Chapter 8
A Framework for Utilizing Automated and Robotic Construction for Sustainable Building

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8.1 Introduction

Automation and robotics has been regarded as a leading area of innovation in construction, for the betterment of the industry. Research has been spread out for decades, and new automation and robotics technologies continue to be developed for the general manufacturing industry as well as for the construction industry (Bock and Linner 2015a). In the meantime, the building sector has received increasing attention under the worldwide agenda for sustainable development, since buildings account for more than 30% of global greenhouse gases (GHG) emissions and more than 40% of global energy consumptions (Unep 2009). Nevertheless, the development of sustainable buildings (SBs) has experienced problematic implementation on all levels [design, construction, operation, etc. (Pan and Ning 2014)]. Performance gaps, poor operation and management exist to impede the achievement of SBs, requiring advanced technologies and intelligent approaches (Goodier and Pan 2010). Construction automation and robotics has the potential to improve sustainability performance in terms of construction waste reduction, resource saving, workplace safety improvement, intelligent living environment, etc. Recently, the EU, for example, started to initiate and fund projects in which improvements in construction automation and prefabrication shall bring down cost for sustainable, highly energy-efficient components and buildings in order to foster their adoption in Europe in a large scale (BERTIM 2016; ZERO-PLUS 2016). Also, some construction companies already use advanced production technologies to reduce waste and resource consumption (Bock and Linner 2015a), and first approaches are on the

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way to use automation technology for controlled disassembly of buildings and urban-mining (Lee et al. 2015).

However, in general, in the architecture and civil engineering filed, up to date most of the relevant research was focused on the adoption of new approaches and technologies in the operation and maintenance stages (Wood 2011) of buildings (e.g. smart grids, building automation, green building technologies, the use of information technology for maintenance automation, etc.), whilst the potential of automated/robotic technologies to achieve sustainability through the construction stage is a field that needs yet to be analyzed and developed in a comprehensive manner. Activities during the construction stage have significant impacts on SB: (e.g. on various types of pollution, construction waste and resource consumption, work conditions and public welfare, cost efficiency (Akadiri et al. 2012), reusability and flexibility of buildings, etc.) which can be controlled and influenced for better outcomes through automated/robotic technologies.

The aim of this paper is to build the basis for the development of a systematic framework and assessment tool for the utilization of automated and robotic construction technologies for achieving SBs. The remainder of the paper is structured as follows. Section 8.2 reviews the state of the art of technology and approaches in construction automation and SB. Based on this, Sect. 8.3 outlines the key dimensions of the framework, and identifies relevant mechanisms and indicators summarized in a framework matrix. Section 8.4 provides a brief outlook on the future work which will detail the indicators, define quantifiable variables, and verify and validate the framework through application in case studies and real world projects.

8.2 Background

This section reviews the state of the art of technology and approaches in construction automation and SB that build the basis for the development of the framework.

8.2.1 Development of Automated and Robotic Technology for Building Construction

Construction automation and robotics generally refers to a wide spectrum of machinery applications for automating construction processes across the whole project lifecycle, from the initial design, on-site and off-site construction, maintenance and operation control, to the eventual disassembly/demolition (Castro-Lacouture 2009). Mahbub (2008) defined that construction automation and robotics as the use of self-control mechanical and electronic machinery with intelligent control to conduct construction tasks automatically. Examples of construction automation are shown in Fig. 8.1.

Historically, the first introduction of automation in construction can be traced back to the manufacturing of industrialized building components and the prefabrication of modular homes in Japan in the 1970s (Bock and Linner 2015a). That introduction laid the foundation for later world-wide exploration of automation in construction. In the 1980s, many single-task prototype robots have been developed, primarily in the consideration of the low productivity and possible future labor shortfall and issues. Later on, full-scale application of on-site automated construction was introduced, with the first building project completed in 1991 in Japan (Bock and Linner 2016a). The adoption of on-site automated construction systems demonstrated multiple benefits including a large reduction of waste, significant time saving, flexible working conditions, and improved quality, but a high capital expenditure (Bock and Linner 2016b; Hasegawa 1999). Recently, the actual R&D activities on a worldwide level are concentrating more on the emerging software and IT technologies, like sensor-based monitoring and tracking, the utilization of robots for automated facade installation (Iturralde et al. 2015), robots and technologies for building renovation (e.g. asbestos removal robots) (Bock and Linner 2015a), and robotic technologies for building deconstruction (Lee et al. 2015).

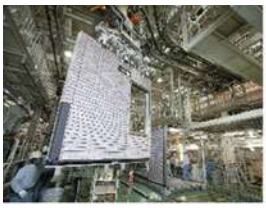
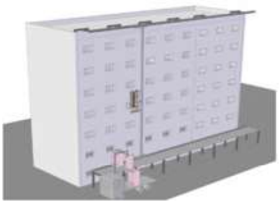
		
Large-scale deployment of sustainable buildings through advanced prefabrication (Image: Sekisui Heim)	Enhanced skills and knowledge workers though cooperative single-task robots (Image: Exoskeleton “Fortis”/ Photo Courtesy of Lockheed Martin Corporation. Copyright 2016)	Improved resource efficiency through automated high-rise construction (Image: Obayashi/ T. Bock)
		
Improvement of renovation rate through automated façade renovation (Image: K. Iturralde/TUM)	Automated building disassembly for urban-mining (Image: HAT DOWN system by Takenaka Corporation/ T. Bock)	Robots for asbestos removal and building renovation (Image: Takenaka Corporation)

Fig. 8.1 Examples for construction automation utilized in the context of sustainable building (Bock and Linner 2015, 2016a, b; this image of Takenaka’s asbestos removal robot is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization [NEDO])

8.2.2 *The Development of SB*

SB is regarded as a holistic and transparent approach for addressing sustainability related to buildings and construction in the consideration of triple bottom line aspects, i.e. economic, environmental and social (ISO 2008). It has been defined in different ways, along with the evolution of the concept of sustainable development (Berardi 2013). Kibert (1994) proposed an early definition of sustainable construction which should produce a healthy built environment in view of resource-efficient and ecological principles in the First International Conference on Sustainable Construction. The term “sustainable building” appeared in journal papers since 1996, followed by a fast-growing trend (Pan and Ning 2014).

Principles and sustainability assessment methods have been developed to interpret the concept of SB. Despite of the diffusions, most of the proposed principles share the common framework of sustainability with economic, environmental and social aspects (Pan and Ning 2014; ISO 2008). However, in terms of assessing the sustainability of a building, most developed methods concern only environmental criteria, covering the efficiency in the resource use, and impacts on human health and environment (Berardi 2013). Accordingly, energy performance and GHG emissions are the most commonly used parameters to assess sustainable buildings (Berardi 2013). In addition, the operational phase, which is responsible for the majority of energy consumption and GHG emission, is often the main or only focus (Unep 2009; ISO 2008; Berardi 2013). Latest studies indicated that greater importance should be attached to the social and economic contexts (Berardi 2013; Selberherr and Girmscheid 2013).

8.3 A Systems Framework of Automation and Robotics for SB

According to the developments and tendencies in automated construction and SB outlined in the previous section, a strategy for the development of the framework and its key dimensions was developed (Fig. 8.2). In the technological dimension, three main automated and robotic technologies (Bock and Linner 2015a, 2016a, b) are considered for achieving SB in the construction phase as follows: (1) Automation in prefabrication: automation and robotics for customized and prefabricated components and modules; (2) Single-task construction robots: elementary technologies and single-task construction robots; (3) automated/robotic on-site factories (AROFs). In the sustainable dimension, impacts pertaining to the triple bottom line can be outlined as follows (ISO 2008), notwithstanding uncertainties exist in the consideration of economic and social aspects in different countries (Unep 2009): (1) Environmental: impacts to resources (materials) and environment; (2) Economic: economic value and productivity; (3) Social: health, satisfaction, cultural value, and equity. This strategy will be used in the subsequent works, to categorize our literature and research findings and identify the relevant indicators and mechanisms through integration across two dimensions. Sustainable dimension will be mapped to technological dimension, to explore how each type of automated and robotic technology can contribute to SB during the construction stage.

8.3.1 Automation in Prefabrication of SB

Automation in prefabrication or robotic industrialization, refers to the automation and robotics applied in the prefabrication of buildings, or components thereof, in the off-site factories (Neelamkavil 2009). Prefabrication as an innovative way of construction, enabling strategies from manufacturing sector, like mass production, to be applied, and allow mechanization, automation, and robotization to easily trespass into the construction industry (Neelamkavil 2009). It is reported that automation in prefabrication has the ability to control the continuous life-cycle flow of energy, resources, information and workforce, achieving sustainability in every aspect of the triple bottom line (Bock and Linner 2015a). Prefabrication has commonly been recognized as an environmentally friendly practice in construction industry, as it contributes to the reduction of environmental impact during construction though the reduced material use, energy consumptions and waste production (Steinhardt et al. 2013; Hampson and Brandon 2004; Linner and Bock 2012). Automated approaches can catalyze the efficient use of natural resources in many ways. For example, optimization of resource utilization can be achieved by scheduling automation in prefabricated flow-shops under different circumstances. Sensor-based control can not only track the material and components for better interactions, but also detect geometry of waste for reuse (Neelamkavil 2009). With industrial robots and automated control, the collection and sorting of waste can be well harmonized and integrated into the prefabrication process (Bock and Linner 2015a). Energy consumption and carbon emissions linking to the working process can therefore be cut down. The negative impacts of prefabrication approach

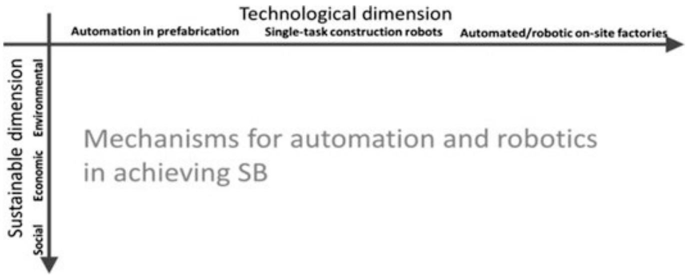


Fig. 8.2 A systems framework of mechanisms of utilizing automated and robotic technologies for SB

on environment lie in the additional energy use and GHG emissions associated with the transportation of prefabricated components. In this respect, automation techniques, like systematization of transportation, can reduce these effects to the minimum (Neelamkavil 2009).

8.3.2 Single-Task Construction Robots for SB

Single-task construction robots are those designed for a single, specific construction task, to be conducted in repetitive manner, which largely emerged in 1980s. Examples like mobile handling robots, concrete finishing robot, ceiling board installation robots, and fire proofing robots (Castro-Lacouture 2009; Cousineau and Miura 1998). These robots can help to do lots of repetitive, dangerous or sophisticated works, relieving pressures on labor shortage and skill mismatch, but also challengeable since they can hardly be cooperative with human beings and be integrated with upstream and downstream processes (Bock and Linner 2016a). Economic factors are sometimes recognized as barriers for single-task construction robots to be implemented on-site (Neelamkavil 2009). Bock and Linner (2016a) reported that experience has demonstrated the poor economic performance of the majority of developed construction robots. Thus, the core of single-task robots in the first place is to replace human workers in hazardous jobs and improving occupational health and safety (Bock and Linner 2016a). Recently, new forms of single-task robots emerged building on aerial approaches, additive manufacturing technologies, exoskeletons, swarm robotic approaches, self-assembling building structures, and even humanoid robot technology, which bring the new tendency goes towards collaborative robots that work together with and assist the human being instead of substituting it. In this respect, human workers are still required to operate complicated machines such as robots. To achieve good social sustainability of applying single-task robots, continuous education and training of workers to upgrade the professional skills is of great importance (Bock and Linner 2016a).

8.3.3 Automated/Robotic on-Site Factories for SB

Automated/robotic on-site factories (AROFs) are complete and integrated on site automation systems used mainly in high-rise construction (Bock and Linner 2016b; ISO 2008). Reduced waste is the major benefit of AROFs, according to the tests of existing prototypes. The first applied AROF in the world, named SMART, achieved a 70% reduction in waste with the integration of off-site prefabrication and on-site automation (Cousineau and Miura 1998). Additionally, the whole process can be integrated and the energy efficiency of machines can be optimized (Bock and Linner 2015b). The environmental value of AROFs can also be linked to component re-use and urban-mining focused deconstruction (Lee et al. 2015). The tendency towards automated construction and deconstruction would allow materials and components be reused so that high-rise buildings and city areas can act as an urban mine. With AROFs, the building under deconstruction can be dis-assembled instead of demolished, and the components do not have to be melted down for energy consumed recycling but can be refreshed and re-used directly in the construction of another building (Lee et al. 2015). AROFs can offer better working environment, improve worker safety and health, and minimize disturbances to neighbors, ensuring the wellbeing of both workers and the public (Cousineau and Miura 1998). Meanwhile, the full scale automation of the building construction can have more significant impacts, compared to the single-task robots, on the employment. The requirement of manual workers on site can be dramatically reduced, whilst more skilled knowledge workers should be engaged in R&D relevant works. Jobs and roles should be redefined to a social sustainable development.

8.3.4 Identification of Indicators and Mechanisms

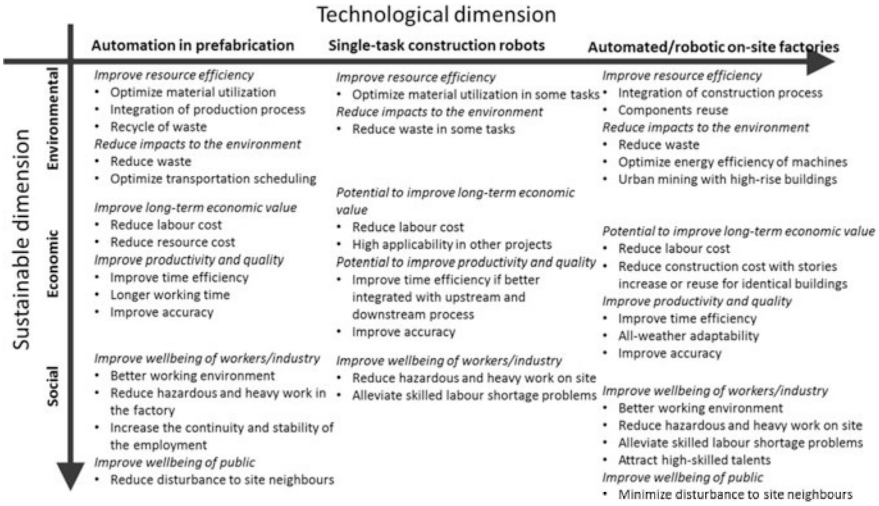
It is possible to identify the main streams from the literature and outline the potential mechanisms as a guide to future practice of automation and robotics in SB. The implications of automation and robotics on environmental, economic and social sustainability in the construction stage are manifold. The adoption of automation and robotics, including automation in prefabrication, single-task construction robots, and AROFs, has the capability to reduce environmental impacts and improve resource efficiency, long-term economic value, productivity, quality, wellbeing of workers, industry and the public. Basic indicators and mechanisms identified by the research presented in this paper are outlined in the following.

Indicators:

See Fig. 8.3.

Mechanisms:

1. ***The relationship between automation and SB is mutually-reinforcing***: Automation in construction is not new, but the real world application is still in its infancy (Bock and Linner 2015b). The lack of economic interest is the main hurdle (Mahbub 2008; Cousineau and Miura 1998). Recently, the industry is embarking on a new paradigm with the upsurge of the concept of SB, and the focus has begun to shift from short-term financial interest to long-term sustainable value (Unep 2009), offering a new cut-in point to automation. Additionally, previous literature has demonstrated that automation and robotics can make a significant contribution to SB in the construction stage from a multifaceted concern (Castro-Lacouture 2009; Cousineau and Miura 1998; Bock and Linner 2015b). Therefore, automation and SB, although often seen as two academic branches with little in-depth blending, can certainly reinforce each other. To expedite their co-production, a new paradigm should be established,



Technological dimension

Sustainable dimension	Automation in prefabrication	Single-task construction robots	Automated/robotic on-site factories
Environmental	*Improve resource efficiency* • Optimize material utilization • Integration of production process • Recycle of waste *Reduce impacts to the environment* • Reduce waste • Optimize transportation scheduling	*Improve resource efficiency* • Optimize material utilization in some tasks *Reduce impacts to the environment* • Reduce waste in some tasks	*Improve resource efficiency* • Integration of construction process • Components reuse *Reduce impacts to the environment* • Reduce waste • Optimize energy efficiency of machines • Urban mining with high-rise buildings
Economic	*Improve long-term economic value* • Reduce labour cost • Reduce resource cost *Improve productivity and quality* • Improve time efficiency • Longer working time • Improve accuracy	*Potential to improve long-term economic value* • Reduce labour cost • High applicability in other projects *Potential to improve productivity and quality* • Improve time efficiency if better integrated with upstream and downstream process • Improve accuracy	*Potential to improve long-term economic value* • Reduce labour cost • Reduce construction cost with stories increase or reuse for identical buildings *Improve productivity and quality* • Improve time efficiency • All-weather adaptability • Improve accuracy
Social	*Improve wellbeing of workers/industry* • Better working environment • Reduce hazardous and heavy work in the factory • Increase the continuity and stability of the employment *Improve wellbeing of public* • Reduce disturbance to site neighbours	*Improve wellbeing of workers/industry* • Reduce hazardous and heavy work on site • Alleviate skilled labour shortage problems	*Improve wellbeing of workers/industry* • Better working environment • Reduce hazardous and heavy work on site • Alleviate skilled labour shortage problems • Attract high-skilled talents *Improve wellbeing of public* • Minimize disturbance to site neighbours

Fig. 8.3 Framework matrix: summarization of identified mechanisms/indicators relevant for characterizing the use of construction automation for SB

considering automation and robotics for achieving SB, which, in turn, could stimulate the uptake of automation in construction.

2. ***Flexibility of automation and robotics is the key to unleash the potential of achieving SB***: The literature has provided evidence of achieving SB in construction stage with automation and robotics (Castro-Lacouture 2009; Cousineau and Miura 1998; Bock and Linner 2015b). But the potential has been strangled in certain scenarios, and economic sustainability cannot be well embodied. For example, AROFs are hardly suit for other buildings in different architecture, single-task robots have fixed functions and the ability to adjust the complicated and dynamic construction workplace is limited (Warszawski and Navon 1998). Meanwhile, automation in prefabrication often enables the use of multipurpose unit to achieve flexible production in a sustainable manner, dramatically improving the efficiency and lowering down the production cost. Therefore, flexibility is the key to unleash the potential of automation and robotics for achieving SB. Technological breakthroughs are needed for greater flexibility and adaptability.
3. ***Attention is needed to the impacts of automation on sustainable labor market***: Safety is apt to be the primary concern for introducing automation. But beyond safety, SB in construction stage also needs to maintain a stable and harmonious labor market. Automation and robotics can alleviate labor shortage (Linner and Bock 2012), but may also lead to a massive labor surplus and high unemployment rate (Sandberg et al. 2008), which inevitably pose a threat to social sustainability. Thus, to minimize these negative impacts, it is essential for continuous training and early identification of irreplaceable skills to enable a gradual shift of workforce from onerous physical labors to light physical or

mental works. Jobs and roles have to be redefined to offer more opportunities in R&D activities.

8.4 Future Work: Detailing and Validation of the Framework

Sustainability considerations require guidelines for making construction automation choices in tune with global sustainability development trends. The work presented in this paper will in a next step be translated into quantifiable indicators and variables. Ultimately the framework will be validated through application in case studies and real world projects as a tool that can be used to guide development and assessment of technologies, strategies and business models for utilizing robotic construction for SB. The framework will also be used to complement and extend existing building standards such as BREEAM (2016) or LEED (2016).

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