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Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong

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ABSTRACT

Prefabrication has been increasingly used in buildings. It is recognised as a solution to reduce waste arising during design and construction phases. However, there is little emphasis on life cycle design issues for prefabricated buildings located in dense high-rise building environments. The purpose of this paper is to review the application and identify benefits and impediments of design for deconstruction and Industrialised, Flexible and Demountable building systems when applied to precast concrete construction. The paper presents the results of a comprehensive literature review, and two case studies of recently completed institutional buildings using prefabrication. The literature review shows that, so far, design for deconstruction is not a common practice in the building industry. The case studies showed some limitations such as the dense urban environment conditions and limited site area. The promotion of a closed-loop material cycle is critical to contribute to sustainability thus minimising CO_2 emissions, natural resources consumption.

1. Introduction

Since the Brundtland report [1], sustainability and sustainable design have become a growing concern throughout the world. It is recognised that buildings consume a large amount of resources during their whole life cycle (including non-renewable ones): energy and materials. Indeed the construction activities have significant negative impacts on the environment, such as air and water pollutions, and waste generation. Life-cycle design has been promoted by implementing design for disassembly and deconstruction to facilitate the reuse and recycling of building components and materials.

Prefabrication is a recent trend in the construction industry, moving the manufacturing process off-site in a safe and controlled environment. The use of precast concrete construction reduces on-site environmental burdens and increases on-site safety and productivity [2,3]. Prefabrication was also recognised as a solution to reduce waste generation during the design and construction phases of projects [2–5].

Yet a large amount of construction waste is produced at the end of a building lifespan, during demolition. Therefore, this possible problem needs to be included within the parameters of sustainable construction [6]. Addis and Schouten [7] argued that potentially-valuable materials are sent to ever-diminishing landfill sites. Various countries, including Hong Kong, are facing similar problems of construction waste management. In fact, considering the limited space available for the disposal of waste, the depletion of resources such as wood, metal and natural gravel, the escalating amount of resource consumption for the manufacturing of construction materials and emissions released into the environment, sustainable construction should encompass closed-loop material flows [8]; so that deconstructed materials are re-directed into the material flow [6]. To achieve this goal, the construction industry will require a fundamental change in the way buildings are designed, constructed and used.

1.1. Closed-loop material strategy in buildings

Kibert [9,10] suggested that the fundamental rules for a closed-loop building material strategy need to ensure that: (1) buildings must be deconstructable; (2) products must be disassemblable; (3) materials must be recyclable; (4) products/materials must also be harmless in production and in use; and (5) materials dissipated from recycling must be harmless. These rules reinforce the observation that building materials must be recoverable and reusable at the end of the building's useful life. According to Kibert [10], closing material loops in construction remains the most challenging green building concept to implement. Kibert [10] identified seven factors that may limit the adoption of closing materials loops in buildings. These limiting factors are:

1. buildings are custom-designed and custom-built by a large group of participants;
2. no single 'manufacturer' is associated with the end product;
3. aggregate, for use in sub-base and concrete, brick, clay block, fill, and other products derived from rock and earth, are commonly used in building projects;

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Table 1
Details of institutional building projects using prefabrication construction.

	HKCC HH	HKCC WK
	Project 1	Project 2
Project description	One 17-storey tower 3-level podium	Two 14-storey towers linked with podium & sky gardens
Year of construction	2005–2007	2006–2007
Site area (m2)	4386	3950
CFA (m2)	30,404	37,424
Podium construction	Conventional construction	Conventional construction
Tower construction	Precasting for structural & non-structural elements	Precasting for structural elements
Precast % (by volume)	47%	40%
Type of prefabricated elements	Semi-precast slab Precast beam & column Precast staircase Precast facade	Semi-precast slab Precast beam Precast staircase
Design characteristics	Non standard block design Modular precast structural grid (8.4 × 8.4 m) Variations of layout on each floor Rotational symmetry	Non standard block design Similar modular precast structural grid from Project 2 Variations of layout on each floor
Life cycle design issues	Reduction of material use and waste generation Flexibility: flexible internal layout, and allowing space for future extension without modifying the existing building structure Modularisation: modular structural system adopted in the two projects resulting in different building layout and design	

4. the connections of building components are defined by building codes to meet specific objectives (e.g., wind load, seismic requirements), not for ease of disassembly;
5. historically, building products have not been designed for disassembly and recycling;
6. buildings can have a very long lifetime exceeding those of the industrial products; consequently, materials have a long “residence” period;
7. building systems are updated or replaced at intervals during the building's lifetime (e.g., finishes at 5-year intervals; lighting at 10-year intervals; HVAC systems at 20-year intervals). (pp.258)

The last factor identified as a limitation is a normal consideration that applies for all building types constructed with conventional or prefabrication construction methods. Although Kibert mentioned the lack of association between the manufacturer and the end product, some manufacturers such as the single family housing manufacturers in Japan do implement this strategy. The manufacturers operate the delivery and the after-sale services (e.g. upgrading modules, and even provide a recycling/refurbishing/relocation programme). Indeed, as opposed to other manufacturing industries (e.g. the car industry), the building industry has not yet implemented legislation to force producers to take responsibility for their products throughout the whole lifecycle [7]. According to Schultmann [11] the design of a building would significantly influence the amount of potentially reusable/recyclable materials at the end of the useful life of a building. Applying prefabrication and close-loop strategy are beneficial as prefabrication reduces up to 60% of the waste produced at construction sites and DfD avoids significant waste generated at the end of the building's useful life. Examining the ways in which life cycle design principles are applied and the resultant costs and benefits are the aims of this paper.

2. Research methodology

This paper presents a comprehensive review of the literature on design for deconstruction (DfD) and building systems that are industrialised, flexible and demountable (IFD). Definitions, principles and applications of DfD and IFD building systems were examined. Additionally, two detailed case studies of recently completed institutional buildings using similar precast components were investigated (Table 1).

The literature review consisted of a review of journals, books, newspapers, reports and websites in the fields of prefabrication, precast construction and life cycle design in buildings. Case studies of existing buildings using DfD or IFD building systems and precast concrete construction were examined. Both qualitative and quantitative data were analysed. Benefits of adopting these principles in buildings were assessed in terms of environmental, economic and social benefits.

For the detailed case studies, the data collection process consisted of (1) a project-oriented questionnaire survey, (2) face-to-face interviews, and (3) site observations. The project-oriented questionnaire was administered by email or in person, and consisted of six questions on the benefits and limitations of using prefabrication in the project. The respondents were asked to assign an appropriate rating on a scale of 1 to 5, from the highest to the lowest level, against each factor. The life cycle design issues were examined in the following topics: (a) reduction of material use and waste generation, (b) flexibility in space planning, (c) modular building structure, and (d) DfD. The respondents consisted of architects, contractors, project managers involved in the two projects. Face-to-face interviews were conducted with architects, contractors, project managers and precast element manufacturers to reinforce data collected in the survey. Also, site observations were conducted at various stages of the construction process at the two construction sites and at the precast manufacturing plant. Drawings and project documentation were collected from the architects, clients, contractors and the buildings department.

3. Results and discussion

3.1. Design for deconstruction

3.1.1. Definitions and principles of DfD

Deconstruction has been identified as an essential means for promoting a closed-loop system for building components [7–16]. Kibert [9,10] defined deconstruction as “the whole or partial disassembly of buildings to facilitate component reuse and materials recycling”. In this study, the term design for deconstruction (DfD) refers to design principles to ensure and facilitate deconstruction for reusing and recycling of building components at the end of a building's useful life. DfD in buildings may significantly reduce waste generation and divert waste away from landfills (diversion rate in the US is about 80%) [13]. According to Crowther [14], there are four scenarios for the reuse of building materials after deconstruction, such as (1) the relocation of the building, (2) the reuse of components, (3) the reprocessing of materials, and (4) the recycling of materials. In these four scenarios, reuse is preferred to reprocessing or recycling as no additional energy is needed while reprocessing or recycling is downgrading and its contribution to new product is limited [8].

3.1.2. Construction details and separation of layers

Crowther [15,16] defined a comprehensive list of 27 principles of design for disassembly. Among these principles, the use of open building system, modular design, structural grid, and the use of prefabricated sub-assemblies and a system of mass production are encouraged. In applying DfD principles, the connections between elements are essential. Indeed, the use of mechanical connections rather than chemical ones is highly recommended [15,16]. This facilitates both the reuse of building elements and the initial assembly process at the construction site saving construction time and cost. Te Dorsthorst and Kowalczyk [17] also argued that aspects of standardisation of building elements in terms of sizes (like length and height) are also critical to facilitate the reuse. According to Crowther [15,16] the design of joints and connectors should withstand repeated uses, and the separation of the structure from the cladding, internal walls, and services is essential.