actually gains strength over time, conserving resources by reducing maintenance and the need for reconstruction.

When structures made of concrete are to be demolished, concrete recycling is an increasingly common method of disposing of the rubble. Concrete debris was once routinely shipped to landfills for disposal, but recycling has a number of benefits that have made it a more attractive option in this age of greater environmental awareness, more environmental laws, and the desire to keep construction costs down.

Generally, concrete debris can be recovered using the following two strategies (Parry, 2004; Soutsos, et al, 2004):

1. crushing onsite and reusing it as compacted base or drain material;
2. hauling it to a recycling facility

Regardless of which recovery strategy is used, the physical processing of the material is the same: the concrete shards are fed into an impact crusher, followed by an electromagnet that removes reinforcing steel, and finally through a series of screens that grade the aggregate according to its size. The process can be illustrated by Figure 2.1.

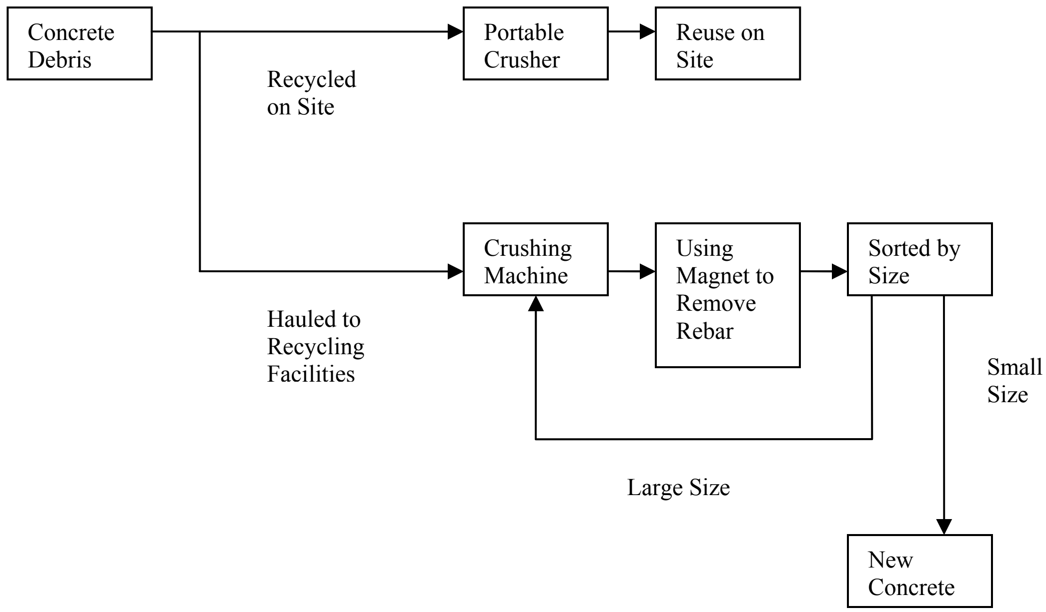

Figure 2.1: The Process of Concrete Recycling

Concrete aggregate collected from demolition sites is put through a crushing machine, often along with asphalt, bricks, dirt, and rocks. Crushing facilities accept only uncontaminated concrete, which must be free of trash, wood, paper and other such materials. Metals such as rebar are accepted, since they can be removed with magnets and other sorting devices and melted down for recycling elsewhere. The remaining aggregate chunks are sorted by size. Larger chunks may go through the crusher again.

Crushing at the actual construction site using portable crushers reduces construction costs and the pollution generated when compared with transporting material to and from a quarry. Large road-portable plants can crush concrete and asphalt rubble at up to 600 tons per hour or more. These systems normally consist of a rubble crusher, side discharge conveyor, screening plant, and a return conveyor from the screen to the crusher inlet for reprocessing oversize materials. Compact, self-contained mini-crushers are also available that can handle up to 150 tons per hour and fit into tighter areas.

However, the concrete made from recycled aggregate is not as strong as the one made from natural aggregate. A decrease in the compressive strength was observed. The mechanical properties of the concrete decreased with the increase in the proportion of aggregate replaced (Topcu and Guncan, 1995). Many attempts to develop high-grade uses of construction waste are reported in the literature (Topcu and Guncan, 1995; Collins, 1996; Tavakoli and Soroushian, 1996). RILEM Technical Committee 121-DRG (1994) recommended that only 20% of the natural aggregate can be replaced with recycled coarse aggregate in the preparation of new concrete of all strength classes, and limited the concrete classes when 100% recycled construction waste is used (Katz, 2004).

Several methods to improve the properties of new concrete made from recycled aggregate were reported in the literature. Sri Ravindrarajah and Tam (1988) improved the properties of new concrete by altering the water/cement ratio, adding pozzolans, and blending recycled and natural aggregates. Montgomery (1998) treated the aggregate with a ball mill in order to remove old cement paste from natural stone. He found that the cleaner the aggregate was, the stronger was the concrete. Winkler and

Mueller (1998) and Montgomery (1998) milled recycled fines and used them as a cement replacement.

Generally, recycling concrete is possible and the process is not complicated. But if we can not make the performance of recycled concrete satisfy the need, there won't be a big market for it. Therefore, we still need to develop better technology to increase its properties. There is still a long way to go for concrete recycling.

2.1.2 Wood

Wood is ubiquitous in the C&D wastes. In the United States, nearly all new single-family and low-rise multifamily residential structures use traditional wood-frame building technology (McGregor, 2006). Moreover, there are also large amounts of wood used in flooring, paneling, siding, roofing, cabinetry, decking, etc (Clean Washington Center, 1997).

Prior to 1990, recycling of wood waste in the United States was limited. Today, there are more than 500 wood processing facilities. Job-sites generate wood in the form of construction, demolition, and land-clearing debris (Table 2.2).

Table 2.2: Wood Wastes Generated on Site

Construction Debris	Off-cuts; Solid Sawn Lumber; Pallets.
Demolition Debris	Timbers, trusses, framing lumber, flooring, decking, and millwork, doors, and window frames
Land-clearing Debris	Stumps; ranches.

Construction debris includes off-cuts of engineered wood products, solid sawn lumber, and pallets from material deliveries. Demolition generates timbers, trusses, framing lumber, flooring, decking, and millwork, doors, and window frames suitable for reuse or recycling depending on their condition. The recycled wood must be free of chemicals, including paint, strain, waterproofing, creosote, pentachlorophenol, petroleum distillates, and pressurizing treatments (Falk and McKeever, 2004). The stumps and branches from land clearing can be chipped and composted, recycled as boiler fuel, or reused on site as landscaping mulch.

The wood recycling practice can be illustrated by Figure 2.2:

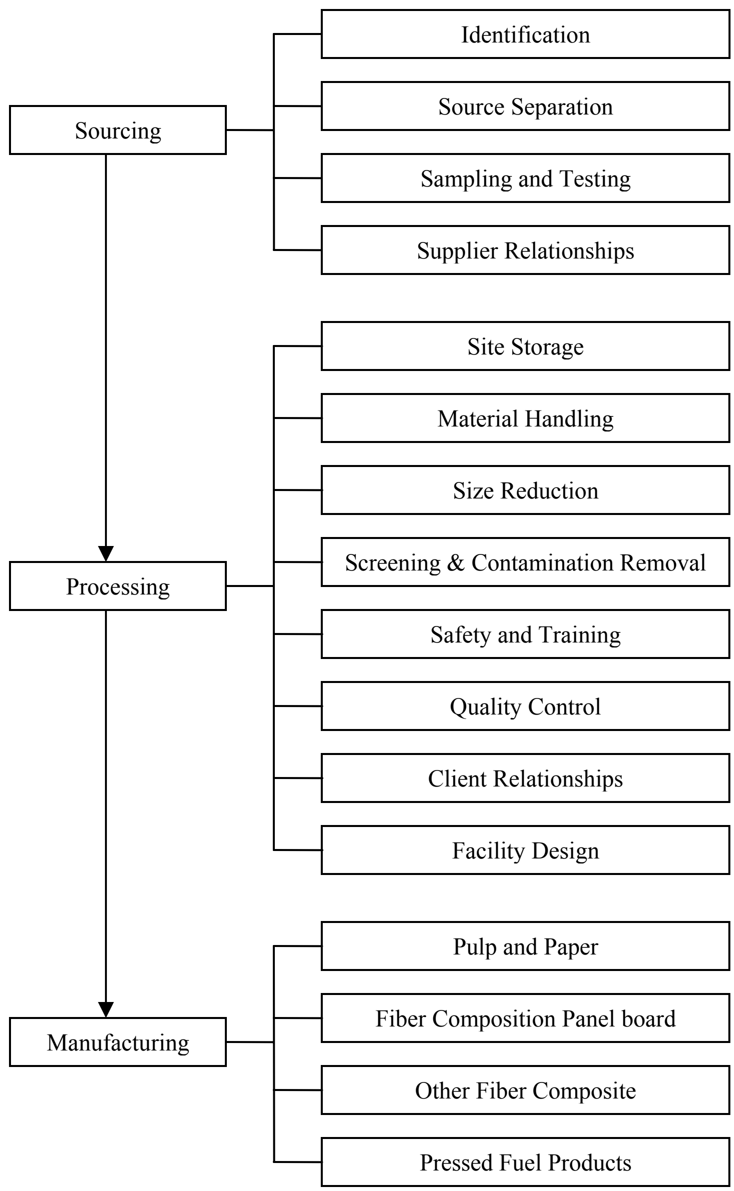

Figure 2.2: Wood Recycling Practices

Most of the above practices can be applied not only to wood but also to most of the wastes in building construction. The markets for recovered wood are dominated by production of landscaping mulch and waste wood for fuel. Chipped or shredded wood is also used as a composting bulk agent, sewage sludge bulking medium and animal bedding (Falk and McKeever, 2004). Recovered wood can be used to manufacturer value-added products such as medium density fiberboard and particleboard. However, these industries demand clean and consistent feedstocks, which can be difficult to achieve with wood from the waste stream.

Deconstruction is very important for lumber reuse, in which way to preserve their integrity and value. It is estimated that the recovery rate for wood in construction is usually between 50-90 percent.

2.1.3 Drywall

Drywall, also known as gypsum wallboard, is manufactured from gypsum, which is a low-value, plentiful mineral that exists in large natural deposits. Recycled gypsum can be used to manufacture new drywall. It can also be used to improve soil drainage and plant growth. Gypsum is a major ingredient in the production of fertilizer products, and an ingredient in the production of cement. It can also be used as an additive to composting operations (Claisse, 2006).

Although recycled gypsum has so many usages, it is seldom recycled in the United States. Because of contaminates in the form of wall-coverings and paints, gypsum wallboard is not recycled. However, after going to landfill, gypsum wallboard produces hydrogen sulfide, which creates an acidic leachate. This phenomenon has caused some municipalities to ban the material from land fills. Therefore, we have to recycle gypsum no matter for the sake of environment or for the law.

The recycling process is shown in Figure 2.3.

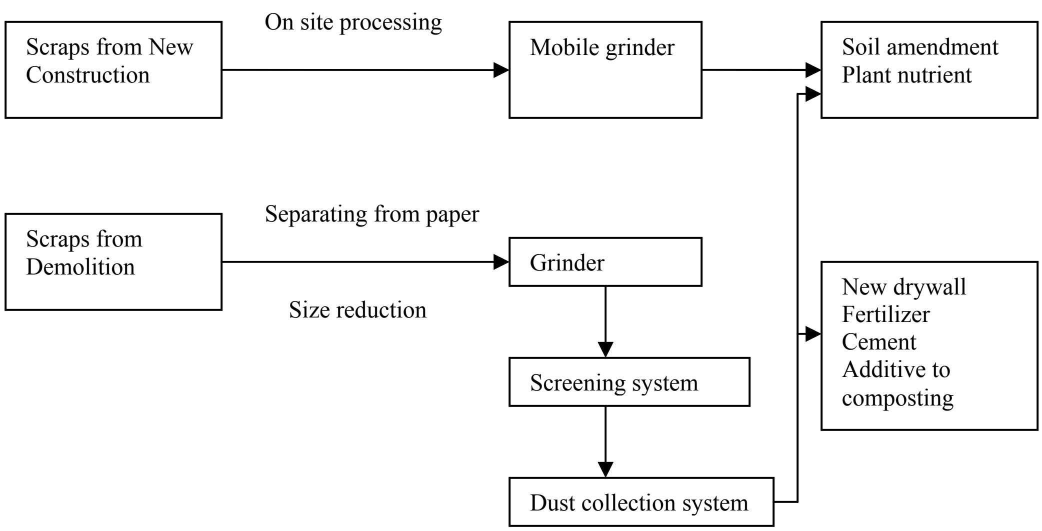

Figure 2.3: Drywall Recycling

Scraps generated during the construction process are clean, while those generated during demolition usually contain paints and fasteners. In recent years, the concept of recycling gypsum drywall at the construction site has been proposed. In this approach, scrap drywall from new construction is separated and processed using a mobile grinder and then size-reduced material is land applied as a soil amendment or a plant nutrient. This approach may be feasible when the soils and grass species show a benefit from the application of gypsum. This recycling technique offers a potential economic benefit when the cost to process and land apply the ground drywall at the construction site is less than the cost to store, haul and dispose of the drywall

For the demolition scraps, several processing methods have been utilized for preparing gypsum drywall for recycling. The two major objectives of processing are separation of gypsum from the paper and the size reduction of the gypsum itself.

Several vendors market self-contained drywall processing equipment. Many of these operate using some type of grinder followed by a screening system, and a dust collection system is typically included. Standard size reduction devices are also found at many waste processing sites can be used to process drywall. Dust issues may need to be addressed and screening will normally be necessary.

2.1.4 Asphalt Roofing

Asphalt roofing materials include composition shingles, built-up roofing, and torch-down roofing. The major components of asphalt roofing waste include asphalt, mineral filler and granules, glass fiber matting, organic paper felt and nails (Karlsson, Robert and Isacsson, 2006). There are a number of potential end usages for asphalt roofing waste including hot mix asphalt, new roofing materials, cold patch, waste-to energy fuel, etc (Katz, 2004; Karlsson, Robert and Isacsson, 2006; Hanson, 1997; Limbachiya, 2004). The table below describes the details of usage of recycled asphalt shingles.

Table 2.3: Potential Usages and Benefitsfor Asphalt Shingles

Usages	Benefits
Hot Mix Asphalt	Reduced demand on virgin asphalt cement Reduced demand on aggregate Improved properties of HMA pavement
Cold Patch	Longer life Easy to apply Good for storage
Dust Control on Rural Roads	Minimized dust Reduced loss of gravel in to side ditches Reduce Vehicle noise Longer life
Temporary Roads or Driveways	Easily installed
Aggregate Road Base	Improved the compaction of the sub-base
New Shingles	Energy saving Not affect the performance
Fuel	Waste to energy

Hot mix asphalt (HMA) is the largest current market for recycled asphalt shingles (Shen and Du, 2005). The added asphalt cement decreases the demand for virgin asphalt cement. This has several benefits. First of all, recycled asphalt is cheaper so that there is an economic advantage to the producers. Cutbacks from shingle factories can be ground up and immediately be added to the hot mix asphalt process, or regenerated with rejuvenating chemicals prior to the hot mix asphalt process (Mallick, 2000). Secondly, hot mix asphalt requires certain gradations of aggregate. The ceramics in the shingles provide a source of aggregate, reducing the demand for mined aggregate. Finally, certain properties of asphalt pavement have been shown to improve with the addition of recycled asphalt shingles. These include rutting and cracking resistance (Hanson, 1997).

The practice of using recycled asphalt shingles as cold patch has been employed for years. Patches using recycled asphalt shingles usually have a longer life than other materials. This is probably due to the fibers form the felts or fiberglass in shingles. Further more, it is very convenient to use this kind of patch. A pothole is simply filled approximately an inch over grade (Shingle Recycling, 2007). No equipment is needed as the patch may be compressed by vehicle traffic. The patch is also less dense than other materials, making it easier to haul. The recycled asphalt shingled cold patch can be stored longer because it does not clump as quickly as other materials (Button, 1996).

Recycled asphalt shingles may be ground and mixed into the gravel used to cover rural, unpaved roads. The advantages include minimizing dust, reducing loss of gravel, reducing noise, and longer life with less maintenance.

Recycled asphalt shingles has been used in temporary roads, driveways, or parking lot surfaces. It is typically ground to 1/4 inch and passed under a magnetic separator in order to sufficiently remove all nails. The processed shingles are spread and compacted for an easily installed surface.

Recycled asphalt shingles have been used as part of the sub-base in road construction. It can also be used to produce new roofing shingles, and a report prepared for the U. S. Department of Energy showed that the addition of up to 20% of recycled shingles did not affect the performance of new shingles. The usage of waste to energy is not recommended due to the air pollution.

2.1.5 Bricks

As shown in Figure 2.4, there are two different ways in which bricks can be recycled.

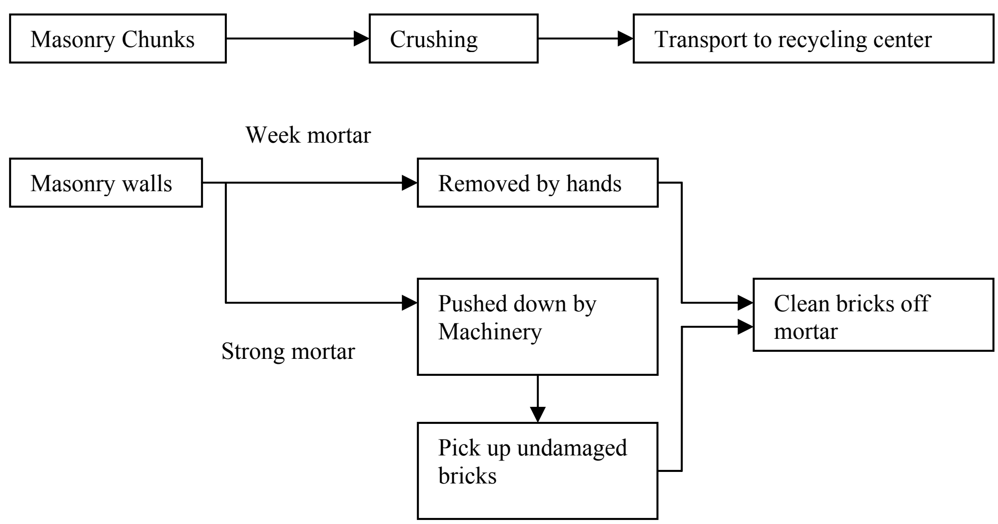

Figure 2.4: Methods of Bricks Recycling

The most common way is crushing them and using the remaining material as a hardcore fill (Gregory, Hughes and Kwan, 2004). A large force is needed in order to crush bricks, which means that heavy machinery is required. These machines are expensive and require a lot of room to operate, so they are only appropriate at sites where there is a large amount of appropriate material that is available to be crushed. The crushing process is simple, and any masonry chunks can be put through the crusher without the need to separate the mortar and bricks. After crushing, the material will be uniformly graded and much easier to transport than demolition rubble. However, hardcore is not a valuable material, and the cost of running a crushing machine is considerable.

The second method of recycling bricks is removing the whole brick by hands (Gregory, Hughes and Kwan, 2004). If the building was constructed using a modern hard cement, it is very difficult to remove the cement from the bricks without causing damage. A demolition contractor will only consider the value of the whole bricks if it was built using a soft lime mortar, which can be easily removed because it is old and weak. It is possible for the contractor to figure out the strength of the mortar by scraping it with a knife or similar instrument. If the mortar is weak enough, it is preferable to demolish the building by hand, one brick at a time, so that each brick can be individually cleaned and placed on a pallet as it is removed. If the mortar is too strong to be removed by hand, the walls can be pushed over with machinery, and the force of the fall will loosen bond between the bricks, allowing them to be picked up and cleaned by hand. This method will cause damage to some of the bricks. The mortar is cleaned from the bricks by hand using a small light hand-axe and an experienced person can clean 1000 bricks in a day (Gregory, Hughes and Kwan, 2004).

Nowadays, used brick is becoming more and more popular because of its unique and antique look. In some areas of the country, old bricks actually have a higher price than new ones.

2.1.6 Metals

Metals are the highly recycled materials due to their own value. Structure steel, the dominating member of all metals in construction, has been recycled for over 150 years, and it always been called “a green material”. The steel industry has well established infrastructure for scrap collection, as this scrap is a feedstock of the steel manufacturing process, which uses between 20% and 100% recycled steel to manufacture new steel, and there is very little difference in strength performance between using recycled steel and virgin material.

The rebar in reinforcing concrete is always made form recycled steel and will be recycled during demolition, so it is a true green product. More than 7 million tons of steel is recycled into reinforcing bars every year, which is the entire feedstock. After demolition, most of the contractors extract and sell the rebars as ferrous scrap. The rebars are melted down to create new steel products.

Metals are always recycled, but seldom reused. If we can reuse metals instead of recycling them, a large amount of energy will be saved. Researches have to be done on how to maximize metals' reuse.

2.1.7 Others

Carpet is composed of face fiber, primary and secondary backings, and an adhesive layer (Figure 2.5).

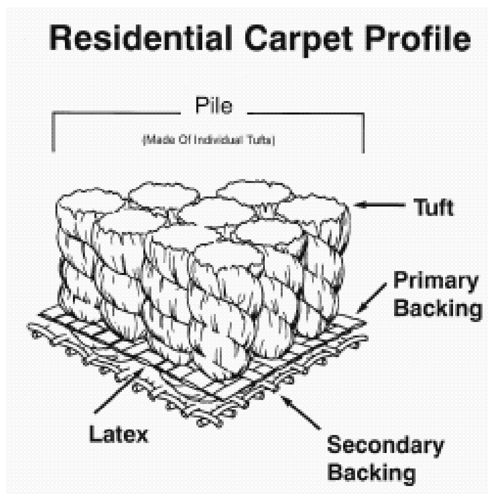

Figure 2.5: Composing of Carpet
(Source: US EPA, 1997)

A lot of programs have been established for carpet recycling. In 1997, manufacturers produced 1.7 billion square yards of carpet, enough to cover New York City's five boroughs more than 1.5 times (EPA, 1998). Carpet covers nearly 70% of floor space of new homes built in the 1990s. In 1996, 70% of annual carpet production was used to replace existing carpet. These replacements produced almost 2 million tons of waste carpet and padding. Although technology exists to recycle carpet and some carpet fibers are desirable in new products, commercial-scale collection and recycling is not yet readily available. Some of the obstacles include the material complexity of carpet and the complex handling practices for carpet waste.

Plastic is the most complex component of C&D debris (Barlaz, Haynie, and Overcash, 1993). Many types are generated: polyvinyl chloride (PVC) window frames, floors, gutters, siding, pipe and wiring insulation; polyethylene (PE) vapor barriers and packaging; high-density polyethylene (HDPE) piping, joint compound, paint buckets and caulk tubes; polystyrene (PS) insulation board; and polypropylene (PP) electrical components. The plastics used in building construction are seldom recycled due to the contamination.

Glass found on construction and demolition sites is primarily plate glass from windows and doors. Many builders place fiberglass insulation leftovers and scraps in partition walls for sound deadening (Searles and Vaux, 2004). Doors and windows have high salvage value for reuse. However, customers are not likely to accept used doors and windows because they are out of fashion. Breakage and obsolescence prohibit their reuse too. Sometimes, the size of the used ones may not fit for new frames. For recycling, because plate glass is made of many different processes and ingredients, manufactures will not normally accept plate glass of unknown origin. However, it is possible to use it as a feedstock for the manufacture of fiberglass.

2.2 Facilities for Building Materials Recycling

The whole recycling process includes collecting recyclable materials, sorting and processing recyclables into raw materials such as fibers, manufacturing raw materials into new products, and selling recycled products.

2.2.1 Recyclables Collection

For MSW recycling, collecting recyclables varies from community to community, but there are four primary methods: curbside, drop-off centers, buy-back centers, and deposit-refund programs (EPA, 2008).

Single-family residential units are often served by curbside programs (White, Franke and Hindle, 1995). These programs may require residents to use one or more containers to separate and store recyclable materials that are diverted from the normal waste stream. Drop-off centers depend on voluntary participation. Buy-back centers offer all of the benefits of drop-off centers and the increased incentives of monetary benefits to participants (Rogoff and Williams, 1994). They are, however, more expensive to operate because they must be staffed, secured, and handle cash. Deposit-refund programs are used in certain states and fit for certain items such as bottles.

As to construction industry, recyclable collection is contractors' responsibility. Some contractors put big containers on job sites to collect recyclables. Demolition contractors sort waste and transport them to transfer stations or just send all the waste to transfer centers without sorting.

2.2.2 Transfer Stations

Regardless of the method used to collect the recyclables, the next leg of their journey is usually the same. Recyclables are sent to a transfer station to be sorted and prepared into marketable commodities for manufacturing (Figure 2.6). Recyclables are bought and sold just like any other commodity, and prices for the materials change and fluctuate with the market.

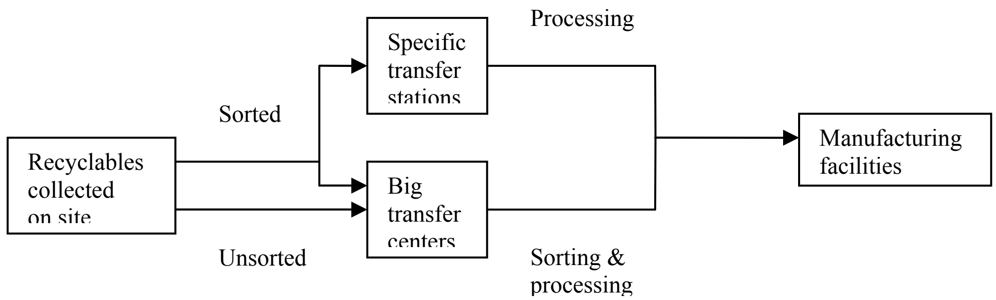

Figure 2.6: Recycling Process

Historically, solid waste was collected in packer-type collection vehicles which delivered the waste directly to landfills (McGraw-Hill, 2001). As landfills closed, haul distances became greater, giving rise to the use of transfer stations in which the waste is transferred to large-capacity transfer trailers the trailers are then hauled to the landfill.

In recent years, transfer stations have also been used for diverting, collecting, and transporting recyclables as well as incorporating material processing systems into the same transfer facility (McGraw-Hill, 2001). Transfer stations currently being designed are typically enclosed in a building to reduce problems associated with noise, odor, and blowing litter and to provide an aesthetically pleasing facility. Advantages associated with transfer stations have resulted in a rapid growth in the number constructed in the past three decades. The principal benefits derived from a transfer station are shown in Table 2.4.

Table 2.4: Benefits Derived form Transfer Stations

Benefits	Description
Economy of haul	Large capacity of transfer trucks Fewer trips Reducing operating cost
Labor saving	Reducing idle time
Energy saving	Less fuel
Reduced wear and tear	Reducing times of going to landfill
Versatility	Processing materials
Reduction of landfill face	Reducing the number of vehicles Smaller working area Less daily cover requirements

Transfer truck legal payloads of 18 to 25 tons can be obtained, compared to the 4 to 10 ton legal payload of most collection trucks (McGraw-Hill, 2001). This results in fewer trips to the disposal or processing site, allowing the collection fleet more time on the route to perform collection service. An overall reduction in capital and operating cost for the collection fleet can result.

Many route trucks operate with two-or three-person crews. The additional travel time of the truck to the disposal site keeps these workers from their collection duties. Since transfer trucks require only a one-person crew, a reduction in nonproductive time can be achieved.

Over- the-road fuel use of collection equipment and transfer tractors are similar. Significant fuel savings will be experienced as a result of the fewer trips required to the disposal or processing site.

A total mileage savings will result from the fewer trips. However, just as important is the reduction in the number of flat tires and damage to power transmission and suspension systems that results from operation on muddy and irregular landfill surfaces.

The flexibility of a transfer system allows the solid waste manager the freedom to shift the waste destination with minimal impact on collection operations.

Since the length of the landfill dumping face is generally determined by the number and type of vehicles using the site, a reduction in the number of vehicles will result in a smaller working area, less daily cover requirements, and safer conditions at the landfill due to reduced traffic. A landfill that receives only waste hauled in transfer trailers may require a working face less than half that required for a landfill receiving a similar quantity of waste hauled in packer-type vehicles.

The transfer station site must have adequate area for on-site roads, utilities, surface-water drainage, and auxiliary facilities (McGraw-Hill, 2001). In some parts of Florida, the land requirements to meet drainage regulations can be as much as 25% of total site. Auxiliary requirements can include offices for staff, a scale house and scales, transfer vehicle storage, maintenance structures, vehicle wash bay, fuel storage and dispensing equipment, and employee parking.

Environmental awareness has led designers of transfer stations to place greater emphasis on minimizing adverse impacts such as noise, dust, and odor. Considerable additional area may be required for landscaping and screening berms to minimize adverse environmental impacts.

2.2.3 Re-manufacturing Facilities

Once cleaned and separated, the recyclables are ready to undergo the next part of the recycling loop. More and more of today's products are being manufactured with total or partial recycled content. The re-manufacturing facilities are usually the same as the manufacturing facilities using the virgin materials.

2.2.4 Market for Recycled Products

Purchasing recycled products is the finial step to complete the recycling loop. By buying recycled, governments, as well as businesses and individual consumers, each play an important role in making the recycling process a success. As consumers demand more environmentally sound products, manufacturers will continue to meet that demand by producing high-quality recycled products.

2.3 Summary

From the above literature review, we can draw the conclusion that the current technologies can support most materials' recycling and the facilities are available to process these recyclables. In other words, we can recycle nearly everything in a building if we really want to. Then why don't we do the environment a favor?

It is obvious that the recycling rate for different materials is quite different. What are the reasons for the difference?

From the literature, we can also find that due to the obsolescence, damages, contaminations, etc., we usually do not recycle certain building materials. Are these the only reasons for the unfavorable recycling rate? Can they be avoided? What are the other reasons? Is there any method to increase the recycling rate? Having these questions in mind, research objectives will be developed.

Chapter 3 Research Objectives and Methodology

After targeting building materials recycling as the research topic and reviewing relevant literatures, some questions keep haunting in mind. What are the reasons for the low materials recycling rate in construction industry? How can we increase the recycling rate? This paper will focus on solving these problems.

3.1 Research Objectives

The main purposes of this paper are

(1) to find out obstacles of building materials recycling; and

(2) to identify the solutions on how to break obstacles and increase the recycling rate.

To achieve these main objectives, some sub-objectives will be developed, too. To fulfill the first objective, the following research questions will be answered:

- What are the causes of obstacles?
- How can we sort them?
- Who are responsible for these obstacles?
- How can we identify the obstacles?
- How can we prove they are the obstacles?

To fulfill the second objective, the following research questions will be answered:

- What are other people's suggestions on increasing building materials recycling rate?
- Is there a more effective way?
- What is building design recyclability?
- What are the principals for building design recyclability?
- What are the variables of design recyclability?
- How can design recyclability increase materials recycling rate?
- How to prove that?

3.2 Research Methodology

To fulfill the above objectives, literature will be reviewed to find the obstacles of building materials recycling. Interview industry professionals will also help to identify the obstacles. A case study will be used to testify these obstacles. Literatures will be reviewed to find the current solutions for increasing recycling rate. After having all the above information, a more effective suggestion will be given. The concept of design recyclability will be developed and the principles of it will be described by analyzing and summarizing the above information and findings. Drives will be derived from principles. The same case will be used to testify the drives.

Chapter 4 Data Analysis and Concept Development

A lot of researches have been done about the obstacles of building materials recycling. However, most of them are based on experience or opinions from industry professionals. None of them has testified their findings. In this paper, after identifying and sorting the obstacles, case studies will be used for testifying. A new concept will be developed to suggest a more effective way to increase recycling rate.

4.1 Identifying Obstacles of Building Materials Recycling

Technically, it is possible to recycle nearly everything in a building, but in reality, the building materials' recycling rate is far from 100%. There are a lot of obstacles for building materials' recycling. Some of them are people's problems, while some of them are related to the materials' characteristics. For example, in order for materials to be reusable, contractors generally must remove them intact, like windows and frames, plumbing fixtures, floor and ceiling tiles, or in large pieces, like drywall and lumber. Some materials may require additional labor before they can be reused. Moreover, in order to be recyclable, materials must be separated from contaminants, such as trash, nails, and broken glass. There are also some other important factors and I'd like to put them into six categories: social, environmental, economic, materials natural, participants, and regional factors (Table 4.1).

Table 4.1: Obstacles of Building Materials Recycling

Social Factors	Lack of education
	People's willingness
	People's preference for fashion
Environmental Factors	Hazardous components
	Low tipping fee
	Site condition
Economic Factors	Materials markets
	Project timeline
	Cost effectiveness
Materials Natural Factors	Quantity too small
	Size too big
	Conjunction
	Complicated composing
Participants' Factors	Contractors' experience
	Labor capability
	Relationships among participants
Regional Factors	Regional traditions
	Regional capacities
	Regional markets

4.1.1 Social Factors

Lack of education

Many people in the US haven't realized how necessary recycling is. The US is a country full of resources, so people may think that they won't bother having nothing to use. However, around the world, many nonrenewable resources are exhausted. If we continue consuming and polluting at current rate, our next generation will have to dig the landfill. The American can not live a good life without a healthy global environment. Therefore, we have to draw people's attention to recycling. Many educators have already tried to integrating recycling into K-12 educational system.

People's willingness

Recycling is usually a voluntary activity. Sometimes, people know that recycling is benign, but they don't have a strong willingness to do it (Teo and Loosemore, 2001). In England, it is common for people to drive their cars to the recycling facilities just for taking a box of old newspapers there. More researches need to be done on how to encourage people to recycle things.

People's preference for fashion

Customers always prefer new and fashionable items to used ones. Sometimes even if we can salvage some components during demolition, we can not find a market for the used ones. Doors, windows and carpet are all this kind of items. If no one wants to buy the reused ones, they are not truly reused.

4.1.2 Environmental Factors

Hazardous components

Throughout the construction industry, we have used and continue to use large quantity of chemical substances and additives in all types of products to enhance technical properties (Sheridan, et al, 2000). Some of these additives have negative impact on environment. Therefore, authorities have frequently enacted regulations or bans to minimize their impacts. Hazardous components prevent recyclable materials from recycling. The following is a table showing hazardous substances in building components (Table 4.2).

Table 4.2: Hazardous Substances in Building Components
(Source: Strufe, 2005)

Substance	Building components and/or materials
Asbestos	Roofs and tiles Glue Sound insulation Fire-resistant sealing Wall plaster
PVC	Gutters and pipes
Lead	Roofs and tiles Electrical cables
Cadmium	Plastic (e.g. cable, pipes and plates) Occurring with zinc Occurring with concrete
Mercury	Fluorescent tubes Switches and relays (electrical installations) Others (e.g. concrete)
Nickel	Stainless steel Surface treatment
Chromium	Stainless steel Others (e.g. painted surfaces)
Copper	Cables and wires • permanent installations • temporary installations Roofs, pipes, etc. Screws, locks, etc. Pigments and dyes
Zinc	Gutters/pipes and galvanised products Plastic (especially gutters and pipes)
PCB	Small capacitors and electrical installations Double-glazed windows (glue) Sealant (softener) Paint (pigments) Fire-resistant additive (paint, glue/binder)
Chlorinated paraffin	Plastic (in general) Sealant (softener) Others (e.g. glue)
CFCs	Thermal insulation—PUR foam Other insulation materials
HCFCs and HCFs	Thermal insulation—PUR foam Foam for joints
Sulphur hexafloride	Soundproof windows

There are environmental regulations about safety of demolition sites to protect workers from hazardous materials, and this makes recycling certain material even harder. The Environmental Protection Agency and the Occupational Safety and Health Administration (OSHA) both have federal regulations governing the management of asbestos containing materials (ACM) and lead-based paint (LBP) in buildings. OSHA worker protection requirements for both ACM and LBP are tougher on deconstruction than demolition because the exposure is much greater.

Low tipping fee

One of the reasons for the unfavorite building materials recycling rate is the lower tipping fees. Because much of the C&D wastes are inert, solid waste rules in most states do not require the landfills to provide the same level of environmental protection as landfills licensed to receive MSW (EPA report, 1998). Therefore, C&D landfills generally have lower tipping fees, and a large fraction of C&D debris generated in the United States ends up in landfills.

Site condition

The demolition job sites always don’t have enough space for storage of recyclables and on-site sorting. Having separate containers for each type of materials can reduce contamination. Each container should be labeled. Therefore, site condition is also an important factor for building materials recycling.

4.1.3 Economic Factors

Materials markets

In some of the research projects, the recovery rate during demolition can be as high as 90%. But will the recyclables really be recycled? How many of them will go to landfill after being recycled on site? These depend on the recycled materials markets. Unfortunately, the markets for recyclables in the U. S. are not enough (Ueda, Nishino and Oda, 2003). If we can not sell the recycled materials, we have to find a place to store them. Then why do we bother recycling them. Since no one what to use the recycled materials, they will go to landfill eventually.

Project Timeline

In order for recycling as many materials as possible, we usually do deconstruction rather than demolition. Deconstruction will take longer time and need more skilled workers than demolition. However, demolition projects always are often on a tight schedule due to financing arrangements. Then, the timeline prevent Contractors from recycling materials. Preplanning can maximize materials recovery in the time allowed. If possible, contractors can do offsite source separation and recycling.

Cost Effectiveness

The feasibility of any recycling program depends on whether the total cost of recycling is less than the sum of cost of labor, tipping, landfill, hauling fees and taxes. If the condition is satisfied, recycling is cost effective. If the recycling cost is more than the landfill, then recycling operations are not cost effective. However, if we consider selling recycled materials as feedstock, there will be some add-on value to the recyclables. But comparing to using virgin feedstock, deconstruction, hauling, and processing costs will always make recycled feedstock more expensive.

4.1.4 Materials Natural Factors

Quantity too small

For single-house demolition projects, the quantity of each material is not big enough for a hauling vehicle to go and pick it up. The common collection truck has a legal payload form 4 to 10 tons. Therefore, small project may look for alternative vehicles to transport recyclables to transfer stations. Another method is transport all of the wastes to transfer center by collection trucks.

Size too big

Some of the materials like timber are too long to be transported. To solve this problem, designers must know what the size limitation of transport vehicles is and design the buildings using smaller size materials.

Conjunction

The conjunction method of different pieces of materials is very import for deconstruction. For example bolts are better than welds in the ease of separation.

However, the ease with which components can be recovered form a building is greatly affected by how the building was put together in the first place.

Complicated composing

Some of the building components have very complicated composing. Take carpet as an example. Carpet is composed of face fiber, primary and secondary backings, and an adhesive layer. It is impossible to separate carpet into four parts and recycling. Then, reuse may be a good option, especially when it is made from carpet tiles.

4.1.5 Participants' Factors

Contractors' experience

Contractors with knowledge of recovery methods and local markets may be able to recover more materials than contractors unfamiliar with reuse and recycling issues. Experienced contractors can be more effective in planning, workforce education, and recyclables transportation. The experienced contractors can deal with oversights quick and sound, too.

Labor capability

If the deconstruction workforce is familiar with reuse and recycling, it will be easier for the contractor to do his job. With proper education, preplan, and some practice, labors will be capable to do their job.

Relationships among participants

Owner, designer and contractor should cooperate with each other to make a building recyclable. The owner should understand recycling and allow contractor to use enough time to salvage recyclables (Ruff, Dzombak and Hendrickson, 1996). It is good for the contractor to build a solid relationship with local recyclers. Nowadays, recycling building materials is contractors' responsibility, but if owners and designers can have some knowledge of recycling, it will make contractors job easier.

4.1.6 Regional Factors

Regional traditions

In the United States, the recycling rates vary from region to region, state to state, city to city. There is a news form the New York Times, titled "Houston Resists Recycling". According to this news, Houston recycles just 2.6 percent of its total waste, according to a study by Waste News, a trade magazine. By comparison, San Francisco and New York recycle 69 percent and 34 percent of their waste respectively (Ellick, 2008). Moreover, 25,000 Houston residents have been waiting as long as 10 years to get recycling bins from the city. Here is a list (Figure 4.1) of recycling rates for top 15 big cities in the US.

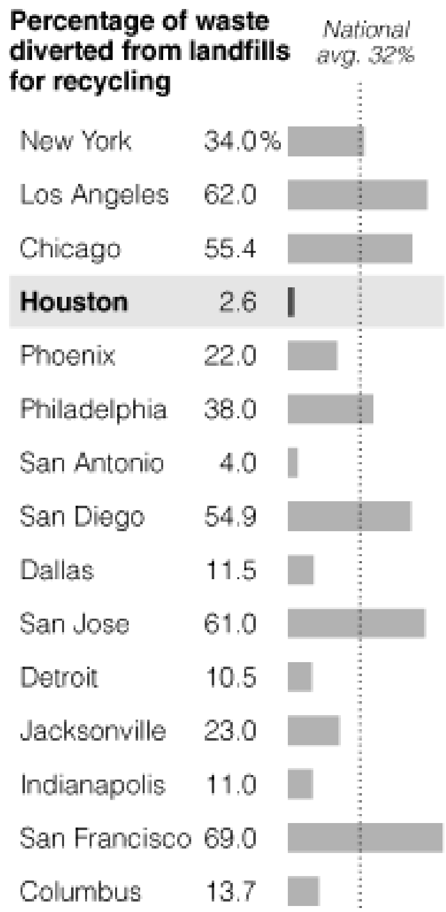

Figure 4.1: Recycling Rate for Top 15 Big Cities
(Source: the New York Times, 2008)

City officials of Houston say real progress on recycling will be hard to come by. Landfill costs there are cheap. The city's sprawling, no-zoning layout makes collection very expensive, and there is little public support for sorting glass, paper and plastics. And there appears to be even less for placing fees on excess trash.

It is a traditional culture for Houston and many other cities in Central America not to care about recycling. People living there just do not have the awareness of recycling. On the contrary, residents in California take recycling as something they have to do.

Regional capacities

Suppose that contractors are experienced and well educated about recycling. They have the ability to do deconstruction and onsite sorting. They are very aspiring to recycling everything if it is possible. They send all the recyclables to nearby transfer stations, and they claim that the recycling rate of their project is nearly 100%. What will happen to the recyclables after they have been sent to transfer stations? In some states, where transfer stations have the technology to process recyclables and sell them to manufacturing facilities, the recyclables are really been recycled. On the contrary, in states which lack the recycling abilities, the recyclables will be sent to landfill eventually. Therefore, even though contractors' participant is important to recycling, it is just one link of the whole chain. Regional capacity for recycling is another vital factor.

Regional markets

After recyclables being sorted and processed, they will be sold to manufacturing facilities. However, for most of the products, we can not only use recycled as feedstock. There are regulations about the highest percentage of recycled feedstock for the product properties. Some manufacturing factories even don't accept recycled materials because virgin materials are cheap and abundant in supply. The recyclables which can not be sold for remanufacturing will go to landfill and become non-recyclables.

4.2 Case Study

Although a lot of researches have identified obstacles of building materials recycling, their findings are mostly based on experience and the opinions gotten form industry professionals. None of them has testified these obstacles. A case study, a face institute (Figure 4.2), will be used in this paper to figure out whether these are real reasons for the low recycling rate and which have more negative effect than the others.

Figure 4.2: A Typical Surgery Building

4.2.1 Face Institute in Texas

The face institute used in this paper is located at 6501 Blanco Road, Castle Hills, Texas. The city of Castle Hills, Texas is a part of San Antonio Metropolitan area. The recycling rate in that area is about 4%, slightly higher than Houston, Texas. This building is a typical surgery building. The building area is 5,517 SF. Table 4.3 shows the materials and components used in that building, with size and quantity.

Table 4.3: Components and Materials of a Typical Surgery Building

Components	Material	Size & description	Unit	Quantity
Rebar	steel		Ton	160
Slab, Beam & Column	concrete		CY	25,000
Formworks	wood		MBF	5.5
External Wall	CMU		SF	1,000
Stone Veneer	limestone		SF	800
Roof trusses	wood	60'Length	ea	4
	wood	40'Length	ea	4
	wood	38'Length	ea	8
	wood	36'Length	ea	8
	wood	34'Length	ea	8
	wood	32'Length	ea	19
	wood	30'Length	ea	8
	wood	28'Length	ea	8
	wood	26'Length	ea	8
	wood	24'Length	ea	13
	wood	22'Length	ea	8
	wood	20'Length	ea	14
	wood	18'Length	ea	8
	wood	16'Length	ea	13
	wood	14'Length	ea	8
	wood	12'Length	ea	18
	wood	10'Length	ea	16
	wood	8'Length	ea	16
	wood	6'Length	ea	19
	wood	4'Length	ea	16
	wood	2'Length	ea	16
Studs	Metal	1/2"-6"	ea	64
	Metal	1/2"-8"	ea	75
	Metal	3/4"-4"	ea	250
Storefront	Alum.& Glass	6'*8'	ea	2
Door	wood	3'*2'	ea	2

	wood	3'*7'	ea	40
	wood	6'*7'	ea	1
	wood	4'*7'	ea	2
	wood	4'*5'	ea	2
	Wood & glass	3'*7'	ea	8
	metal	3'*7'	ea	6
	metal	4'*7'	ea	1
Window	glass	11'-4 1/2"*8'	ea	1
	glass	5'-8 3/4"*8'	ea	2
	glass	13'-8 1/2"*3'	ea	1
	glass	10'-3"*3'	ea	1
	glass	16'-8"*5'-6"	ea	1
	glass	5'-7 1/2"*5'-6"	ea	1
	glass	14'-4"*8'	ea	1
	glass	8'-1"*8'	ea	1
	glass	3'-9"*8'	ea	1
	glass	7'-9 1/2"*8'	ea	3
	glass	12'-3 1/2"*8'	ea	1
	glass	8'-3"*8'	ea	2
	glass	2'-8"*3'-10"	ea	1
	glass	2'*3'	ea	2
	glass	4'*4'	ea	2
Wall	gypsum board	5/8" thick	SF	10,000
Ceiling	gypsum board	5/8" thick	SF	5,000
Floor	carpet		SF	2,000
	vinyl tile		SF	3,000
Base	rubber	4" thick	SF	5,000
	vinyl		SF	50
Door hardware	metal		ea	64
Door frame	metal	3'*2'	ea	2
	metal	3'*7'	ea	54
	metal	6'*7'	ea	1
	metal	4'*7'	ea	3
	metal	4'*5'	ea	2
Window frame	metal	11'-4 1/2"*8'	ea	1
	metal	5'-8 3/4"*8'	ea	2
	metal	13'-8 1/2"*3'	ea	1
	metal	10'-3"*3'	ea	1
	metal	16'-8"*5'-6"	ea	1
	metal	5'-7 1/2"*5'-6"	ea	1
	metal	14'-4"*8'	ea	1

	metal	8'-1"*8'	ea	1
	metal	3'-9"*8'	ea	1
	metal	7'-9 1/2"*8'	ea	3
	metal	12'-3 1/2"*8'	ea	1
	metal	8'-3"*8'	ea	2
	metal	2'-8"*3'-10"	ea	1
	metal	2'*3'	ea	2
	metal	4'*4'	ea	2
X-Ray Protection	lead gypsum board	5/8" thick with 1/16" lead	SF	300
Fire alarm control panel	NA		ea	1
Smoke Detector	NA		ea	20
Cold water pipe	steel		LF	160
Hot water pipe	steel		LF	320
Backflow prevent valve	steel		ea	1
Butterfly valve	steel		ea	50
Heavy duty floor drain	NA		ea	2
Hub drain	NA		ea	1
Vent pipe	steel		LF	300
Sanitary sewer pipe	steel		LF	320
Circulation pump	NA		ea	1
Water closet	NA		ea	4
Lavatory	NA		ea	4
Sink	NA		ea	19
Water heater	NA		ea	1
Duct heater	NA		ea	1
Fan	NA		ea	2
Air diffuser	NA	10"DIA, 24"face	ea	18
	NA	8"DIA, 12"face	ea	14
	NA	6"DIA, 12"face	ea	18
Grille	NA	8*8	ea	2
	NA	12*12	ea	7
	NA	14*14	ea	15
	NA	24*12	ea	1
Louver	NA	12*12	ea	1
	NA	18*18	ea	1
	NA	30*24	ea	1
Conductor	copper		LF	2,000
Tube	NA		LF	13,000
Junction box	NA		ea	9
Telephone outlet	NA		ea	37

Safety switch	NA		ea	6
Lighting	NA	2'*4'	ea	56
	NA	pole mounted	ea	2
	NA	surface mounted	ea	8
	NA	darkroom light	ea	1
	NA	utility drum light	ea	4
	NA	incandescent can	ea	7
	NA	wall mounted	ea	2
	NA	floodlight	ea	1
	NA	compact can	ea	8
	NA	recessed can	ea	8
	NA	under counter light	ea	2
	NA	sign light	ea	1
	NA	lamp mounted	ea	8
	NA	emergency lighting	ea	6

This is just a traditional design, which didn't embody recycling at all. It used nearly all typical building materials for such a small building, including steel, concrete, wood, CMU, limestone, aluminum, glass, gypsum board, vinyl tile, rubber, etc. The following table (Table 4.4) describes whether these components and materials can be recycled and what prevent them from being recycled.

Table 4.4: Obstacles of Texas Face Institute Recycling

Compo -nents	Material	Recyclable or Not	Why not														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Rebar	steel	Y	-----														
Slab, Beam & Column	concrete	N		○				○	○	○				○			○
Formwork	wood	N	○	○										○			○
External Wall	CMU	N		○				○	○	○		○		○			○
Stone	limeston	Y	-----														

Veneer	e																
roof trusses	wood	N			○			○	○	○		○		○			
Studs	Metal	N										○		○			
storefront	Alum.& Glass	N				○			○								
Door	wood	N	○			○		○	○								
	Wood & glass	N	○			○			○						○	○	
	metal	N				○			○								
Window	glass	N				○		○	○						○	○	
Wall	gypsum board	N		○			○	○	○	○			○	○			○
Ceiling	gypsum board	N		○			○	○	○	○			○	○			○
floor	carpet	N				○		○	○				○			○	
	vinyl tile	N	○			○		○	○	○		○				○	○
Base	rubber	N	○				○	○	○	○					○		○
	vinyl	N	○				○	○	○	○							○
door hardware	metal	N							○			○		○			
door frame	metal	N							○			○		○		○	
window frame	metal	N							○			○		○		○	
X-Ray Protection	lead gypsum board	N		○				○	○	○	○		○				
Fire alarm control panel	NA	Y	-----														
Smoke Detector	NA	N						○	○		○			○			○
cold water pipe	steel	N													○		
hot water pipe	steel	N												○	○		
Backflow prevent valve	steel	N												○	○	○	
butterfly valve	steel	N												○		○	
heavy duty floor drain	NA	N						○	○					○		○	
hub drain	NA	N						○	○					○		○	

vent pipe	steel	N												○			
sanitary sewer pipe	steel	N												○		○	
circulation pump	NA	Y	-----														
water closet	NA	N				○		○	○							○	○
lavatory	NA	N				○		○	○					○			○
sink	NA	N				○		○	○					○			○
water heater	NA	Y	-----														
duct heater	NA	Y	-----														
fan	NA	Y	-----														
air diffuser	NA	Y	-----														
grille	NA	N						○	○					○		○	○
louver	NA	N						○	○					○		○	○
conductor	copper	N						○	○								
tube	NA	N						○	○								○
junction box	NA	N	○					○	○							○	○
telephone outlet	NA	N	○					○	○							○	○
safety switch	NA	N						○	○								○
lighting	NA	N			○			○	○								

Note: In this table, the numbers represent the following reasons:
1: Low salvage value
2: Quantity too small
3: Size too big
4: Out of fashion
5: Site condition
6: Regional materials market
7: Regional traditions
8: Regional capacities
9: Hazardous components
10: Conjunction method
11: Complicated composing
12: Contamination
13: Obsolescence
14: Damages
15: Cost effectiveness

Among the total 48 items, only 8 of them can be recycled in the area of San Antonio, TX. The other 40 items can not be recycled there. Table 4.5 will summarize the results of table 4.4

Table 4.5: Analyzing the Obstacles of Texas Face Institute Recycling

Ranking	Obstacles	Quantity of items	Total non-recyclable items	Percentage
1	Regional traditions	32	40	80%
2	Regional materials market	26	40	65%
3	Contamination	22	40	55%
4	Cost effectiveness	18	40	45%
5	Damages	16	40	40%
6	Out of fashion	10	40	25%
7	Regional capacities	9	40	22.5%
8	Low salvage value	8	40	20%
9	Conjunction method	7	40	17.5%
10	Quantity too small	6	40	15%
11	Obsolescence	5	40	12.5%
12	Site condition	4	40	10%
12	Complicated composing	4	40	10%
14	Hazardous components	2	40	5%
15	Size too big	1	40	2.5%

From the above table, it is obvious that the regional factors are responsible for most of the non-recyclable items. Contamination contributes a lot, too. If we can avoid regional factors, the recycling rate should increase tremendously.

4.2.2 Face Institute in California

Supposing this face institute is located in Los Angeles, California, where people are willing to recycle everything. Therefore, the regional traditions will not be an obstacle of materials recycling. Then the table will be like this (Table 4.6).

Table 4.6: Obstacles of California Face Institute Recycling

Compone-nts	Material	Recy-cled or Not	Why not														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Rebar	steel	Y	-----														
Slab, Beam & Column	concrete	Y	-----														
Formworks	wood	N												○			○
External Wall	CMU	Y	-----														
Stone Veneer	limestone	Y	-----														
roof trusses	wood	Y	-----														
Studs	Metal	Y	-----														
storefront	Alum.& Glass	Y	-----														
Door	wood	Y	-----														
	Wood & glass	Y	-----														
	metal	Y	-----														
Window	glass	Y	-----														
Wall	gypsum board	Y	-----														
Ceiling	gypsum board	Y	-----														
floor	carpet	Y	-----														
	vinyl tile	Y	-----														
Base	rubber	Y	-----														

	vinyl	Y	-----														
door hardware	metal	Y	-----														
door frame	metal	Y	-----														
window frame	metal	Y	-----														
X-Ray Protection	lead gypsum board	N									○		○				
Fire alarm control panel	NA	Y	-----														
Smoke Detector	NA	N									○			○			○
cold water pipe	steel	Y	-----														
hot water pipe	steel	Y	-----														
Backflow prevent valve	steel	N												○	○	○	
butterfly valve	steel	N												○		○	
heavy duty floor drain	NA	N												○		○	
hub drain	NA	N												○		○	
vent pipe	steel	Y	-----														
sanitary sewer pipe	steel	N												○		○	
circulation pump	NA	Y	-----														
water closet	NA	Y	-----														
lavatory	NA	N												○			
sink	NA	N												○			
water heater	NA	Y	-----														
duct heater	NA	Y	-----														
fan	NA	Y	-----														
air diffuser	NA	Y	-----														
grille	NA	N												○		○	

louver	NA	N												○		○	
conductor	copper	Y	-----														
tube	NA	Y	-----														
junction box	NA	Y	-----														
telephone outlet	NA	Y	-----														
safety switch	NA	Y	-----														
lighting	NA	Y	-----														

Note: In this table, the numbers represent the following reasons:
1: Low salvage value
2: Quantity too small
3: Size too big
4: Out of fashion
5: Site condition
6: Regional materials market
7: Regional traditions
8: Regional capacities
9: Hazardous components
10: Conjunction method
11: Complicated composing
12: Contamination
13: Obsolescence
14: Damages
15: Cost effectiveness

Table 4.7: Analyzing the Obstacles of California Face Institute Recycling

Ranking	Obstacles	Quantity of items	Total non-recyclable items	Percentage
1	Contamination	11	12	91.7%
2	Damages	7	12	58.3%
3	Hazardous components	2	12	16.7%
3	Cost effectiveness	2	12	16.7%
5	Obsolescence	1	12	8.3%
5	Complicated composing	1	12	8.3%

Among the 48 items, 36 of them are recyclable in California and 12 of them are non-recyclable. The building is the same one, which means the quantity of materials, the size of components, the conjunction methods, etc. are all the same. These are obstacles in Texas, and there are still problems in California. However, comparing with these factors, regional tradition is the leading one. If people are willing to recycling materials, they can conquer other obstacles, and make items recyclable.

The regional market is another important factor for recycling. However, in some states like California, they always recycle more materials than the amount that local markets can absorb. They will transport recycled materials overseas. It may not be cost effective, but they just do that for the sake of environment. Therefore, if people's will for recycling is strong, we can conquer the minor obstacles and make recycling possible.

4.3 Strategies for Increasing Building Materials Recovery Rate

After identifying and testifying the obstacles, we can try to figure out the ways to break them and increase the recycling rate. A lot of researchers have focused on how to increase building materials recovery rate, especially in Japan and Europe (Boonstra and Knapen, 2000; Bossink, 2002). Other manufacturing industries such as electronic industry and automobile industry have gone further in recycling than construction industry (Bohr, 2006; Onuki, 1998).

4.3.1 Extended Producer's Responsibility

Extended producer's responsibility (EPR) has been used as a policy tool for electronics recycling in some counties for years. As to construction industry, it is still an unacquainted concept. EPR is a way to ensure that the polluter pays for the environmental impacts that its product causes (Hanisch, 2000). EPR requires producers to be financially or physically responsible for their products after their useful life. By placing the end of life burden on the manufacturer, it is expected that it will look for ways to design products to minimize end of life costs such as disassembly and disposal costs through instruments like design for recyclability, reduced material usage, product disassembly, reduced or eliminated use of toxic materials, remanufacturability (Guggemos and Horvath, 2003). The following table shows the policy tools to achieve EPR (Table 4.8).

Table 4.8: Policy Tools for Achieving EPR
(Source: Guggemos and Horvath, 2003)

Instrument type	Policy tool
Regulatory instruments	Product takeback (PTB)
	Minimum recycled content standards
	Secondary materials utilization rate requirements
	Energy efficiency standards
	Disposal bans and restrictions
	Materials bans and restrictions
	Product bans and restrictions
Economic instruments	Advance disposal fees
	Virgin materials taxes
	Removing subsidies for virgin materials
	Deposit/refund
	Environmentally preferable products procurement
Information instruments	Seal-of-approval types of environmental labeling
	Environmental information labeling
	Product environmental profiles for whole life cycle of materials
	Product hazard warnings

Construction industry is a unique industry that has both product manufacturing and service components. The following table compares construction with other industries (Table 4.9).

Table 4.9: Construction versus Other Industries
(Modified form Guggemos and Horvath, 2003)

Issue	Packaging	Electronics
Product lifetime	Short (<1 year)	Moderate (1–5 years)
Product design and fabrication	Same: producer	Same: producer
Industry make-up	Small and large companies	Few large companies
Product identification	Easy	Easy
Product modifications during O+M	None	None
Product uniqueness	No	No: many of same model

Issue	Cars	Buildings
Product lifetime	Moderate (5–10 years)	Long (>10 years)
Product design and fabrication	Same: producer	Architect designs, contractor builds
Industry make-up	Few large companies	Many small companies
Product identification	Easy	Difficult
Product modifications during O+M	Few, if any	Many, at different times
Product uniqueness	No: many of same model	Prototype

For the unique characteristics of construction industry, taking back an entire building is not feasible. However, it may be possible to take back certain building materials or components such as air conditioning, elevators, boilers, water tanks, switchgears, electric panels, and other engineered-to-order products. These components have shorter lives than the building structure. The producer is easily identified through markings on component.

4.3.2 Deconstruction

The cost and ease of removal of components from a building at the end of its life are significant factors affecting the amount of reuse and recycling that occurs (Rose, Ishii and Stevels, 2002). The ease with which components can be recovered from a building is greatly affected by how the building was put together in the first place. Designers need to think about not only how materials will be put together but also how components will be separated at the end of life.

For easy disassembly, components should be incorporated into buildings in a way that facilitates separation, and materials should be chosen that can be readily reused or recycled. To facilitate disassembly, the designer should consider the following things (Table 4.10).

Table 4.10: Considerations for Deconstruction during Design Phase

Factors	Descriptions
Conjunctions	Components with fasteners and connections that are designed to be easy and quick to take apart, such as bolts rather than welds, are more likely to be reused or recycled
Deconstruction Plan	Whoever is doing the reclaiming, whether the manufacturer or a third party, may need instructions, such as disassembly or refurbishment plans, or information, such as specifications for the materials
Timeline	Time should be allowed for a building to be disassembled at the end of its useful life
Recycling Route	Choosing materials and parts, such as steel and components, that have recognized routes for recycling and reuse will greatly encourage their reuse in future

Designers should consider at the outset how components will be replaced in the building during its useful life and how the building will be dismantled at the end of its life to maximize the usefulness of the components and materials. The design team needs to think through, at the concept stage, the building's lifetime changes. Potential problems during refurbishment and eventual deconstruction should be investigated. For example, allowing site access for machinery and designing floors to take the additional load of demolition plant and rubble should be a consideration.

Furthermore, the chronology of the deconstruction process is very important. The proper sequence of disassembly increases jobsite safety and efficiency. It also protects recyclables from unnecessary damage. There are five basic steps for deconstruction as shown in Table 4.11.

Table 4.11: Basic Steps to Building Deconstruction
(Source: Chini and Bruening, 2003)

1) Remove the trim work, including door casings and moldings.
2) Take out kitchen appliances, plumbing, cabinets, windows, and doors.
3) Remove the floor coverings, wall coverings, insulation, wiring, and plumbing pipes.
4) Disassemble the roof.
5) Dismantle the walls, frame, and flooring, one story at a time.

4.3.3 Systems and Two Stage Buildings

Systems building is an integrated system assembled from a series of multiple independent subsystems (Kim, Brouwer and Kearney, 2004). Since different components in a building have different life time, independent subsystems provide convenience for maintenance and renovation. As to recycling, if components can be dismantled easily and undamaged, it will be more likely to reuse or recycle them.

Building systems are classified into two groups: the infrastructure and the infill. This classification provides the principal guideline for implementing the two stage buildings. The infrastructure is designed to be permanent, while the infill is designed to be easily replaceable.

An innovation project in Osaka, Japan, named NEXT 21, best illustrated these concepts (Kim, Brouwer and Kearney, 2004). That is an experimental multi-family housing fitting for high-density urban area. The components are easy to be taken out, and it is good for renovation and recycling.

4.3.4 Alternative Materials

Considering using more recyclable materials to take place of current materials is another attempt to increase recycling rate (Reid, 2003). Bamboo is considered to be a highly recyclable material, but in the US, no facility can recycle bamboo, and it has to be transported to other countries.

Another suggestion about alternative materials is using straw. Baled straw can be stacked like bricks for both load bearing and non-load bearing infill walls. Straw fiber can be processed and manufactured as medium density fiberboard, structural stressed skin panels, and non-structural partitions.

4.4 Building Design Recyclability

After finding the obstacles of building materials recycling and reviewing other people's suggestion on increasing building materials recycling rate, I realize that if designers can implement recycling on the first stage of a project, it will be very convenient for contractors to do recycling. Then the concept of design recyclability comes to my mind.

4.4.1Defining Building Design Recyclability

Recyclability is a word used to describe characteristics of materials. One of the definitions of recyclability from European Environment Information and Observation Network is “Characteristic of materials that still have useful physical or chemical properties after serving their original purpose and that can, therefore, be reused or remanufactured into additional products”.

Recyclability describes the ability of materials to be recovered at the end of their original service life. Design is not something that can be recycled, but design can make materials recycling easier. Therefore, we can use recyclability to describe the potential possibility for a design to provide convenience for materials recycling.

We can define recyclable design and building design recyclability as follows: “According to the design, with good performance of contractors, all the materials for buildings can be recycled at the end of their service lives or the recycling rate can reach to a satisfying level, we can call this design a recyclable design, and the ability to provide convenience for achieving higher materials recycling rate is building design recyclability.”

There is a common misunderstanding of recyclability. Many organizations set using recycled materials as one of the criteria for design recyclability (Environmental Defense, 1999). Actually, using recycled materials has nothing to do with the recycling rate, even though it is benign. It is recommended to using recycled materials, but that is not an issue to discuss here.

4.4.2 Principles for Building Design Recyclability

After clearly understanding the definition of building design recyclability, we should also find out how designs can make materials more recyclable and what to do to make a design become a recyclable design. I will address the principles for building design recyclability form three phases: pre-design phase, design phase, and post-design phase (Table 4.12).

Table 4.12: Principles for Building Design Recyclability

Phases	Principles
Pre-design Phase	Inspire designers' willingness for recycling
	Get information of materials recyclability
	Get information of different lifetime of components
	Get information of regional capacities
	Get information of regional markets
	Communicate with owner about recycling issues
Design Phase	Consider using systems, layers, and two stages building design
	Choose recyclable materials
	Use functional components instead of aesthetics components
	Reduce the number of different materials used
	Use regular size components
	Avoid using complex composite materials
	Use mechanical fixings and other conjunction methods that are easy to separate
	Use prefabricated components that are assembled on site
	Avoid using hazardous components
	Leave sufficient space for deconstruction
	Consider alternative materials
	Avoid mistakes
Post-design Phase	Communicate with contractor
	Avoid change orders
	Record the materials
	Develop a deconstruction plan
	Communicate with deconstruction contractor

4.4.2.1 Pre-design Phase

Inspire designers' willingness for recycling

Thoughts determine actions. The designers should know the importance of recycling and be willing to recycling. After that, they will have the motivation to develop recyclable designs.

Get information of materials recyclability

Designers can not only be aspiring, but they should also be knowledgeable. They should know the recyclability of different materials. However, only these kinds of information are not enough. Regional factors are more important to the final recycling rate.

Get information of different lifetime of components

The lifetime of various components in a building can vary considerably, from a range of 25-100 years for the main structure to perhaps a range of only 5-10years for internal fit out and even shorter periods for furniture and decoration, which are largely driven by fashion in stead of physical obsolescence. Having these kinds of information in mind, designers can use proper materials for different components according to their lifetime. This information also helps when considering using subsystems and layers.

Get information of regional capacities

Regional capacity for recycling is another vital factor. In some states, where transfer stations have the technology to process recyclables and sell them to manufacturing facilities, the recyclables are really been recycled. On the contrary, in states which lack the recycling abilities, the recyclables will be sent to landfill eventually. Therefore, if designers are familiar with regional recycling capacities, they can choose to use the materials which can be recycled locally. In this way, we can avoid the appearance of non-recyclables at the first stage.

Get information of regional markets

Designers should have the information of regional recycling markets, too. If no market for some kind of recyclables, we'd better considering other materials.

Communicate with owner about recycling issues

After getting all the information of recycling and determining to deliver a recyclable design, designers should communicate with owners about their idea. Owner is the payer for everything. Therefore, without owner's agreement, nothing can be implemented.

4.4.2.2 Design Phase

Consider using layers, systems and two stages building design

Systems and two stage building design is good for renovation and deconstruction. Parts are easy to be separated with little damage. The building built in layers can be easily replaced as necessary throughout the life of the building. The components with the shortest lifetimes should be in the most easily accessible layers.

Choose recyclable materials

Choose materials and components, like steel, that have been widely recognized as recyclable materials. According to the information about regional recycling capacities and regional recycling markets, choose materials that can be easily recycled and sold in that area.

Use functional components instead of aesthetics components

Customers always prefer new and fashionable items to used ones. Therefore, aesthetics components always have shorter life, while functional components can last longer. Sometimes even if we can salvage some aesthetics components, we can not sell them because they are already out of fashion.

Reduce the number of different materials used

Reduce the number of materials used to manufacture a component or assembly. Reducing the number of materials also simplifies the separation process and supports recycling. Try to reduce the types of materials used for the whole building. Because sometimes during demolition, the quantity for a single type of material is too small for a collection truck to pick it up.

Use regular size components

Regular size components are most easily be reused and resold. If the size is too big to be transported, the material can not be recycled. Using regular size components, such as roof trusses, doors, and windows, can make them more likely be reused, which can achieve better environmental benefit than recycling.

Avoid using complex composite materials

Complex composite materials are difficult to be separated and recycled. This category often includes treatments and finishes applied on site. Carpet, composed of face fiber, primary and secondary backings, and an adhesive layer, is another example.

Use mechanical fixings and other conjunction methods that are easy to separate

Methods of fixing are important for deconstruction. Reversible mechanical fixings are preferable. Generally, mechanical fixings are preferable, which are easier to separate than adhesives or cement. Materials secured with bolts or screws are easier to deconstruct than those secured with nails or rivets. Processes that are inherently irreversible, such as welding, should be avoided.

Use prefabricated components that are assembled on site

Prefabricated components that are assembled on site can often be easily disassembled for reuse or recycling. Designers may try to use more prefabricated components to increase recovery rate.

Avoid using hazardous components

Hazardous materials create many future problems and should be avoided. Throughout the construction industry, we have used and continue to use large quantity of chemical substances and additives in all types of products to enhance technical properties. Some of these additives have negative impact on environment. Therefore, authorities have frequently enacted regulations or bans to minimize their impacts. Hazardous components prevent recyclable materials from recycling. Designers should figure out ways to avoid using these hazardous materials.

Leave sufficient space for deconstruction

Sufficient space should be provided for the machinery that will be needed for deconstruction.

Consider alternative materials

Considering using more recyclable materials to take place of current materials is another attempt to increase recycling rate.

Avoid mistakes

Designing mistakes will cost a lot, and there are a lot of consequent re-work and materials waste. For everyone’s good, mistakes should be avoided, although it is impossible.

4.4.2.3 Post-design Phase

Communicate with contractor

Before the beginning of job site work, designers should communicate with contractor about their recycling goals and effort. A recyclable design is just the first step to recycling, and contractor's proper practice is crucial to the finial out come, too.

Avoid change orders

Just like design mistakes, they are annoyed and unavoidable. Since they will bring huge materials waste, all the parties should try the best to minimize them.

Record the materials

During a building's life there should be a log that includes information on the design of the original building, specifications for materials used in construction, and details of renovation work carried out during the life of the building. These will help demolition contractor to identify materials and make deconstruction easier. Contractors are suggested to mark parts for simple material identification. Mark all materials with standard material identification codes.

Develop a deconstruction plan

A deconstruction plan should be provided by designer. Deconstruction is the reverse of construction, and the designers should consider this process and prepare a strategy for the deconstruction of the building.

Communicate with deconstruction contractor

If possible, designers may communicate with deconstruction contractors to help them to follow the deconstruction plan or to form a more feasible one. If not, a detailed deconstruction plan will help, too.

4.4.3 Generating Drives

With the principles for building design recyclability, designers may roughly know to deliver a recyclable design. However, because it is impossible for them to follow all the principles and some principles may not count for as much as others, it is hard to determine whether a design is a recyclable design without quantified variables.

The quantification of variables will be a very complicated process. Different types of variables must use different method to quantify. This paper will focus on developing the framework of building design recyclability, and I will just identify the drives. The variable quantification will be the major task for future researches.

Drives are derived from principles, shown in Table 4.13.

Table 4.13: Drives for Building Design Recyclability

Phases	Principles	Drives
Pre-design Phase	Inspire designers' willingness for recycling	Education about recycling
	Get information of materials recyclability	Knowledge of materials recyclability
	Get information of different lifetime of components	Knowledge of materials lifespan
	Get information of regional capacities	Knowledge of regional recycling capacities
	Get information of regional markets	Knowledge of regional recycling markets
	Communicate with owner about recycling issues	NA
Design Phase	Consider using systems, layers, and two stages building design	Systems design Layers design Two stages design
	Choose recyclable materials	Regional highly recyclable materials used
	Use functional components instead of aesthetics components	Functional instead of aesthetics
	Reduce the number of different materials used	Number of types of materials used
	Use regular size components	Standard size components used
	Avoid using complex composite materials	Complex composite materials used
	Use mechanical fixings and other conjunction methods that are easy to separate	Conjunction method used
	Use prefabricated components that are assembled on site	Prefabricated components used
	Avoid using hazardous components	Hazardous components
	Leave sufficient space for deconstruction	Space for deconstruction
	Consider alternative materials	Alternative materials
	Avoid mistakes	NA
Post-design Phase	Communicate with contractor	NA
	Avoid change orders	NA
	Record the materials	Record for materials
	Develop a deconstruction plan	Deconstruction plan
	Communicate with deconstruction contractor	NA

This is the first attempt to develop the framework of building design recyclability. This concept contains various types of information. What has been done in this paper is just a beginning and the drives identified above are far from enough. More effort is needed to fully develop the concept of building design recyclability.

4.4.4 Testifying Drives

The same case will be used to testify the above drives. Details are shown in Table 4.14.

Table 4.14: Results of Implementing Design Recyclability

Components	Material	Recyclable or Not	Obstacles	Drives	Recyclable or Not after Implementing Design Recyclability
Rebar	steel	Y	-----	-----	Y
Slab, Beam & Column	concrete	N	2, 6, 7, 8, 12, 15	a, b, c, d, f, n, o, p	Y
Formworks	wood	N	1, 2, 12, 15	a, b, c, d, f	Y
External Wall	CMU	N	2, 6, 7, 8, 10, 12, 15	a, b, c, d, f, k, p	Y
Stone Veneer	limestone	Y	-----	-----	Y
roof trusses	wood	N	3, 6, 7, 8, 10, 12	a, b, c, d, f, k, i	Y
Studs	Metal	N	10, 12	a, b, c, d, f	Y
storefront	Alum.& Glass	N	4, 7	a, b, c, d, f	Y
Door	wood	N	1, 4, 6, 7	a, b, c, d, f, i	Y
	Wood & glass	N	1, 4, 7, 13, 14	a, b, c, d, f, i	Y
	metal	N	4, 7	a, b, c, d, f, i	Y
Window	glass	N	4, 6, 7, 13, 14	a, b, c, d, f, k, i	Y
Wall	gypsum board	N	2, 5, 6, 7, 8, 11, 12, 15	a, b, c, d, f	Y
Ceiling	gypsum board	N	2, 5, 6, 7, 8, 11, 12, 15	a, b, c, d, f	Y
floor	carpet	N	4, 6, 7, 11, 14	a, b, c, d, f, I,	Y
	vinyl tile	N	1, 4, 6, 7, 8, 10, 14, 15	a, b, c, d, f	Y

Base	rubber	N	1, 5, 6, 7, 8, 13, 15	a, b, c, d, f, p	Y
	vinyl	N	1, 5, 6, 7, 8, 15	a, b, c, d, f	Y
door hardware	metal	N	7, 10, 12	a, b, c, d, f, k	Y
door frame	metal	N	7, 10, 12, 14	a, b, c, d, f, k	Y
window frame	metal	N	7, 10, 12, 14	a, b, c, d, f	Y
X-Ray Protection	lead gypsum board	N	2, 6, 7, 8, 9, 11	a, b, c, d, f, m	Y
Fire alarm control panel	NA	Y	-----	-----	Y
Smoke Detector	NA	N	6, 7, 9, 12, 15	a, b, c, d, f	Y
cold water pipe	steel	N	13	a, b, c, d, f	Y
hot water pipe	steel	N	12, 13	a, b, c, d, f	Y
Backflow prevent valve	steel	N	12, 13, 14	a, b, c, d, f	Y
butterfly valve	steel	N	12, 14	a, b, c, d, f	Y
heavy duty floor drain	NA	N	6, 7, 12, 14	a, b, c, d, f	Y
hub drain	NA	N	6, 7, 12, 14	a, b, c, d, f	Y
vent pipe	steel	N	12	a, b, c, d, f	Y
sanitary sewer pipe	steel	N	12, 14	a, b, c, d, f	Y
circulation pump	NA	Y	-----	-----	Y
water closet	NA	N	4, 6, 7, 14, 15	a, b, c, d, f	Y
lavatory	NA	N	4, 6, 7, 12, 15	a, b, c, d, f	Y
sink	NA	N	4, 6, 7, 12, 15	a, b, c, d, f	Y
water heater	NA	Y	-----	-----	Y
duct heater	NA	Y	-----	-----	Y
fan	NA	Y	-----	-----	Y
air diffuser	NA	Y	-----	-----	Y
grille	NA	N	6, 7, 12, 14, 15	a, b, c, d, f, n	Y

louver	NA	N	6, 7, 12, 14, 15	a, b, c, d, f	Y
conductor	copper	N	6, 7	a, b, c, d, f	Y
tube	NA	N	6, 7, 15	a, b, c, d, f	Y
junction box	NA	N	1, 6, 7, 14, 15	a, b, c, d, f	Y
telephone outlet	NA	N	1, 6, 7, 14, 15	a, b, c, d, f	Y
safety switch	NA	N	6, 7, 15	a, b, c, d, f	Y
lighting	NA	N	3, 6, 7	a, b, c, d, f	Y

Note: In this table, the numbers and letters represent the following reasons and drives:
1: Low salvage value
2: Quantity too small
3: Size too big
4: Out of fashion
5: Site condition
6: Regional materials market
7: Regional traditions
8: Regional capacities
9: Hazardous components
10: Conjunction method
11: Complicated composing
12: Contamination
13: Obsolescence
14: Damages
15: Cost effectiveness
a: Education about recycling
b: Knowledge of materials recyclability
c: Knowledge of materials lifespan
d: Knowledge of regional recycling markets
e: Systems, layers, and two-stages design
f: Using regional highly recyclable materials
g: Functional instead of aesthetics
h: Number of types of materials used
i: Standard size components used
j: Complex composite materials used
k: Conjunction method used
l: Prefabricated components used
m: Hazardous components
n: Space for deconstruction
o: Record for materials
p: Deconstruction plan

From the above table, it is obvious that after implementing design recyclability, it is possible to recycle everything in a building. Therefore, implementing design recyclability will be an effective way to increase building materials recycling rate.

Chapter 5 Conclusions and Recommendations

Finally, all the findings in this paper will be summarized here and all the doubts and questions generated during the research process will be list as recommendations for future research directions.

5.1 Findings and Summary

Recycling of building materials is an important aspect of sustainable construction, while sustainable construction is a critical issue to fulfill the overall sustainable development. However, the current materials recycling rate for construction industry is far from satisfying. Researchers have proved that technologies for building materials recycling are ready for applying, and recycling facilities are usually available. Then why is the building materials recycling rate still low?

Many answers have been found for the above question. Numerical obstacles of building materials recycling have been identified, and they can be put into six categories: social, environmental, economic, materials natural, participants, and regional factors.

Although a lot of researchers have identified obstacles of building materials recycling, most of them are derived from experience and none of them has testified their findings. This paper used a case study for testifying. After allocating obstacles to each non-recyclable materials and components, some interesting phenomena come out.

1. Regional factors are responsible for most non-recyclable materials, and many non-recyclable materials will become recyclable if building's location changed;
2. There are always multiple obstacles for a single item;
3. Some obstacles are leading ones. If we can break these leading obstacles, non-recyclable materials will become recyclable even though other obstacles still exist;
4. Contamination is another major obstacle which prevents many materials from being recycled;
5. Increasing people's willingness for recycling can help to conquer most obstacles.

After identifying the obstacles of building materials recycling, researchers have addressed some solutions to solve these problems. However, in current construction practice, too many responsibilities of recycling on site have been put onto contractors, while the designers' role in recycling has always been omitted. As primary participants in the first stage of a project, designers' action can change the out come of recycling tremendously. If designers can deliver a recyclable design, it will be very easy for contractors to do their job and fulfill the goal of recycling. Using more recyclable materials and making building more deconstructable can make designs more recyclable. However, to make a design recyclable, there are many other issues for designers to consider, too.

The concept of building design recyclability has been defined and explained. The principles for it have been described from three phases: pre-design phase, design phase and post-design phase. Variables have been derived form principles, and they need to be quantified. This is the first attempt for developing the concept of building design recyclability. It is not a fully developed edition but a start. Further researches are needed.

5.2 Future Research Directions

Since the leading obstacles always determine whether the materials can be recycled or not, it is important to identify leading obstacles and break them.

This paper is the first stage of delivering the concept of building design recyclability. Quantifying variables will be the focus of further research. We may learn from the LEED certification system, to see how they quantifying variables and crediting activities.

Another research direction will be delivering the concept of green design. Recyclable design is part of green design. Green design will be a more comprehensive concept including energy saving, minimizing impact to surrounding, using recycled materials, etc.

Construction industry is still behind other manufacturing industries in recycling, due to its uniqueness and traditional waste behaviors. There is a long way to go for us to fulfill sustainable construction. The research about sustainable construction and materials recycling will be continued.

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