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DESIGN FOR DISASSEMBLY - THEMES AND PRINCIPLES

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The disassembly of buildings to recover materials and components for future reuse is not widely practiced in the modern construction industry. This note covers a range of themes and offers a set of principles, or guidelines, for design for disassembly that can be applied to a project in order to facilitate and encourage greater rates of reuse and recycling in the future. The note builds upon the previous note DES31 'Design for Disassembly' by offering more specific guidance on why, when, what and how to design for disassembly. Further to that, it describes a more developed relationship between significant issues surrounding design for disassembly.

Keywords: design disassembly, recycle, reuse, waste management.

INTRODUCTION

Current practice in the disassembly of existing buildings shows that there are numerous technical barriers to the successful recovery and reuse of components and materials. These barriers stem mainly from current construction practice that sees the assembly of materials and components as a unidirectional practice with an end goal of producing a final building. Such a linear view of the built environment severely limits the end-of-life options when a building has reached the end of its service live. A more cyclic view of the built environment, and the materials within it, recognises the need to consider, at the design stage of a project, the disassembly process and well as the construction process. Such consideration can be expressed as the need to design for disassembly.

While current industrialised building practice in Australia pays little attention to the issues of reuse and recycling, there are numerous historic examples of buildings that have been successfully disassembled for reuse, many of which have been specifically designed for such disassembly. Buildings such as the portable colonial cottages of nineteenth century Australia, and London's crystal palace of 1851, were successfully assembled, disassembled, relocated and then re-assembled. Analysis of many examples such as these highlights common strategies for design for disassembly that can offer useful information to designers seeking to improve the rates of future material and component recovery.

A review of architectural history, and of related industries, such as industrial design, shows that there are two types of knowledge that are relevant in order to design for disassembly. Firstly, there are the broad themes that address the issues of *why, what, where*, and *when* to disassemble, and secondly there are the specific design principles of *how* to design for disassembly. There are three broad themes that significantly impact on the decision making process of designing a building for future disassembly. They are:

- A holistic model of environmentally sustainable construction
- The reading of a building as a series of layers with different service lives
- A recycling hierarchy that recognises the different benefits of different end-of-life scenarios

ADOPTING A MODEL FOR SUSTAINABLE CONSTRUCTION PRACTICE

Before attempts are made to design for disassembly, the consequences must be understood within a wider picture of the built environment, and indeed within the global environment. While to design for future reuse will have obvious environmental benefits such as a possible reduction in material waste, and a reduction in energy consumption, there are also potential environmental costs such as greater initial energy consumption, and the possible use of more toxic materials due to their improved durability. While these environmental costs are almost certainly of a smaller impact, they must be recognised and considered. To manage this process a model is required that allows the place and role of design for disassembly to be seen within the overall picture of environmentally sustainable construction.

Life cycle assessment

The notion of life cycle assessment (LCA) is a well recognised way of understanding, assessing, and planning a reduction in the environmental consequences of our actions. A life cycle assessment of a system or product identifies all of the inputs and outputs, both beneficial and not so, during the entire life cycle of that system or product. It is usual to visualise this analysis as a two dimensional graph or matrix that plots environmental resources against the stages of the life of the system or product life. In this way all of the cumulative environmental impacts can be seen and analysed. This model, with its two axes of environmental resources and life cycle stages, does not however offer strategies for dealing with the unwanted impacts, such as resource consumption, pollution, loss of biodiversity, and reduced human health and safety.

A model of sustainable construction

To propose solutions to these problems, a third axis of 'principles' for environmental responsibility can be added. In this way a three dimensional matrix can be created. Charles Kibert (1994) of the University of Florida proposes such a model. This model, with the three axes of *environmental resources*, *life cycle stages*, and *principles of sustainability*, can be used to illustrate the large number of issues that pertain to a sustainable construction industry, and the interrelationships between them. The model can also be used as a tool to manage the decision making process during a construction project. At any point of intersection along the three axes there will be a range of decisions to be made, each with further impacts along those axes that must be considered.

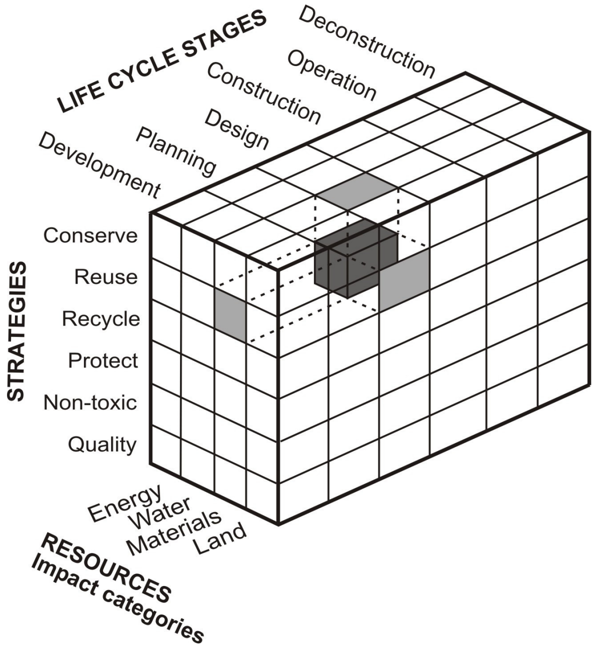

Figure 1. Modified representation of a model for sustainable construction, highlighting the main area of concern for design for disassembly (Based on Kibert 1994)

It can be seen in this model that there is a time and place for the strategy of the future *reuse* of *materials* can be applied at *the design* stage of a building. This is to say that this model has identified a place for *design for disassembly*. This model highlights the fact that such an activity should exist within the general field of sustainable construction, and also shows the potential relationships with other environmental issues and strategies. This model assists the designer in an understanding of *why* when designing for disassembly. It can therefore be used as a design tool to make the designer aware of possible conflicts that may occur between alternative principles of design for disassembly. These might include conflicts such as a desire to recycle materials to reduce waste creation, but the energy of recycling may actually be greater, due to increased transportation, than the energy of creating new materials, or the conflicting issues of deciding whether to use a long life durable material that has a higher toxic content.

TIME RELATED BUILDING LAYERS

When we discuss a building, we tend to think of it as just that, a single building. Buildings are conceived, designed, constructed, used, and disposed of as complete entities. This notion of the singular building is however flawed, in part, resulting from our reading of the building over a limited time frame. Most buildings live long lives in some form or another and usually change during that time. This results in a series of different buildings over time that may or may not share certain physical parts. Typically the structure of a building may be retained while the internal spaces are changed with components removed and replaced, or services upgraded.

Analysis of vernacular architecture, especially by the noted Dutch writer John Habraken (1998), typically identifies two layers of building. Firstly, the structural frame which has a long service life, and secondly, the space making elements of partitioning walls that may be removed and reused or replaced over time as spatial needs change. In these buildings technological steps are taken to allow for such changes over time through the design for disassembly of those components which have a shorter service life expectancy.

Recognition of the different service lives of different parts of building was a popular topic with architects in the 1960's when groups such as Archigram in Britain and the Metabolists in Japan were experimenting with building systems where such disassembly was not only possible but highlighted in the aesthetic character of the projects. Interestingly these architects often proposed specific service lives for different parts of buildings depending on their life expectancy.

For a similar but much expanded analysis of the different service lives of the layers of buildings, the work of American writer Stewart Brand is noteworthy (1994). Brand dissects the layer of a building into, Structure, Skin, Services, Space plan, and Stuff, and also adds the layer of the Site on which the building stands. Brand (1994) goes to great lengths to explain the technical and social benefits of designing and constructing buildings in a layered manner. Like Habraken (1998) he recognises the lessons already learned by vernacular builders and further suggests specific lessons for building designers based on the historic study of buildings and their adaptation, addition, and relocation over time.

Table 1. Building layers and their life spans (Brand 1994)

Layer	Life span (years)
Site	**Eternal**
Structure	**30 - 300**
Skin	**20**
Services	**7 - 15**
Space plan	**3 - 30**
Stuff	**Daily**

Peter Graham (2005), in the EGD note GEN 66 'Design for Adaptability', explains the significance of building layers in designing for future building adaptability. There is also significant relevance in these time related building layers to the concerns of design for disassembly. It is at the junctions of layers that disassembly will need to occur. These junctions need to be designed to facilitate appropriate disassembly at the places where it will be required – that is between components of different service life expectance. Facilitating such disassembly will allow buildings to develop over time in an environmentally and socially responsible way. An understanding of time related building layers will assist the designer in understanding *where* and *when* to design for disassembly.

HIERARCHIES OF RECYCLING

Linear life 'cycle'

The usual mode of operation in our industrialised society is one of single use and disposal. Materials are extracted from the natural environment, processed, manufactured, used once, and then disposed of, usually back into the natural environment resulting in pollution, resource depletion, habitat loss, and excessive energy consumption. In the building industry this mode of operation is certainly the dominant one. This so called 'life cycle' is in fact not at all cyclic, but rather linear, starting with material extraction and ending in the dumping of unwanted waste. Such a model for how materials pass through the built environment identifies a number of life cycle stages; extraction, processing, manufacture, assembly, use, demolition, and disposal.

Life 'cycle' options

This model is not the only option, and it is not difficult to reconfigure these stages into a true cycle of material life in which unwanted building materials and components, or indeed whole buildings, can be recycled or reused. With the appropriate disassembly strategy, such recycling can occur in many different ways.

It can be seen that there are a range of possible so called recycling scenarios with a range of outcomes. If the technical outcomes of the deconstruction process are considered, four differently scaled outcomes are possible. These are:

- The reuse of a whole building
- The production of a new building
- The production of new building components
- The production of new building materials

These would relate to four possible end-of-life scenarios:

- Building reuse or relocation
- Component reuse or relocation in a new building
- Material reuse in the manufacture of new building components
- Materials recycling (down cycling) into new building materials

If the strategy of design for disassembly were applied to the built environment, the life cycle stage of demolition could be replaced with a stage of disassembly. 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. Figure 2 shows the current dominant scenario in which demolition results in large quantities of waste creation. It also shows the possible alternative end-of-life scenarios in which waste can be significantly reduced if not eliminated entirely.

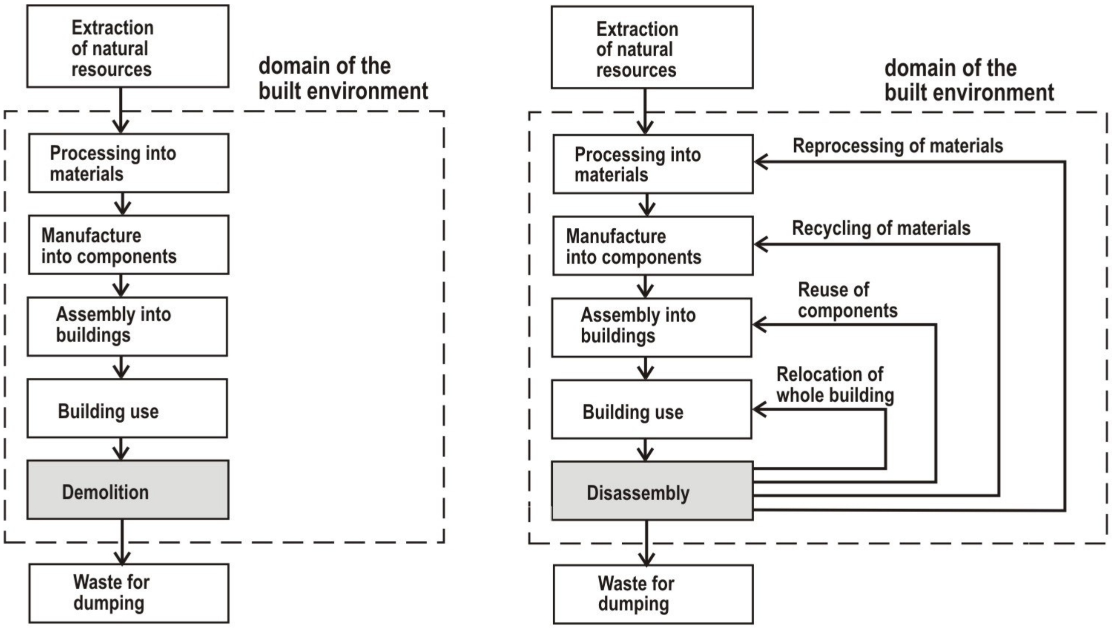

Figure 2. Dominant end-of-life scenario, and alternative scenarios, for the built environment

Perhaps the most significant aspect of these scenarios is that some of them are more environmentally desirable than others. The reuse of a building component has the added advantage of requiring less energy or new resource input than the recycling of base materials. In a society where all energy has some environmental cost, and indeed where most is produced through major environmentally damaging processes such as the burning of fossil fuels, any strategy that reduces energy and resource use has environmental advantages. Buildings might for example be better designed for the reuse of components rather than simply the recycling of materials. In reality it will be advantageous for buildings to be designed for all of these levels of ‘recycling’ since the future reuse possibilities of a building can not be accurately predicted decades before eventual disassembly.

An understanding of a hierarchy of recycling offers guidance of *what* to disassemble for any given end-of-life scenario. It must be noted that it may not always be preferable to design for disassembly at building or component level. It is quite possible that for a particular project there are other environmental concerns such as autonomous energy generation, or the avoidance of all toxic content, that may outweigh the benefits of a design for disassembly strategy. This is why the holistic picture of a sustainable construction industry is needed to guide this decision making process.

PRINCIPLES OF DESIGN FOR DISASSEMBLY

These three broad themes of a model for environmentally sustainable construction, time related building layers, and a recycling hierarchy, are important in assisting to manage the process of design for disassembly. They do not however answer the question of *how* to design for disassembly. For that, a number of design principles or design guidelines are required.

While the design for disassembly of buildings is not common practice, there are a number of important historic examples of buildings that have been disassembled, either by design or otherwise, that can offer significant information about the technical aspects of such disassembly, these include: traditional and vernacular timber buildings, temporary buildings for military use such as the Nissen hut, the Dymaxion projects of Buckminster Fuller, the Fun Palace of Cedric Price, the Centre George Pompidou, Lloyds of London, and several of the projects of Nicholas Grimshaw. Review of these buildings and many others, some realised projects and some conceptual investigations, reveals a pattern of common solutions or approaches to the difficulties of design for disassembly. These common approaches offer recurring principles as design guidance. These principles may be seen as design guidelines or design techniques for architects and building designers.

Use recycled and recyclable materials - to allow for all levels of the recycling hierarchy, increased use of recycled materials will also encourage industry and government to develop new technologies for recycling, and to create larger support networks and markets for future recycling.

Minimise the number of different types of materials - this will simplify the process of sorting during disassembly, and reduce transport to different recycling locations, and result in greater quantities of each material.

Avoid toxic and hazardous materials - this will reduce the potential for contaminating materials that are being sorted for recycling, and will reduce the potential for health risks that might otherwise discourage disassembly.

Avoid composite materials and make inseparable subassemblies from the same material - in this way large amounts of one material will not be contaminated by a small amount of a foreign material that can not be easily separated.

Avoid secondary finishes to materials - such coatings may contaminate the base material and make recycling difficult, where possible use materials that provide their own suitable finish or use mechanically separable finishes (Note: some protective finishes such as galvanising may still on balance be desirable since they extend the service life of the component despite disassembly or recycling problems).

Provide standard and permanent identification of material types - many materials such as plastics are not easily identifiable and should be provided with a non-removable and non-contaminating identification mark to allow for future sorting, such a mark could provide information on material type, place and time or origin, structural capacity, toxic content, etc.

Minimise the number of different types of components - this will simplify the process of sorting and reduce the number of different disassembly procedures to be undertaken, it will also make component reuse more attractive due to greater numbers of fewer components.

Use mechanical connections rather than chemical ones - this will allow the easy separation of components and materials without force, reduce contamination of materials, and reduce damage to components.

Use an open building system where parts of the building are more freely interchangeable and less unique to one application - this will allow alterations in the building layout through relocation of component without significant modification.

Use modular design - use components and materials that are compatible with other systems both dimensionally and functionally. This type of modular co-ordination, that today we in some part take for granted, not only has assembly advantages, but clearly also has disassembly advantages, such as standardisation of disassembly procedure and a broader market for reused components.

Use construction technologies that are compatible with standard, simple, and 'low-tech' building practice and common tools - specialist technologies will make disassembly difficult to perform and a less attractive option, particularly for the user. Specialist technologies, materials, and systems that have limited application today may not be readily available in the future when a building is to be disassembled.

Separate the structure from the cladding, internal walls, and services - to allow for parallel disassembly such that some parts or systems of the building may be removed without affecting other parts. Most construction methods can be considered as being either a system of load bearing walls, or a system of separate structural frame and in-fill. The system of separate frame and in-fill is by far the more compatible of the two with a range of disassembly requirements.

Provide access to all parts of the building and to all components - ease of access will allow ease of disassembly, allow access for disassembly from within the building if possible.

Make components and materials of a size that suits the intended means of handling - allow for various handling operations during assembly, disassembly, transport, reprocessing, and re-assembly. The handling of building materials and components is an important consideration in any building, more so if the building is to be disassembled and components later re-assembled.

Provide a means of handling and locating components during the assembly and disassembly procedure - handling may require points of attachment for lifting equipment as well as temporary supporting and locating devices. The provision of a means of handling components is not often considered in building design because the current approach within the building industry is that a component will only be handled once during the initial assembly.

Provide realistic tolerances to allow for manoeuvring during disassembly - the repeated assembly and disassembly process may require greater tolerance than for the manufacture process or for a one-off assembly process.

Use a minimum number of fasteners or connectors - to allow for easy and quick disassembly and so that the disassembly procedure is not complex or difficult to understand. Such a principle will assist in the repair of the component or in the rebuilding of it, though it is not so relevant for the reclaiming (for recycling) of the material, which might be recovered by simply breaking the component.

Use a minimum number of different types of fasteners or connectors - to allow for a more standardised process of assembly and disassembly without the need for numerous different tools and operations.

Design joints and connectors to withstand repeated use - to minimise irreparable damage or distortion of components and materials during repeated assembly and disassembly procedures, to allow for the rigors of repeated assembly and disassembly.

Allow for parallel disassembly rather than sequential disassembly - so that components or materials can be removed without disrupting other components or materials, where this is not possible make the most reusable or ‘valuable’ parts of the building most accessible, to allow for maximum recovery of those components and materials that are most likely to be reused.

Provide permanent identification of component type - in a co-ordinated way with material information and total building system information, ideally electronically readable to international standards.

Use a structural grid - the grid dimension and orientation should be related to the materials used such that structural spans are designed to make the most efficient use of material type and allow coordinated relocating of components such as cladding. This will also result in more components of same/standard size, and the grid responds to issues of material efficiency.

Use prefabricated subassemblies and a system of mass production - to reduce site work and allow greater control over component quality and conformity. The prefabrication of these components reduces the amount of on-site work required and thereby eases the process of assembly, and later disassembly, of the building.

Use lightweight materials and components - this will make handling easier and quicker, making disassembly and reuse a more attractive option. This will also allow disassembly for regular maintenance and replacement of parts.

Permanently identify points of disassembly - so as not to be confused with other design features and to sustain knowledge on the component systems of the building. As well as indicating points of disassembly, it may be necessary to indicate disassembly procedures as instructions.

Provide spare parts and on-site storage for them - particularly for custom designed parts, both to replace broken or damaged components and when required for minor alterations to the building design. Storage for spare components is an integral part of the building design.

Retain all information on the building construction systems and assembly and disassembly procedures - efforts should be made to retain and update information such as ‘as built’ drawings including all reuse and recycling potentials as an assets register. The retention of such complete information about the whole building enhances its potential value for relocation, reuse, or recycling.

It is apparent from this list of design for disassembly principles that there will be many occasions when there will be a conflict between some of them. For example, the need to *minimise the number of different material types* will not always be compatible with the need to *use light weight materials*. In such a case the potential environmental benefits from each principle may need to be compared and evaluated in light of the broader issues. The principles in themselves offer guidance on *how* to design for future disassembly, but as already noted there are broader themes that must be engaged with in order to answer the more challenging questions of *what*, *where*, *when*, and indeed *if*, to disassemble. One of the ways in which a broader understanding of the issues can assist is illustrated in the following table which shows how different principles will be more or less relevant to different proposed end-of-life scenarios. The table rates each principle against the four end-of-life scenarios of the recycling hierarchy, and ranks them as ‘highly relevant’, ‘relevant’, or ‘not normally relevant’. This ranking allows the designer to assess the principles by the technical benefits they may produce. This offers a way, based on level of recycling, to determine the most appropriate principles to apply to a building design.

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Table 2. Principles of Design for Disassembly and their relevance to the hierarchic levels of recycling

Legend of 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 them and parts during disassembly**	·	·	·	●
27	**Retain all information of the building components and materials**	·	·	•	●

CONCLUSIONS

Any comprehensive strategy to design an individual building for future disassembly must operate within the existing structure of the construction industry, and the quickly developing recycling and reuse industry. The individual nuances of any architectural project, and the expected long term environmental outcomes, make it difficult to propose generic principles that will always be appropriate. The guidance offered here must be taken as a starting point for the development of individual strategies for individual buildings. Design for disassembly will be of most benefit, both environmentally and economically, to clients who own their buildings for long periods of time and who periodically upgrade or retrofit them. The benefits will also be potentially even greater for clients who own large numbers of buildings used for similar purposes. Three such client groups would be universities, hospitals, and government departments, especially departments such as defence. In these instances the long term benefits of design for disassembly are more likely to be appreciated and realised, than with developers and short term building owners who are more likely to be driven by economic imperatives than environmental ones.

It can be seen though that the technological steps that might be taken, through design, to improve the rates of material and component recovery in the future, are neither complex nor alien to current industry practice. Further they are compatible with general good design practice, and with attempts to improve the environmental sustainability of the construction industry. In order however to facilitate best disassembly practice in the future we must practice design for disassembly now.

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BIOGRAPHY

Dr Philip Crowther, PhD, BArch (Hons), BBE, BA (Film), is an architect and full time lecturer at Queensland University of Technology, Brisbane. Philip teaches design and technology in the undergraduate architecture programme. He has been the Australian representative on the International Council for Research and Innovation in Building and Construction (CIB) Task Group 39 - *Deconstruction.* As well as research interests in design for disassembly he is interested in design for self-build and the empowerment of owner occupiers to construct to their own needs.