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DEVELOPING AN INCLUSIVE MODEL FOR DESIGN FOR DECONSTRUCTION

Dr Philip Crowther (Queensland University of Technology, Australia)

SUMMARY

One of the major hindrances to successful deconstruction, for the reuse of building materials and components, is the difficulty in recovering items in good condition. Modern construction methods are very dependent on permanent fixing methods that allow for little else but destructive demolition. If buildings were initially designed for deconstruction, it would be possible to successfully recover much more material for reuse. This would have significant advantages both economically and environmentally.

In an attempt to establish a knowledge base for understanding design for deconstruction, this paper poses a number of questions. These questions can in part be answered by a number of related theories and research fields. The relationships between these theories and design for deconstruction are investigated and developed. There are four main parts to these investigations:

- an understanding of how design for deconstruction fits into the broader issues of sustainable construction
- the theory of time related building layers
- the theory of a hierarchy of recycling and reuse
- a list of design for deconstruction principles

KEYWORDS: deconstruction, design, model, principles, recycling, reuse.

THE QUESTIONS OF DESIGN FOR DISASSEMBLY

As there are no formal rules for design-for-recycling, we resort to heuristics [1].

The Need for Understanding

Design for deconstruction in architecture is not widely practised and not widely understood. As has been shown in the reports of the preceding Task Group 39 meeting [2] there is little research in this field and only recently have efforts been made to co-ordinate what research there is. As such there are no currently existing rules, guidelines, or principles for design for deconstruction in architecture, nor are there any models for design for deconstruction in architecture.

Tools for assessing the potential for reuse and recycling of building materials have been proposed, though these have been developed for the assessment of existing buildings [3] [4]. A tool for assessing proposed building designs and for guiding the design process to increase rates of future recycling has not been developed.

In brief, 'buildings are not currently designed to be eventually disassembled' [5].

What Knowledge is Needed
There is a basic lack of understanding or knowledge of design for deconstruction in architecture. The types of knowledge that might be needed can be investigated by asking a number of basic questions:

- Why deconstruct
- When to deconstruct
- Where to deconstruct
- What to deconstruct
- How to deconstruct

Why Deconstruct
The general need for an improvement in the current rates of materials and component reuse is well accepted. Any response to this must however fit within the broader understanding of sustainable construction. It is not beneficial to design for deconstruction to increase rates of recycling if the overall life cycle environmental costs of such a strategy are actually greater than the potential benefits.

An understanding of this holistic relationship must form part of any understanding of design for deconstruction in order that the benefits are realised. The issues of design for disassembly need to be located within a general model for sustainable construction so that the external consequences of a design for deconstruction strategy might be highlighted and considered.

When to Deconstruct and Where to Deconstruct
Different parts of buildings have different life expectancies, for economic, service, social, and fashion reasons. An understanding of the life expectancy of parts of a building is an integral part of a strategy of designing for deconstruction. The theory of time related building layers, the idea that a building can be read as a number of distinct layers each with its own different service life, offers some insight into the relationship between life expectancy and deconstruction. Knowing which layer a component is from, and where the layer begins and ends, assists in determining when and where to deconstruct.

What to Deconstruct
There are many possibilities for the recycling of materials and components, from complete relocation and reuse, to material recycling or incineration for energy. The question of what to deconstruct can in part be answered by asking what is the intended form of recycling. What is deconstructed for material recycling may be different to what is deconstructed for component relocation. There is therefore a relation ship between the hierarchy of recycling options and design for deconstruction.

How to Deconstruct
There are several sources of information of how to deconstruct. These include industrial design, architectural technology, buildability, maintenance, and international research into

deconstruction. While the question of how to deconstruct buildings has not been well investigated in the past, the above sources of information can be searched for recurring themes. These themes can then be developed as principles for design for deconstruction.

A list of principles for design for deconstruction can act as performance guidelines to assist in the design of a building or to assess a building design for disassembly. Such a list of principles is one of the major components of a knowledge base of deconstruction.

A MODEL FOR ENVIRONMENTALLY SUSTAINABLE CONSTRUCTION

General Model of Life Cycle (Assessment)

Of all the current models for understanding, assessing, and reducing the environmental consequences of our actions, life cycle assessment (LCA) is perhaps the most useful.

> The notion of life cycle assessment has been generally accepted within the environmental research community as the only legitimate basis on which to compare alternative materials, components and services and is, therefore, a logical basis on which to formulate building environmental assessment methods [6].

The idea of the life cycle is that all stages in a system (product or service activity) are recognised, from inception to final disposal. A life cycle assessment is made by investigating all the environmental consequences of each stage in the life cycle of the system. Such an assessment can be represented as a two dimensional matrix. Such a matrix offers a good model for the environmental assessment of a system (product, service, building). In order to do more than simply assess the system, to actually understand how the system might be altered to reduce the environmental burden, it is necessary however to add a third dimension. This will be a dimension of strategic solutions, or of principles for sustainable activity.

Principles for Sustainable Activity

In order to understand what can be done to reduce the environmental burden of human activity, it has been convenient to consider the range of measures that might be taken within a smaller number of broader principles. There are potentially thousands of strategies that might be implemented in the design of a building in order to reduce the environmental burden of that building. Management of these strategies, and of conflict between them, can be better handled by addressing a few overriding aims.

Numerous authors have proposed such broad principles for sustainable activity, and many of these relate directly to the built environment and to sustainable architecture. The writings, and the built work, of Brenda and Robert Vale illustrate a number of ‘green’ architecture principles. They suggest six basic principles that could constitute sustainable architectural practice [7];

- *Conserving energy*, a building should be constructed so as to minimise the need for fossil fuels to run it
- *Working with climate*, buildings should be designed to work with climate and natural energy sources
- *Minimise new resources*, a building should be designed so as to minimise the use of new resources and. At the end of its useful life, to form the resources for other architecture

- *Respect for users*, a green architecture recognises the importance of all the people involved with it
- *Respect for site*, a building will 'touch-this-earth-lightly'
- *Holism*, all the green principles need to be embodied in a holistic approach to the built environment

The Royal Australian Institute of Architects' Environmental Design Guide also offers a number of principles for achieving sustainable architecture [8];

- Maintain and restore biodiversity
- Minimise the consumption of resources
- Minimise pollution of air, soil and water
- Maximise health, safety and comfort of building users
- Increase awareness of environmental issues

Another author who offers a list of broad principles is Kibert [9]. His concerns are developed from a number of issues of sustainable construction which include; energy consumption, water use, land use, material selection, indoor environmental quality, exterior environmental quality, building design, community design, construction operations, life cycle operation, and deconstruction. Several principles of how to achieve more environmentally responsible construction are proposed with respect to these issues;

- Minimise resource consumption
- Maximise resource reuse
- Use renewable or recyclable resources
- Protect the natural environment
- Create a healthy, non-toxic environment
- Pursue quality in creating the built environment

These lists of principles are all attempts at grouping the various strategies for achieving sustainable architecture. While these groups vary slightly they all address issues of material use, energy use, health, and a holistic view.

Adopted Model for Sustainable Construction

Returning to the two-dimensional model of life cycle assessment, it is now possible to add the third dimension of principles of sustainable architecture. Such a combination has already been investigated by Kibert. By combining the two axes of time (Phase) and impact categories (Resources), with the axis of principles, a simple conceptual model is produced. This model then can be graphically represented as three radiating axes (see Figure 1).

Using this model it is possible to place a particular issue within the broader context of sustainable architecture. In this way it is possible to highlight where the issue of design for deconstruction sits within the broader context of sustainable construction. Design for deconstruction deals with the *design* of a building, for the *reuse* (in preference to recycling or disposal), of *materials*. While it might be considered that design for deconstruction is intended to deal with the *deconstruction* stage of the life cycle, it is a strategy that must be implemented at the design stage, as such it deals with *design* issues that will have later ramification at the deconstruction stage. It might also be considered that design for deconstruction is an issue relating to the *recyclable* nature of a building. However, design for deconstruction is an attempt to raise materials and components up the recycling hierarchy, away from recycling, and up to a more environmentally preferable point of *reuse*. For these reasons design for disassembly is primarily, but not exclusively, an issue of design for the reuse of materials.

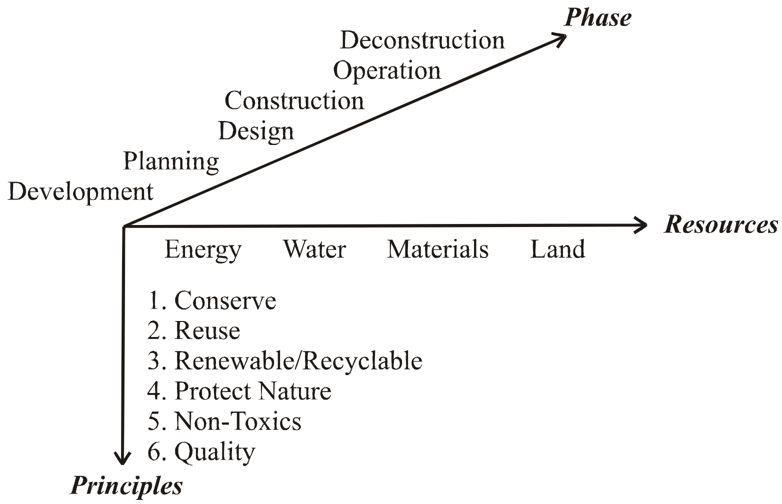

Figure 1 A Conceptual Model for Sustainable Construction [10].

Conclusions to a Model for Environmentally Sustainable Construction

This section has shown how a model for sustainable construction can be built from the principles of sustainable architecture, the categories of resources (or environmental impacts), and the life cycle stages of a building. Such a model has been adopted as a way of locating the issue of design for deconstruction within the broader field of sustainable architecture. Understanding this relationship between design for deconstruction and other sustainability issues is an important part of the knowledge base of design for deconstruction in architecture.

THE THEORY OF LAYERS

A Tradition of Building Layers

The notion of the building as a whole object is still very much the dominant way of thinking about buildings. They are conceived, designed, constructed, and used as complete entities. We speak of 'a' building in the singular. This notion of the singular building may however be a misconception, in part, resulting from our reading of the building in a limited time frame. Few, in any, buildings actually remain in their initial state of construction for more than a few years or at most a few decades. Alterations, repairs, additions, and maintenance continually work to alter the building. In the longer time frame, the building is constantly changing in response to changing user demands and changing environmental conditions. There is in fact not 'a' building at all but a series of different buildings over time.

Much vernacular building, especially in timber, has made practical use of the notion of time related layers. Traditional Japanese domestic buildings are constructed using a primary frame of major timber members that are placed according to structural requirements of the roof and walls. A secondary frame of timber members is then constructed in accordance with the spatial requirements of the occupants. This secondary frame may be deconstructed and remodelled to suit changes in the occupants' requirements without affecting the primary structure and without the wastage of building materials that other techniques produce [11].

> Japanese wooden architecture . . . is a complete architectural system in which the expansion, remodelling, removal and reconstruction of buildings is possible according to life styles [12].

Similar technologies in Europe and other parts of the world were also utilised to produce buildings that consisted of a primary frame and a series of secondary enclosing, and space defining, elements [13].

The Beginnings of a Theory of Building Layers

While there are vernacular traditions of designing and constructing buildings so that they can respond more readily to changes over time in a layered way, an expressed theoretical stance on this issue as a way of *modern* building did not first appear untill the writings of the Japanese Metabolism architects and of John Habraken in the 1960's. Habraken [14], in later writings, discusses the *traditions of two stage building* as he calls it, in which vernacular buildings are constructed first as a primary structural frame which typically supports the roof, then a secondary system of construction which defines the internal spaces. Habraken claims that virtually all timber framed structures can be analysed in terms of the two-level theory.

Before this however, Habraken had already used this theory of *two stage building* to address his concerns with social mass housing and the design of housing with more input from the users. Habraken writes at length on the social problems of current (1950's) mass housing models and the lack of user satisfaction. His main technical solution to these problems is in the proposal for *Support Structures*.

> A support structure is a construction which allows the provision of dwellings which can be built, altered and taken down, independently of the others [15].

In building terms the proposal is for a large multi-storey concrete frame with floors, 'one above the other, stretching out through the town' [16]. Between the floors, dwellings are built, side by side, similar to units in a high-rise housing block, but with each dwelling being independently designed and built. The main structure contains all the relevant services and circulation spaces.

Habraken's proposal provides medium to high-density housing but avoids the problems of the anonymous unit in the giant housing block. The support structure and the dwelling unit are treated as separate individual layers where the dwellings can be changed with no effect on the support. Similarly the dwellings can be designed independently of the support structure or the adjoining dwellings. Habraken [17] makes the distinction that while the support structure may look like the unfinished frame of any large building, it is in fact 'not an uncompleted building, but in itself a wholly completed one'.

Habraken has made the first conceptual step in dissecting the building into layers. He recognises that there can exist, within the one building, two buildings with two different service lives, as in vernacular timber building; the *permanent* support, and the *temporary* dwelling.

Developing the Theory of Building Layers

Another innovative thinker who was also concerned with the life expectancy of buildings and in particular the way that different parts of a building might have different life expectancies was Cedric Price. His design scheme of 1961 for the *Fun Palace* was an inspirational work in the realm of adaptable buildings. It was influential, a decade later, on the design for the Pompidou Centre by Rogers and Piano. Price's design consisted of a steel framed structure that contained hanging auditoria with movable floors, walls, ceilings and walkways. The whole building had been designed with obsolescence in mind and was serviced by cranes on the top of the structure which allowed the component parts of the building to be manipulated, relocated, removed or replaced to suit various proposed activities [18].

Although the Fun Palace was not realised, the Inter-action community centre in Kentish Town was built in the 1970's following many of the same principles. This multi purpose community centre, of approximately 2000 square metres floor area, was designed with unlimited permutations of flexible space to house continually changing uses. It consisted of a major steel structure set out on a regular grid with a series of secondary flexible enclosed spaces that were independent of the main structure and could be disassembled and reassembled independently of it. Separate self contained modules, that housed service zones such as toilets, could be plugged into the frame where ever they were required.

A strong hierarchy of structure allowed the building to expand or contract in the future without interrupting the existing building. The Inter-action centre was actually classified by the council as a *temporary* structure and the architect prepared complete instructions for the buildings eventual disassembly [19].

Many architects were influenced by the work of Price. One such group of British architects, calling themselves Archigram, produced an almost endless stream of designs for portable, adaptable and temporary buildings during the late 1960's and early 1970's.

One of their schemes, the Plug-in City, was directly concerned with separating the time related layers of the building. The Plug-in City, in which 'the whole urban environment can be programmed and structured for change' [20], was based on a steel mega-structure that contained the major transport corridors and services. This structure supported a series of detachable living and working units than could be manoeuvred by cranes fixed to the main structure. The units responded to a hierarchy of obsolescence where those parts of the building that would need to be serviced or replaced most frequently were most accessible. For example the living modules and shopping areas, that had a three year to eight year rating, were nearer the top of the structure, and the heavy elements such as railways and roads, with a twenty year life expectancy, were nearer the bottom. Other service life expectancies were:

- Bathroom and kitchen 3 years
- Living rooms and bedroom 5-8 years
- Location of house module 15 years
- Tenancy in a shop 6 months
- Shopping location 3-6 years
- Workplaces and offices 4 years
- Roads and civil works 20 years

At the same time as Archigram were investigating high tech architecture in Britain, the Metabolism Group in Japan were pursuing similar idealised environments. They took the two-stage building principles of time traditional timber dwellings and applied it to modern high tech architecture. The key to the work of the Metabolists was a philosophy of allowing for replaceability and changeability of components in such a way as to not disturb the remainder of the building. This designing for disassembly was evident in early works such as the Mova-house system, which, in a similar design to the Plug-in City, used housing modules, with a life expectancy of twenty five years, that were attached to a mega-structure support system [21].

In writing about the philosophies of the Metabolist group, Kurokawa [22] offers the following hierarchy of service life expectancies for various elements of the built environment:

- Services 5 years
- Space for consumer goods 5 years
- Shops, businesses, education facilities 10 years
- Dwellings 25 years
- Public spaces between buildings 125 years
- Cultural facilities and monuments 625 years
- Natural areas 15 000 years

Although much of the Metabolist Group's work was unrealised, the 1970 World Exposition in Japan did allow for some of the disassembly technology to be tested in full scale. The Capsule House in the Theme Pavilion of Expo '70 and the Takara Pavilion both allowed the building to be altered over time by designing a building that consisted of a primary structural frame and a secondary collection of space making elements.

These visionary projects, many of them unrealised, all exhibit a common practice of separating the building into a number of time related layers. While these projects might be called experimental in their way of dealing with technology, other architects and researchers, who were dealing with more traditional building technology, were also investigating the notion of time related layers.

Expanding the Theory of Building Layers

In investigating the office accommodation needs of London banks, accountant, and financiers, Duffy and Henney [23] independently established a theory of building layers. Duffy [24] writes that, 'our basic argument is that there isn't such a thing as a building . . . a building properly conceived is several layers of longevity of built components'. Duffy introduces here his own theory of layers of building, time related layers that can change independently of each other.

Unlike Habraken who establishes two layers within the building, or the Metabolists and Archigram who define no fixed number of layers, Duffy and Henney [25] identify four layers of building in descending order of longevity; the *Shell*, the *Services*, the *Scenery*, and the *Set*.

Importantly, Duffy and Henney also assign a service life to each of these layers. This service life is based on the expected life span of the layer based on experience of changes resulting from the users changing demands and the need to upgrade or expand plant and equipment. The rate of change for each layer is different as technological and social changes impact differently on different parts of the built environment.

- The *Shell,* Duffy describes as the foundations, the structure of the building, with a life span of fifty years. The shell is a framework onto which services and space making components can be attached in an adaptable way. He also makes suggestions on the spans of floor plates, the location of service cores and the grid of the floor and ceiling.

- The *Services* include electrical, hydraulic, HVAC, lifts, and data, which have a life span of ten to fifteen years.

- The *Scenery* is the internal partitioning system, the finishes and the furniture, which have a life span of five to seven years.

- The *Sets* are the arrangements of movable items that the users move freely about the building to suit their daily or weekly needs.

Duffy's development of this theory of layers is derived from an analysis of office buildings, particularly in London, but the theory is just as appropriate to other building types though the life spans may be slightly different.

The relevance of the theory of layers is in that the parts of the building with a short service life can be separated from the parts of the building with a long service life. This means that when for example the services of a building are no longer providing a service that meets with contemporary requirements, the whole building does not have to be upgraded or replaced, just the services.

It is interesting to note that Duffy limits his analysis of the buildings to what might be interpreted as the internal parts of the building; the furniture, internal partitions, services (that serve the internal spaces), and the shell of the building (a term which implies enclosure). This is not surprising since his concern is primarily with the provision of accommodation, in the form of office buildings, for financial and business corporations. Duffy's concern is with providing internally adaptable buildings so that the building itself does not need to be replaced when the internal spaces no longer satisfy the users needs.

For a similar but expanded analysis of the layers of buildings that also includes the fabric of the building itself in more detail, the work of Stewart Brand is noteworthy. Brand [26] builds directly on Duffy's theory of layers but expands it, by dissecting the *Shell* into *Structure* and Skin, and adding the layer of the *Site* on which the building stands. Brand also assigns each layer an expected service life.

- The *Site* is defined as geographical setting, the ground on which the building sits. 'Site is eternal'.

- The *Structure* is the foundations and load bearing components of the building, those parts that make the building stand up. Structure is expected to last from 30 to 300 years.

- The *Skin* of the building is the cladding and roofing system that excludes (or controls) the natural elements from the interior. This will last an expected twenty years due to wholesale maintenance, changing technology and fashion.

- The *Services,* which are defined the same as Duffy, have an expected life of from seven to fifteen years.

- The *Space Plan,* which corresponds to Duffy's *Scenery*, will change every three years in a commercial building and up to every thirty years in a domestic building.

- The *Stuff*, which corresponds to Duffy's *Sets*, will change daily to monthly. Brand points out that furniture is called *mobilia* in Italian, for good reason.

Brand goes to great lengths to explain the technical and social benefits of designing and constructing buildings in a layered manner. Like Habraken he recognises the lessons already learned by vernacular builders. He further suggests specific lessons for designers based on historic study of layered buildings and their adaptation, addition, and relocation over time.

Duffy and Brand both suggest typical service life expectancies for their layers. Duffy establishes his times from the point of view of designing adaptable office accommodation. Brand's times are derived from a general understanding of how buildings change over time. Cook et al [27] also suggest appropriate life expectancies, though theirs are for a particular building design (the Plug-in City). Other writers have also suggested times for the service life expectancies of different layers of buildings, based on different concerns (see Table 1).

Table 1 Life spans of building layers in years (and their sources)

LAYER				**Reference**
Structure	**Skin**	**Services**	**Space plan**	
50	50	15	5-7	Duffy 1989
30-300 (typically 60)	20	7-15	3-30	Brand 1994
40	15	3	5-8	Cook 1972
25-125	25	5	5	Kikutake 1977
60-100	15-40	5-50	5-7	Curwell 1996
60 (assumed maximum life of building)	20	7-15	3-5	Storey 1995
65	65	10-40	5	Howard 1994
50 (assumed maximum life of building)	30-50	12-50	10	Adalberth 1997
40 (assumed maximum life of building)	36	33	12	McCoubrie 1996
-	15-30	7-30	-	Suzuki 1998
40 (for brick veneer house)	12-30	30-40	8-40	Tucker 1990

Curwell [28] and Storey [29] write with regard for issues of sustainability and 'green' building. Their concerns are for designing more environmentally sustainable buildings that will have a reduced environmental burden by accounting for the different life spans of certain elements or layers.

Howard and Sutcliffe [30], Adalberth [31], McCoubrie and Treloar [32], and Suzuki and Oka [33], write with regard for issues of embodied energy. Their concern is also for environmental sustainability, primarily through reduced energy consumption and reduced embodied energy, which is achieved through reduced material use or greater material recycling.

Tucker and Rahilly [34] are concerned with the life cycle cost (in monetary terms) of the building, in this case housing. Their research attempts to establish maintenance programmes for government housing assets through an understanding of the separate life expectancies of different parts of the building.

While the times that are established by each of these writers are different, there is still a common acceptance that different parts of buildings have different service lives and that these parts might be considered in layers. While Duffy and Brand discuss these layers explicitly, the other writers do not, but the layers none the less exist within the times proposed for various elements.

The number of layers proposed by Brand should not be seen as an upper limit. The six layers he proposes are convenient for illustrating his argument of buildings changing over time, but when the consideration is of building deconstruction, it may be appropriate to divide the building into more or less layers depending on the building typology and the specific design. The lesson is simply that items or components of substantially different service life expectancies should be treated as separable in the building design. In general though, a study of architectural technology suggests that Brand's six layers are appropriate for most building designs.

Building Layers and Deconstruction

These theories of building layers can have a major impact on the design of, or analysis of, buildings for deconstruction. The interfaces between the layers can obviously become primary points of deconstruction for the building. The argument is not just however that they *can* become points of deconstruction, but that they *should* become points of deconstruction. As Habraken, Duffy and Brand point out, separation of the building layers along the lines of layer longevity is of paramount importance in making a more technically and socially adaptable and responsible building.

This importance of longevity layers has already been recognised in the field of design for deconstruction of buildings. Fletcher, Popovic and Plank [35] write that the theory of 'time dependant layers . . . will be fundamental in thinking about buildings in the future', specifically with regard to disassembly for materials and component recovery. They do not however indicate how this theory can be implemented within a strategy of design for deconstruction, nor how it actually interacts with other ideas of material recovery or sustainable architecture.

Other researchers have also recognised the importance of the theory of layers regarding building deconstruction for material recovery. Craven, Okraglik and Eilenberg [36] place the model of time related layers within a system of life cycle assessment. In a life cycle assessment the cumulative effects of a building over time are made evident, and within this model the importance of material and component recovery are highlighted.

The concept of buildings as a collection of time related layers is fully consistent with the approaches of life cycle assessment in which the life span of the building becomes an important multiplying factor for all other environmental considerations. Failure to separate the layers will result in total building failure at that point in time when the first layer fails. The resulting need for total building replacement defies all environmentally sustainable principles.

Although Craven highlights the importance of the theory of layers using a life cycle assessment model, he also stops short of suggesting how this theory might be used. While he recognises the strategy of design for deconstruction, no attempt is made to link it with the theory of time related layers to design buildings in a way that will improve the current rates of material and component recovery.

Conclusions to the Theory of Layers

The theory of time related building layers is then an important consideration in determining at what points in a building deconstruction might occur. Ideally to achieve full deconstruction for recovery of materials and components, all parts of the building should be totally separable. This would however be prohibitively complex and expensive. The theory of layers allows the components of the building to be broken down into packages of same or similar life expectance so that a whole package might be conveniently deconstructed from the building for replacement, recycling and/or reuse elsewhere.

This section shows how buildings can be considered not as a single entity but as a collection of layers, each with a different service life. A model with six layers is adopted; site, structure, skin, services, space plan, and stuff. These layers are useful in physically determining the places within a building that deconstruction might most usefully occur, and at what time deconstruction might occur.

RECYCLING HIERARCHY

The Flow of Materials

The use of resources in our industrialised 20th century society is very much a matter of use it once and throw it away, and the built environment is no exception. The commonly used model for this consumption of materials and energy is based on a linear system of the building over time. This linear model of the building's life treats the project as a once through system in which the building progresses through a number of stages from inception, through design, construction, operation and maintenance, refurbishment, and finally to demolition. Similarly the model for how raw materials pass through the built environment uses a number of life cycle stages from extraction, through processing, manufacture, assembly, use, demolition, and disposal (see Figure 2). This life cycle model is commonly used in discussing the life cycle impacts of a building or product (as in a life cycle assessment) and is often referred to as a 'cradle to grave' model.

Such a once-through life cycle is not the only option. The building industry does not have a good understanding or practical record in this matter, but the disciplines of industrial design and product manufacture have addressed many of these issues and developed strategies within the field of industrial ecology.

Recycling Hierarchy in Industrial Ecology

Industrial ecology identifies many ways to reduce the environmental impact of a product or service, and one of the major strategies proposed is to alter the once-through cycle to increase the rates of recycling. The scenario of recycling, as it is commonly referred to, can however be better understood if it is replaced with the notion of *end-of-life scenarios*. There are in fact many possible end-of-life scenarios for any given product or building but they can be loosely classified into a few basic scenarios. Several writers have suggested appropriate options for end-of-life scenarios for industrial products.

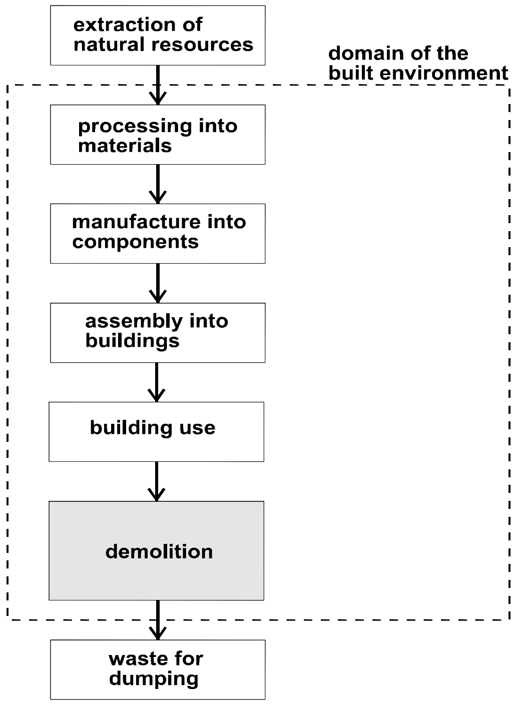

Figure 2 Dominant Life Cycle of the Built Environment (cradle to grave)

Young [37], in writing on industrial design and product manufacture for reduced life cycle energy consumption, discusses the '3Rs' model. The three Rs are *re-use*, *remanufacturing* and *recycling*. Young expands on this to also include *maintenance* as an end-of-life scenario.

- *Re-using* involves a product being simply re-used more than once for its intended purpose. For example, a milk bottle being returned to the dairy to be refilled with milk.
- *Remanufacturing* involves the product being returned to the place of manufacture to be disassembled into its base components which, if still serviceable, are then re-used in the manufacture of new products.
- *Recycling* involves the collection of products for separation into their base materials, which can then be re-used as a resource to replace raw materials in the production process.
- *Maintenance* involves the repair and servicing of a product to extend its initial service life.

Importantly Young notes that some of these scenarios are more environmentally favourable than other scenarios. From the point of view of conserving energy during manufacturing, Young notes that re-use is preferable to remanufacturing, which is in turn preferable to recycling. This hierarchy is established based on the energy costs of collecting, transporting and processing products through the various scenarios. In general the least processing, the least energy and the least environmental burden.

The dissection of recycling into separate distinguishable scenarios has also been addressed by Ayres and Ayres [38] within a general discussion of industrial ecology strategies. They identify the scenarios of *re-use*, *repair*, and *remanufacture* as well as *recycling*. Ayres and Ayers' use of the terms re-use, remanufacture and recycling are the same as Young's, but repair is somewhat different to the scenario of maintenance. Ayres uses the term in a way that describes the mending of a product for re-use elsewhere rather than mending a product for continued use in its original application.

Like Young, Ayres and Ayres note that the scenarios of 're-use, repair and remanufacture avoid many of the problems of recycling'. The problems identified are waste production and pollution directly resulting from the act of recycling, and the fact that recycling may not always reduce waste and pollution creation but may potentially increase them.

Also writing on the topic of Industrial Ecology, Graedel and Allenby [39] propose the end-of-life scenarios of *maintenance*, *recycle subassemblies*, *recycle components*, and *recycle materials*. Within the context of Young's or Ayres and Ayers' scenarios, the recycling of components and subassemblies might alternatively be called remanufacturing since it involves the same process of disassembling components for use in new products. Graedel and Allenby also recognise the environmental hierarchy of the scenarios, in which maintenance is preferable to remanufacturing, which is in turn preferable to recycling.

Yet another group of end-of-life scenarios is proposed by Mabrab [40] who explicitly refers to the scenarios as a hierarchy. He uses the terms reuse, re-manufacture, recycle to high-grade materials, recycle to low-grade materials, incineration for energy content, and dump in landfill site. Here the scenario of maintenance is lost, but the scenario of recycle has been further broken down to high-grade and low-grade materials. A new scenario of incineration for energy content has also been added. Magrab notes that 'the higher one is in the . . . hierarchy the more the investment of raw materials, labor and energy is conserved'.

Recycling Hierarchy in the Built Environment

While the field of industrial design has addressed some of the issues of reuse and recycling through the theories of industrial ecology, the field of architecture and building design has not. Most writers in the field of environmentally sustainable architecture have noted the environmental advantages of reuse and recycling, and there are many excellent examples of built work where materials and components have been reused. Despite this there has been until recently a lack of critical analysis of the possible effects that reuse and recycling might have on the built environment, and in particular a lack of debate on the implications of a hierarchy of end-of-life scenarios.

Three groups of writers who have noted the relevance to the built environment of a hierarchy of end-of-life scenarios are Fletcher, Popovic and Plank, Guequierre and Kristinsson , and Kibert and Chini.

Fletcher, Popovic and Plank [41], build directly on the lessons of industrial ecology and start their analysis of the problem with the four end-of-life scenarios identified by industrial ecologists; *reuse*, *repair*, *reconditioning*, and *recycling of materials*. The model is then simplified by grouping the scenarios into two levels; the product level, and the material level. The scenarios of reuse, repair, and reconditioning are placed in the product level since they are concerned with product components or subassemblies. The scenario of recycling is placed in the material level since it is concerned with base materials.

In adapting this model to the built environment, and in an attempt to accommodate the theory of time related building layers, this two level approach is then prefaced by a third level, the systems level.

- *Systems level: Adaptable building which can change to suit changing requirement*

- *Product level: The products (or layers) of the building are designed to allow upgrading, repair and replacement. The replaced products can then enter the replenishing loop.*

- *Material level: When a product has been stripped back t its constituent materials these can undergo recycling.*

Exactly how the theory of time related building layers relates to the hierarchy of end-of-life scenarios in this model is not explained. The model does however recognise a hierarchy in which some options are environmentally preferable to others, such as product level reuse being a more 'efficient use of resources' than material level recycling.

Guequierre and Kristinsson [42] have also identified a number of end-of-life scenarios for materials in the built environment. Unlike Fletcher, Popovic and Plank, and the industrial ecology researchers, Guequierre and Kristinsson are not as concerned with the design of new buildings or products, but with the analysis of existing buildings to determine the most appropriate end-of-life scenario. Their concerns are not with how to achieve a higher end-of-life scenario through design, but with what can be done with existing building materials and components. For this reason their model includes the non-reuse scenarios of *landfill*, and *incineration*.

Guequierre and Krstinsson's model is also simplified by grouping the product scaled scenarios together. This results in a model with the four scenarios of; *repair of products*, *recycling of materials*, *incineration*, and *landfill*. Since the model has been devised as an assessment tool for existing buildings, there is no consideration of a scenario for whole building reuse as a system.

Kibert and Chini [43] write on the topic of deconstruction as a means to reducing the environmental burden of the built environment. They propose an explicit waste management hierarchy that includes the levels of landfill, burning, composting, recycling, reuse, and reduction. In this hierarchy the level of recycling is further broken down in to downcycling, recycling and upcycling, in which each is slightly more environmentally advantageous that the previous. The level of reuse is similarly broken into the reuse of materials and the more advantageous reuse of components or products.

The previously unmentioned level of reduction is an important waste management strategy with profound environmental benefits, but in the context of this study it has little bearing on recycling of building materials and components, other than to suggest a general reduction in material usage.

On the separate topic of buildability, not related to recycling, there is one interesting piece of research that identifies a hierarch in building assembly. Moore [44] builds an assembly process hierarchy based on Furguson's buildability hierarch. This hierarchy consists of materials, components, subassemblies and final assemblies (buildings). Though this hierarchy is concerned with levels of assembly and production in an effort to determine better buildability, it is still relevant to deconstruction and recycling.

A Proposal of Levels

In comparing the proposed end-of-life scenarios of the industrial designers with the architects, it can be seen that the subtle differences between product reuse, remanufacture, and repair may not be as relevant to the construction of the built environment as to product manufacturing (see Table 2). If the building is considered as a product, then the vagaries of the sub-assemblies may be beyond the direct control and concern of the product (building) designer. It is appropriate then to combine product remanufacture and product repair, since both are concerned with the production of 'new' products. In this way it is possible to consider the technical results of the scenarios as a way of defining them.

Table 2 Levels of Hierarchy of End-of-life Scenarios (Recycling).

Reference	**Young (1995)**	**Ayres (1996)**	**Graedel (1995)**	**Magrab (1997)**	**Fletcher (2000)**	**Guequierre (1999)**	**Kibert & Chini (2000)**	**Crowther (2000)**
Most desirable ↑					System level			Reuse building
	Reuse	Reuse		Reuse	Product level	Repair product	Reuse of product	Reuse product
	Maintain	Repair	Maintain		Product level	Repair product	Reuse of material	Reprocess material
End-of-life scenarios	Reman-ufacture	Reman-ufacture	Recycle component	Reman-ufacture	Product level	Repair product		Reprocess material
	Recycle	Recycle	Recycle material	Recycle	Material level	Recycle material	Recycle	Recycle material
↓							Compost	
				Burning		Burning	Burning	
Least desirable				Landfill		Landfill	Landfill	

There are four (differently scaled) possible technical results, which have been previously proposed by the author [45];

- the reuse of a whole building
- the production of a 'new' building
- the production of 'new' components
- the production of 'new' materials

These would relate to the four end-of-life scenarios of;

- **building reuse** or relocation
- **component reuse** or relocation in a new building
- **material reuse** in the manufacture of new component
- **material recycling** into new materials.

If the strategies of *recycling* as used in industrial ecology were applied to the built environment, the life cycle stage of demolition could be replaced with a stage of deconstruction. The typical once-through life cycle of materials in the built environment could then be altered to accommodate the possible end-of-life scenarios and produce a range of alternative life cycles (see Figure 3).

We can now look briefly at some examples of these scenarios.

Building Reuse
The first scenario is that of relocation or reuse of an entire building. This may occur where a building is needed for a limited time period but can later be reused elsewhere for the same or similar purpose. A good example of this is the Crystal Palace of 1851. This modular exhibition building designed by Joseph Paxton was based on a simple system of prefabricated structural and cladding units that could be easily joined together. These factory produced elements allowed for the quick assembly and disassembly of the building, and its eventual relocation and reuse after the exhibition [46].

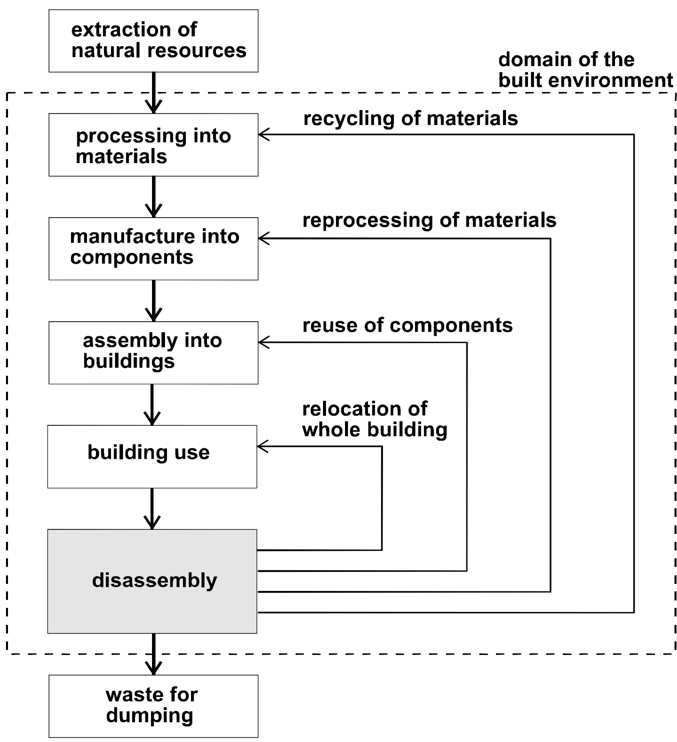

Figure 3 Possible End-of-life Scenarios for the Built Environment

Component Reuse
The second scenario is the reuse of components in a new building or elsewhere on the same building. This may include components such as cladding element or internal fitout elements that are of a *standard* design. A recent example of this is the IGUS factory by Nicholas Grimshaw. The cladding of this building consists of panels that are interchangeable and can be easily moved by just two people. This allows the buildings cladding to be altered to suit changes in the internal use of the building. It is also possible for these components to be used on other buildings of the same design [47]. This scenario of reuse saves on resources, waste disposal, and energy use during material processing as well as energy use during component manufacture and transport.

Material Reuse
The third scenario, that of reprocessing of materials into new components, will involve materials or products still in good condition being used in the manufacture of new building components. A good example of this is the re-milling of timber. In most parts of the world that use timber as a building materials there is a strong vernacular tradition of constructing buildings so that members may be removed and reused or re-processed into smaller members. Even today we still see the reuse of old timber in this way. As well as the waste disposal advantages of the recycling scenario, this reprocessing also reduces the energy required for material processing.

Material Recycling
The final scenario, recycling of resources to make new materials, will involve used materials being used as a substitute for natural resources in the production of manufactured materials. One of the most common current examples of this is the crushing of reinforces concrete to make aggregate that is used for road base. While this scenario does reduce the solid waste stream, other environmental issues may actually not be so positive. While the natural resource use and waste disposal problems are alleviated, the total energy use, and the resultant pollution, may actually be greater than if new resources were used.

Recycling Hierarchy and Design for Deconstruction
The relevance of the hierarchy of end-of-life scenarios to the design process is that it is possible to design a product or building to facilitate the more environmentally advantageous scenarios.

Graedel and Allenby [48] make an important contribution to the debate by noting that the end-of-life scenarios that are possible for a product will be determined by the physical characteristics of that product. That is to say that the actual design of the product will determine whether it is possible to achieve the environmentally preferable scenarios of maintenance and reuse, rather than just recycling or disposal. Attempts to address this issue have been through promoting the notion of design for disassembly and in the development of guidelines for design for disassembly in the field of industrial design.

In building design, Guequierre and Kristinsson [49], like Graedel and Allenby, make the point that there are physical features of the product (building) that will determine which end-of-life scenarios are possible or probable. This notion suggests that it will be possible to design a product (building) in a way that will facilitate or encourage the implementation of the higher (more environmentally preferable) end-of-life options.

Conclusions to Recycling Hierarchy
This section has shown how the concept of *recycling* can be more appropriately represented by a group of end-of-life scenarios;

- building reuse or relocation
- component reuse or relocation in a new building
- material reuse in the manufacture of new component
- material recycling into new materials.

These scenarios can be arranged in a hierarchy, in which reuse is (generally) more environmentally beneficial than recycling or disposal. Environmentally responsible building design should attempt to facilitate the higher level scenarios.

There is a direct relationship between the physical design features of a building and what can be done with the building, or its components, when the end of its service life has been reached. It will therefore be possible, through design for deconstruction, to produce new buildings that can achieve more environmentally beneficial end-of-life scenarios.

PRINCIPLES OF DESIGN FOR DECONSTRUCTION

Sources of Information

The strategy of design for deconstruction, has not yet become a major issue in the construction industry. There are however various sources of information on design for deconstruction that can be assessed for recurring themes [50]. These themes have been developed into principles to be used by building designers to either develop building designs, or to assess existing designs or buildings, for future disassembly. The sources of information used in this research include:

- Industrial design
- Architectural technology
- Buildability
- Building maintenance
- Research into deconstruction

Industrial Design

In the fields of industrial and product design, there is already a good understanding of the environmental benefits of recycling and reuse. The concept of Industrial Ecology has to some extent addressed the notion of reduced environmental impact through improved rates of material and component reuse to minimise waste. There are in fact many researchers who have already identified explicit guidelines for design for deconstruction, or design for disassembly, of industrial or manufactured products. Similarly numerous car, computer and household product manufacturers have already implemented the actual practice of design for disassembly.

A study of industrial design practice and research reveals a number of these design for disassembly or deconstruction guidelines that may have application in the construction industry. These guidelines typically cover issues such as material compatibility, connection type, number of connections, handling facilitation, and information management.

Architectural Technology

While design for disassembly or deconstruction has not become a major part of mainstream construction practice, there have been a considerable number of unique architectural efforts that have used such a technique. Throughout history there have been many cases of buildings designed for deconstruction, either to allow for material reuse or for whole building relocation. From primitive huts to the Crystal Palace, and from traditional Japanese timber building to the schemes of Archigram and the Metabolists, there are valuable lessons in design for deconstruction.

A survey of these historic examples reveals a number of common technological trends that suggest the possibility of developing guidelines for designing for deconstruction in buildings.

These trends can be roughly grouped in to ideas about materials, structural systems, access, connection type, number of components, and appropriate technology.

Buildability

If the process of deconstruction is considered as the opposite of the process of construction, there may be some value in the study of making construction easier. If a building is easier to put together, it should be easier to take apart. The notion of buildability, making buildings easier to construct, has received some research attention. This research has resulted in some explicit guidelines for buildability that should also assist in design for deconstruction. These guidelines are primarily concerned with issues of handling, access, and prefabrication.

Building Maintenance

The maintenance of buildings often requires the replacement of components or materials. To achieve such replacement it is necessary to deconstruct parts of the building. Research into this facet of building maintenance may therefor offer guidance on how to make such disassembly easier. Investigation of research into replacement maintenance has resulted in some principles of design that make such replacement easier. These principles can be adapted to inform the field of design for deconstruction for reasons other than maintenance.

Research into Deconstruction

The International Council for Research and Innovation in Building and Construction (CIB) Task Group 39 on *Deconstruction* is concerned with research into the disassembly and deconstruction of buildings to achieve higher rates of material and component reuse and recycling. This group has identified a number of research projects dealing primarily with the deconstruction of existing building [51]. From this research, and other related projects, a number of desirable attributes of buildings can be deduced if buildings are to be designed to be easily deconstructed in the future.

List of Principles

A total of twenty-seven principles can be derived from all information sources [52]. The basis for inclusion of a principle is in how explicitly it is presented as a principle, and in how broadly it is mentioned. Most principles are informed by several of the fields studied.

These principles have been previously presented in a relationship with the hierarchy of recycling. This has taken the form of categorising the principles into four exclusive groups relating to the four end-of-life scenarios. While this categorisation replicated research in industrial design that attempted to link principles and the recycling hierarchy, it was eventually considered to be undesirable due to the exclusivity of the categorisation method.

A more appropriate way to represent the relationship between principles and the recycling hierarchy, one which allows for principles to be relevant to all end-of-life scenarios, is in a tabulated matrix (see Table 3). In this way the relevance of each principle to each level of recycling can be noted.

CONCLUSIONS

This paper concludes that a thorough understanding of design for deconstruction in architecture must concern itself with four major issues:

- an overriding *model of sustainable construction*

- the theory *of time related building layers*
- a *hierarchy of recycling*
- the *principles* of design for deconstruction

Knowledge of these issues will help to answer basic questions of why, when, where, what and how to design for deconstruction.

Design for deconstruction is one of many useful strategies to assist in reducing the environmental burden of our built environment. It has not however been well investigated, or well implemented on a broad scale. With a greater understanding of the issues and their interrelationships it is hope that design for deconstruction might become an important consideration in any construction project.

Table 3 Principles of Design for Deconstruction and the Hierarchy of Recycling

Legend – level of relevance: ● highly relevant • relevant . not normally relevant

No.	Principle	Material recycling	Component remanufacture	Component reuse	Building relocation
1	Use recycled and recyclable materials	●	●	.	.
2	Minimise the number of different types of material	●	●	.	.
3	Avoid toxic and hazardous materials	●	●	.	.
4	Make inseparable subassemblies from the same material	●	●	.	.
5	Avoid secondary finishes to materials	●	●	.	.
6	Provide identification of material types	●	●	.	.
7	Minimise the number of different types of components	.	•	●	●
8	Use mechanical not chemical connections	.	●	●	●
9	Use an open building system not a closed one	.	.	●	•
10	Use modular design	.	.	●	•
11	Design to use common tools and equipment, avoid specialist plant	.	•	●	●
12	Separate the structure from the cladding for parallel disassembly	.	.	●	•
13	Provide access to all parts and connection points	•	•	●	●
14	Make components sized to suit the means of handling	.	•	●	●
15	Provide a means of handling and locating	.	.	●	●
16	Provide realistic tolerances for assembly and disassembly	.	.	●	●
17	Use a minimum number of connectors	.	•	●	●
18	Use a minimum number of different types of connectors	.	•	●	●
19	Design joints and components to withstand repeated use	.	.	●	●
20	Allow for parallel disassembly	•	•	●	•
21	Provide identification of component type	.	•	●	•
22	Use a standard structural grid for set outs	.	.	.	●
23	Use prefabrication and mass production	.	.	●	●
24	Use lightweight materials and components	●	●	●	●
25	Identify points of disassembly	.	•	●	●
26	Provide spare parts and on site storage for during disassembly	.	.	.	●
27	Sustain all information of components and materials	.	.	•	●

REFERENCES

1 **Kriwet, A., Zussman, E. and Seliger, G.** Systematic Integration of Design-for-Recycling into Product Design, *International Journal of Production Economics*, vol. 38.1995, p. 19.

2 **Kibert, C. J. & Chini, A. R.** *Overview of Deconstruction in Selected Countries*, CIB publication no. 252, 2000.

3 **Guequierre, N. M. J. and Kristinsson, J.** Product Features that Influence the End of a Building, *Proceedings of the 8th Durability of Materials and Components Conference*, 1999.

4 **Sassi, P. and Thompson, M. W.** Summary of a Study on the Potential of recycling in the Building Industry and the Development of an Index System to Assess the Sustainability of Materials for Recycling and the Benefits from Recycling, *Proceeding of the Eurosolar Conference,* 1998.

5 **Kibert, C., Senzimir, J. & Guy, B.** Construction Ecology: Natural Systems Models for the Built Environment, *Strategies for a Sustainable Built Environment - Proceedings of the 2nd Southern African Conference on Pretoria*, 23-25 August 2000, p. 25-1.

6 **Cole, R. J.** Emerging trends in building environmental assessment methods*, Building Research and Information*, vol. 26, no. 1, 1998, pp. 12-13.

7 **Vale, B. and Vale, R.** *Green Architecture: Design For a Sustainable Future*, Thames and Hudson, London, 1991.

8 **Royal Australian Institute of Architects**, Environmental Design Guide – GEN 1:3-5, RAIA, Canberra.

9 **Kibert, C. J.** Establishing Principles and a Model for Sustainable Construction, *Sustainable Construction - Proceedings of the First International Conference of CIB TG 16*, November 6-9, 1994, p. 7.

10 Ibid, p. 11.

11 **Itoh, T.** *Traditional Domestic Architecture of Japan*, Weatherhill/Heibonsha, New York, 1972, p. 43.

12 **Kikutake, K.** On the Notion of Replaceability, *World Architecture*, vol. 33, 1995, p. 27.

13 **Habraken, N. J.** *The Structure of the Ordinary*, MIT Press, Cambridge, 1998.

14 Ibid, pp. 100-105

15 **Habraken, N. J**. *Supports: an alternative to mass housing*, The Architectural Press, London, 1972, pp. 59-60.

16 Ibid, p. 60.

17 Ibid, p. 61.

18 **Landau, R.** A Philosophy of Enabling: The Work of Cedric Price, *AA Files*, no. 8, Spring 1985, p. 4.

19 Inter-action Centre, *RIBA Journal*, November 1977.

20 **Cook, P. et al.** *Archigram*, Studio Vista, London, 1972, p. 36.

21 The Approach of Kiyonori Kikutake, *Architectural Design*, October 1964, p. 514.

22 **Kurokawa, K.** *Metabolism in Architecture*, Westview Press, Boulder, 1977.

23 **Duffy, F. and Henney, A.** *The Changing City*, Bulstrode Press, London, 1989.

24 **Duffy, F.** Measuring Building Performance, *Facilities*, May 1990, p. 17.

25 **Duffy, F. and Henney, A.** op. cit. pp. 60-62.

26 **Brand, S.** *How Buildings Learn*, Viking, New York, 1994, p. 12.

27 **Cook, P. et al.** op. cit.

28 **Curwell, S.** Specifying for Greener Buildings, *The Architects' Journal*, 11 January 1996, pp. 38-40.

29 **Storey, J. B.** Designing for Durability: In Pursuit of Sustainability, *Rethinking the Built Environment: Proceedings of the Catalyst '95 Design and Environment Conference*, 13-16 July 1995, pp. 362-367.

30 **Howard, N. and Sutcliffe, H.** Precious Joules, *Building (London)*, 18 March 1994, pp. 48-50.

31 **Adalberth, K.** Energy use During the Life Cycle of Buildings: a Method, *Building and Environment*, vol. 32, no. 4, 1997, pp. 317-320.

32 **McCoubrie, A. and Treloar, G.** Life Cycle Embodied Energy in Office Furniture, *Proceedings of the Embodied Energy: the current state of play Seminar - Deakin University, Geelong*, November 1996.

33 **Suzuki, M. and Oka, T.** Estimation of Life Cycle Energy Consumption and CO2 Emission of Office Buildings in Japan, *Energy and Buildings*, vol. 28, 1998, pp. 33-41.

34 **Tucker, S. N. and Rahilly, M.** Life Cycle Costing of Housing Assets, *In Building Maintenance and Modernisation Worldwide (ed. Q. Lee Kiang)*, Longman, Singapore, 1990.

35 **Fletcher, S. L., Popovic, O. & Plank, R.** Designing for Future Reuse and Recycling, *Proceedings of the "Deconstruction - Closing the Loop" conference*, BRE, Watford, UK, 18 May 2000.

36 **Craven, D. J., Okraglik, H. M. and Eilenberg, I. M.** Construction Waste and a New Design Methodology, *Sustainable Construction - Proceedings of the First International Conference of CIB TG 16*, Tampa, Florida, November 6-9, 1994, pp. 89-98.

37 **Young, J. M.** *Life Cycle Energy Modelling of a Telephone*, http://sun1.mpce.stu.mmu.ac.uk/pages/projects/dfe/pubs/dfe22/report22.htm, 13 August 1998.

38 **Ayres, R. U. and Ayres, L. W.** *Industrial Ecology: Towards Closing the Materials Cycle*, Edward Elgar, Cheltenham, 1996, pp. 13-15.

39 **Graedel, T. E. and Allenby, B. R.** *Industrial Ecology*, Prentice Hall, Englewood Cliffs, New Jersey, 1995, pp. 260-275.

40 **Magrab, E. B.** *Integrated Product and Process Design and Development: The Product realization Process*, CRC Press, Boca Raton, New York, 1997, p. 152.

41 **Fletcher, S. L., Popovic, O. & Plank, R.** op. cit.

42 **Guequierre, N. M. J. and Kristinsson, J.** op. cit.

43 **Kibert, C. J. & Chini, A. R.** op. cit.

44 **Moore, D. R.** Product Buildability Assessment Through Modelling*, Proceeding of the Product and Process Modelling in the Building Industry conference*, BRE, Watford, 1998.

45 **Crowther, P.** Developing Guidelines for Design for Deconstruction, *Proceedings of the "Deconstruction - Closing the Loop" conference*, BRE, Watford, UK, 18 May 2000.

46 **Peters, T. F.** *Building the Nineteenth Century*, MIT Press, Cambridge, 1996.

47 **Bryden, M.** Factory With Built-in Flexibility, *The Architects' Journal*, 24 March 1993, pp. 33-44.

48 **Graedel, T. E. and Allenby, B. R.** op. cit. pp. 261-262.

49 **Guequierre, N. M. J. and Kristinsson, J.** op. cit.

50 **Crowther, P.** op. cit.

51 **Kibert, C. J. & Chini, A. R.** op. cit.

52 **Crowther, P.** op. cit.