Renewable and Sustainable Energy Reviews 62 (2016) 1171–1183

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Life cycle performance of modular buildings: A critical review

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ARTICLE INFO

Article history:
Received 27 August 2014
Received in revised form
14 February 2016
Accepted 3 May 2016

Keywords:
Off-site construction
Modular construction
Life cycle assessment
Sustainability
Life cycle performance

ABSTRACT

Off-site construction has gained more attention from both academia and industry during the last few years. Modular construction is one of the most efficient off-site construction methods. In this method, different parts (components) of a building are designed and fabricated off the construction site in factories as one or more modules, and then they are assembled on site to form the final product. Studies have shown that the modular building technique is applicable to different types of buildings, including residential, commercial, educational, and medical. Environmental performance is one of the most significant dimensions leading to sustainability. Since buildings account for a substantial portion of environmental burdens, the main focus of this study is on the environmental performance of modular facilities over their life cycle. This article also presents a comprehensive critical literature review on the benefits and challenges of the modular construction method, compared to its conventional counterpart. It is concluded that, on average, modular buildings have been shown to provide a better life cycle performance, for example a building's energy performance, among others. Further life cycle research, considering all the dimensions of sustainable construction, is recommended in order to develop a robust picture of the sustainability of modular construction.

Contents

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http://dx.doi.org/10.1016/j.rser.2016.05.031
1364-0321/

1. Introduction

Conventionally, a building is constructed on the construction site after the design phase and a contractor is hired to build it. This process is commonly known as “on-site”, “site-built”, “stick-built”, “conventional”, or “traditional” construction. Since the late 19th century, this method of construction has been the accepted construction method and nowadays it accounts for a significant portion of the housing industry [1]. For example, in 1998, on-site homes accounted for over 75% (0.9 million homes out of the 1.2 million) of annual new homes built in the United States [2].

However, in the past few decades, the construction industry has been exposed to the process of industrialization and has experienced different methods of construction. As a result, off-site construction came into practice as an alternative to the on-site method. Off-site construction refers to the process of manufacturing and preassembling of building elements, components or modules prior to their installation on the final jobsite [3]. Based on the degree of work off the construction site, off-site construction is categorized into the following levels [4]:

- Component subassembly: Small scale elements are assembled in factory environments (e.g., windows);
- Non-volumetric preassembly: Items are assembled in factory environments to form non-volumetric units before installation on construction sites (e.g., cladding panels);
- Volumetric preassembly: Similar to the previous level, items are assembled in factory environments but form volumetric units (i.e., units enclose usable space) before installation on construction sites. Units are usually fully finished internally (e.g., toilet pods); and
- Complete (modular) construction: Items are assembled in factory environments to form fully finished modules. Whole buildings are formed by a number of modules.

Modular construction, as one of the off-site construction methods, is fast evolving as an effective alternative to traditional on-site building. The technique is widely used in North America, Japan, and in parts of Europe [5,6]. In general, the adaptation of off-site construction methods in developing countries has not been as fast as that of developed countries [7].

Modular buildings are a set of modules that are built in an off-site fabrication center, delivered to the construction site, assembled, and placed on the permanent foundation. A modular building normally has multi-rooms consisting of three-dimensional modules. The modules are built and preassembled in factory environments and all the mechanical, electrical, plumbing, and trim work is done [8]. Upon completion by the manufacturer, these units are shipped to the site for installation on foundations much like a site-built project [9,10]. About 85–90% of the modular construction is done off the construction site and the remaining work (10–15%), including foundations and utility hookups, is done on site [9]. The application of modular construction is found mainly in general building construction, particularly apartment buildings, schools, hotels, student housing, hospitals, offices, single-family developments, correctional facilities, floating projects, and other buildings where units are repetitive [5,11].

Despite the many well-documented benefits that can be derived from the use of off-site construction techniques, applications are still limited. For example, the US modular industry accounts for only 2–3% of the total new single-family houses and equal or less than 1% of the total new multi-family houses between 2000 and 2014 [12]. A key reason for clients’ reluctance to accept innovated construction techniques is the difficulty of ascertaining the benefits that off-site construction adds to a project [13]. For many of those involved in the construction process, the benefits of using off-site construction techniques were not well understood [2]. As a result, decisions surrounding off-site construction techniques are largely made based on anecdotal evidence rather than rigorous data [13–15].

It is claimed that modular construction provides a wide range of environmental, economic, and social advantages; thus, it can contribute to achieving the goals of sustainability [16,17]. These advantages, can justify the use of modular construction by the construction industry practitioners as an effective alternative, more than in the past. To gain a deeper understanding of the modular construction's overall sustainability compared to its conventional counterpart (i.e., on-site construction), it is imperative to investigate the sustainability performance of modular buildings over the entire life cycle. Therefore, the main objective of this study is to critically review the research studies that have been carried out to evaluate the life cycle performance of modular construction. The thorough literature review conducted in this study did not find any life cycle analyses of modular construction that address all the sustainability dimensions (i.e., environmental, economic, and social). There are only a few environmental life cycle studies that evaluated the environmental performance of modular buildings. Therefore, the primary focus of this paper is on the environmental dimension. In addition to the main objective, key benefits and challenges of modular construction are also investigated.

This paper is organized as Introduction, Methodology, Benefits and Challenges of Modular Construction, Life Cycle Performance of Modular Buildings, Discussion, and finally, Conclusions. The methodology section describes the methodological framework used in this paper, where two independent studies (Study 1 and Study 2) have been carried out. Study 1 summarizes the benefits and challenges of the modular construction method. Study 2 reviews the publications which compared modular to conventional building construction, in terms of life cycle performance.

This paper contributes to the current body of knowledge by providing a deeper insight into the environmental performance of modular buildings compared to conventional buildings (Study 2). Furthermore, the strengths and weaknesses of using modular construction were critically analyzed (Study 1). The outcomes of this study may help construction industry practitioners, such as decision makers, policymakers, clients, developers, engineers, contractors, and modular manufacturers, to have a better understanding of modular construction and devise appropriate strategies to overcome the identified challenges. The paper also identified some research gaps in the field of modular construction.

2. Methodology

A methodological framework for both Study 1 and Study 2 of the paper is presented in this section.