

# CRITICAL SUCCESS FACTORS TO LIMIT CONSTRUCTABILITY ISSUES ON A NET-ZERO ENERGY HOME

Can B. Aktas,<sup>1</sup> Katelyn C. Ryan,<sup>2</sup> Michael E. Sweriduk,<sup>3</sup> and Melissa M. Bilec, PhD<sup>4\*</sup>

## ABSTRACT

*The objective of this study was to identify the critical success factors (CSFs) to limit constructability issues on a net-zero energy home, in an effort to enhance sustainability and increase competitiveness in the residential construction industry. An extensive literature review was conducted to determine common constructability issues and to compile success factors identified previously by other researchers for traditional home construction. The CSFs were then narrowed to a group of thirteen CSFs unique to net-zero energy home construction. This framework of net-zero energy CSFs was supported by a case study of a net-zero energy home under construction in Pittsburgh, Pennsylvania. Through the use of observational research on this home, the importance of each CSF was defined, and their contributions to a net-zero energy home was discussed based on evidence from the case study. CSFs and constructability issues identified in this research will assist the residential construction sector's continued effort to reduce energy use, enhance conservation, and promote sustainability through the support of net-zero energy residential construction. CSFs will promote sustainability by increasing the ease and efficiency of the design and construction of net zero energy homes which will in return make the homes more cost efficient to build and an affordable option for home buyers.*

## KEYWORDS

critical success factors; residential; constructability; green design

## INTRODUCTION

Residential construction is a primary area of concern for improving sustainability, as residences consume 22% of energy in the United States (EIA 2008). In recognition of this considerable energy consuming sector, the U.S. Department of Energy (DOE) has recently contributed significant investment in research and development for sustainable residential building

<sup>1</sup>Assistant Professor, University of New Haven. Email: canbaranaktas@gmail.com

<sup>2</sup>MCSI Researcher, Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, PA 15261. Email: katelyn.ryan1@gmail.com

<sup>3</sup>MCSI Researcher, Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, PA 15261. Email: mes176@pitt.edu

<sup>4\*</sup>Corresponding Author, Assistant Professor, Department of Civil and Environmental Engineering, Mascaro Center for Sustainable Innovation, University of Pittsburgh, Pittsburgh, PA 15261. Email: mbilec@pitt.edu

technology. Although many advances have been made, sustainable construction presents challenges related to cost, technology, and large scale production and installation. In order for the residential construction sector to be successful in implementing sustainable building practices, including the goal of a net-zero energy (NZE) home, challenges related to cost, technology, and scale involved in the building process need to be overcome. In an effort to enhance sustainability in the residential construction industry, critical success factors (CSFs) were developed to limit constructability issues on net-zero energy homes. Increasing the constructability of a NZE home is a viable way to reduce cost through the elimination of time and material waste.

While many definitions exist for net-zero energy, in general, a NZE home produces as much energy as it consumes on an annual basis. The current study emphasizes quality in home construction and design by promoting energy conservation, safety, and comfort, in addition to energy generation and reduction. It must be noted that there is not a consensus on the very definition of a NZE building. Nevertheless, Marszal et al. (2011) present a concise review of definitions and methodologies for NZE buildings used by different institutions or standards.

Guidelines are needed to improve constructability of projects by describing methods to measure and evaluate success (Gambatese 2007). The current research contributes to assessment of project success on NZE homes. The developed CSFs act as a framework for improving the constructability of an NZE home. Information necessary to develop the NZE home CSFs were obtained through a partnership with Integrated Building and Construction Solutions (IBACOS) and S&A Homes. This framework is unique in that it specifically addresses the needs of designers and builders of NZE homes, which are significantly different from the needs of traditional home designers and builders. The framework is intended to act as a guide to new or on-going participants in the high-energy performance building market to increase constructability while maintaining a focus on quality. Building on the guideline developed by Gambatese et al. (2007), the NZE CSFs will aid in the advancement of sustainable residential construction by providing designers and builders with the advantages of the economies of scale that are associated with production building.

Background on the NZE home is described, including identifying building components related to increasing energy efficiency. *A literature review of the success factors and constructability are discussed in tandem with the developed NZE CSFs to reduce redundancy.* The research methodology is outlined through the use of a process map and explanation of the observational research techniques used to obtain the data in this study. Analysis and discussion of each CSF is then presented, where examples from the NZE case study are used to justify each of the NZE CSFs. Finally, the conclusions discuss the impact of the NZE CSFs and potential areas for future research.

## NET-ZERO ENERGY HOME

The net-zero energy home in this case study was constructed by the Best Practices Research Alliance (Alliance), a partnership of companies dedicated to improving practices in the homebuilding industry. The ultimate goal of the Alliance is that, through research and analysis, the construction of NZE homes will become a feasible reality in production building in the near future.

The project was overseen by IBACOS, which is also the founder of the Best Practices Research Alliance. Their guiding philosophy is that a home should be energy efficient, durable, safe, healthy, comfortable, and environmentally responsible. IBACOS is also a leading partner

in the DOE's Building America program. The Building America program was founded by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy in order to focus research efforts on the development of high energy efficiency technologies and practices for use on both new housing and the retrofitting of existing homes.

The goal of this particular NZE home project was to evaluate the feasibility of designing and constructing net-zero energy homes in a cold climate region using widely available materials and common construction practices. The focus on such materials and practices is done with the intention of improving constructability in an effort to better facilitate the understanding and incorporation of net-zero energy practices into the construction industry. The home, which is located near Pittsburgh, PA, has been designed to achieve NZE through an energy strategy of 70% conservation and 30% renewable energy generation. Pittsburgh is located in a cold climate zone with 33% higher heating degree days and 50% lower cooling degree days than the U.S. average based on recent 12 months data (NCDC 2012).

The home will use electricity as its only form of energy. Energy is generated on-site through the use of photovoltaic panels. Upon completion of construction, the home will remain unoccupied and monitored for a period of three years in order to verify the energy performance of the home, and also to provide data to the Alliance for use in future NZE projects. The energy conservation of the home was measured against Building America's benchmark standard home. After the monitoring phase, the home will be put on the market for home buyers.

The home has 2-storeys with a built-in basement and garage that has been designed to be air and water tight. Sprayed fiberglass insulation, multilayered doors, triple paned windows, and thick exterior walls with insulation are among features to provide the necessary insulation. These features were designed to maintain occupants comfort while using little to no energy. Figure 1 represents drawings of the completed home.

Several alterations were made to the mechanical systems in the NZE home when compared with a traditional home. The HVAC system was optimized to provide the highest levels of energy efficiency, comfort, and air quality. The primary source of heating is an electric

**FIGURE 1.** Rendering of Completed Net-Zero Energy Home. [Adapted from S&A Homes (2010)]



ground source heat pump (GSHP) system with a 2-stage heating and cooling water-to-air heat pump that has an integral hot water generator. The GSHP system consists of two vertical closed loops and two horizontal closed loops. Ventilation proved to be an important consideration in initial planning for the NZE home. The high energy requirements of the home could only be achieved through stringent air tightness, which in turn necessitated a mechanical ventilation system. The system utilizes an Energy Recovery Ventilator (ERV) that allows exiting conditioned air to exchange energy with incoming unconditioned air. The standard ductwork was used within the house although all designs were engineered to meet the needs of the NZE home. Both the ventilation and air conditioning systems use low volume and low mass ductwork with fewer distribution locations in order to reduce material costs. Additionally, all ductwork is kept within conditioned space to decrease energy loss to the outside environment.

Other systems within the NZE home were designed to ensure overall quality, including the plumbing, windows, lighting, and appliances. Although the plumbing consists of commonly-used materials and parts, the design of the system is more complex than systems found in traditionally-built homes. The primary source of domestic hot water (DHW) is an energy efficient electric water heater. The heater was supported by a drain water heat recovery system and a desuperheater. The drain water heat recovery system provides pre-tempered water to the DHW generation and distribution system. The desuperheater performs a similar function, collecting waste heat from the GSHP. All plumbing fixtures and faucets are low-flow, reducing water usage.

A listing of key specifications of the home is found in Table 1 with a particular focus on the thermal envelope and mechanical systems.

## LITERATURE REVIEW

Existing literature was reviewed to gain a full understanding of constructability and typical constructability issues encountered in home construction. Observational techniques were also reviewed to define the process of quantitative data collection that was used to select the CSFs. Additional information on how the CSFs were selected is discussed in subsequent sections.

### **Constructability**

Many definitions exist for constructability. However, the most commonly cited definition was set forth by the Construction Industry Institute (CII) and was taken as a basis during the study:

*“Constructability is the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives”*  
(CII 1986).

Since CII first raised the issue of constructability, it has been an important area of construction research in the United States (Wong, Lam et al. 2007), as well as globally (Saghatforoush 2009). One of the earlier studies by Uhlik and Lores (1998) showed that 90% of general contractors did not have a scheduled constructability program implemented in their activities at the time. With increasing construction costs and intensified local as well as global competition, combined with stringent requirements of manufacturing a NZE home, only a few stakeholders can accept the time and resource waste common in conventional home construction due to repeated mistakes or common problems occurring in the workplace. Constructability is an abstract concept that enables successful realization of building projects given that critical

**TABLE 1.** NZE HOME SPECIFICATIONS

	TECHNICAL SPECIFICATION
<b>ABOVE GRADE WALL</b>	<ul style="list-style-type: none"> <li>• R-30 blown in fiberglass within cavities</li> <li>• Fully sheathed with 1.27 cm OSB</li> <li>• R-10 (5 cm) unfaced extruded polystyrene (XPS) exterior insulating sheathing with intercepted recessed furring strips</li> <li>• Housewrap over rigid foam insulation used as primary drainage plane and air barrier</li> <li>• Low VOC interior paint</li> </ul>
<b>BAND JOISTS</b>	<ul style="list-style-type: none"> <li>• R-10 (5 cm) unfaced XPS exterior insulating sheathing</li> <li>• 15 cm spray polyurethane foam within cavities</li> </ul>
<b>ROOF/ATTIC</b>	<ul style="list-style-type: none"> <li>• 43.2 cm R-60 blown fiberglass</li> <li>• Roof trusses have high heel heights (33 cm) that allow for slightly reduced depth of insulation (30.5 cm) at eaves including an air space (2.5 cm) between the underside of the roof deck and the eave baffle for attic ventilation</li> <li>• Asphalt shingles with high solar reflectance</li> </ul>
<b>BELOW GRADE WALL</b>	<ul style="list-style-type: none"> <li>• 2.5 cm xps exterior insulation behind brick veneer above grade</li> <li>• Finished basement: <ul style="list-style-type: none"> <li>– 5 cm XPS interior insulation and 2 × 4 framed wall with blown fiberglass cavity insulation inboard of the foam</li> </ul> </li> <li>• Unfinished Basement: <ul style="list-style-type: none"> <li>– 7.6 cm Polyisocyanurate rigid foam insulation directly applied to foundation wall with foil facing to act as thermal barrier</li> </ul> </li> </ul>
<b>SLAB/FOOTINGS</b>	<ul style="list-style-type: none"> <li>• R-10 (5 cm) XPS insulation directly below the slab</li> <li>• Footings formed using remain-in-place type of drainage and radon mitigation systems</li> </ul>
<b>FLOOR SYSTEM</b>	<ul style="list-style-type: none"> <li>• 35.6 cm deep Pre-engineered wooden open web floor trusses</li> </ul>
<b>WINDOWS</b>	<ul style="list-style-type: none"> <li>• Triple glazed, gas filled, vinyl framed, single hung, standard grid pattern</li> </ul>
<b>BUILDING AIR TIGHTNESS</b>	<ul style="list-style-type: none"> <li>• Exterior wall housewrap taped at all seams and integrated with the ceiling and foundation air barriers</li> </ul>
<b>HEATING AND COOLING</b>	<ul style="list-style-type: none"> <li>• 2-stage heating &amp; cooling water-to-air heat pump with integral hot water generator and 'true' dehumidification options; nominal 2-ton cooling with minimum part-load cooling EER of 26.0 and part-load heating COP of 4.6</li> <li>• Two separate ground-loop systems; one vertical well configuration and a second horizontal ground-loop buried in a single layer within the existing excavation depth (placed at the base of the footing depth), 20 cm of compacted crushed limestone cover the loops installed in two lifts of 10 cm.</li> </ul>
<b>VENTILATION</b>	<ul style="list-style-type: none"> <li>• Energy recovery ventilation of 83% sensible efficiency and 0.69 latent recovery at 65 cfm</li> <li>• Dedicated multi-point distribution system (using high velocity/low volume ductwork)</li> </ul>
<b>AIR DISTRIBUTION</b>	<ul style="list-style-type: none"> <li>• High sidewall outlets</li> <li>• Low-mass ductwork sealed and within conditioned space;</li> <li>• Reduced distribution locations</li> <li>• One supply location on each floor</li> </ul>
<b>DHW</b>	<ul style="list-style-type: none"> <li>• GSHP desuperheater serving a 400-l preheat storage tank with an efficiency factor of 0.91, which serves a 200-l conventional electric water heater with an efficiency factor of 0.95;</li> <li>• Cross-lined polyethylene piping and low-flow fixtures and appliances;</li> <li>• Plate and frame heat recovery system</li> </ul>
<b>LIGHTING</b>	<ul style="list-style-type: none"> <li>• 100% of fixtures utilize high-efficiency lighting technologies (e.g., fluorescent, led, etc.)</li> </ul>
<b>APPLIANCES</b>	<ul style="list-style-type: none"> <li>• Top-tier Energy Star appliances</li> </ul>

factors are correctly identified (Arditi 2002; Lam 2009; Saghatforoush 2009; Lam 2012). The topic still deserves attention as Hlad (2009) found that constructability was ranked to be the second most important factor for sustainable practices by builders, after cost.

The identification of constructability issues during the construction of a NZE home is a primary component of the current study due to the high-level of technology that is utilized in the production of the home to achieve its efficiency goals. Traditional home building already has a known set of constructability issues. With the addition of the complexities associated with NZE building, it is essential to identify and limit constructability issues to ensure the successful completion of the home.

### ***Critical Success Factors and Project Success***

Within any process, the main factors that contribute to project success are named as CSFs. Although project managers may list several such factors, the rate of failed projects remains high. One reason contributing to this result is that CSFs are rarely specific enough for project managers to act on (Zwikaël 2006; Ng 2010). CSFs defined for a conventional home should not be expected to be the same as a NZE building. While there are no clear definitions for project success, a definition of success that was adopted by the project managers of the NZE home was used as a reference point. Accordingly, a successful project is described as a project that is completed on time, within budget, and that meets the performance expectations of the occupants in the residential home.

The three main categories of CSFs are: project management; human-related; and design. Each category includes multiple success factors that were identified as critical components to a NZE home following reported data and data gathered by using observational research guidelines. From numerous different CSFs proposed by other researchers, 13 factors were identified to contribute to NZE homes. These CSFs are critical to the successful completion of an NZE home, see Table 2.

Four success factors are within the project management category, and these factors are critical to limiting the constructability issues that are present in many design-build projects and especially present in net-zero energy home construction. The four factors are: *communication; planning effort; quality assurance and quality control; and overall management actions*. Given the advancement in the technology, lack of knowledge, and inherent complexity of an NZE home, communication between all project participants is imperative. Clear lines of communication are essential to reduce non-productive effort, eliminate mistakes, and reach objectives within the allocated time and resources (Clarke 1999). Planning effort is especially critical due to the multitude of intricate details involved in the design of the home. In a study by Jergeas and Van der Put (2001), project planning was identified to have a potential to benefit a project immensely and limit constructability issues while a failure to properly plan can lead to serious problems. Quality assurance and quality control (QA/QC) are typical to most projects and directly relate to the definition of project success by insuring that the expectations of the owner will be met. An owner's main concern is that the project meets the standards of the intended use and that it has no long-term deficiencies or maintenance issues (Sanvido, Grobler et al. 1992). Overall management actions refer to the skills and effectiveness of the manager of a specific project. A project manager has to be well-versed in the technology and have strong organizational, technical, and coordination skills in order to tie all the complexities of the project together (Chua, Kog et al. 1999).

**TABLE 2.** Critical Success Factors

Category	Net-Zero Energy CSFs	Data Sources
Project Management	Communication	Chan et al. (2004), Lam et al. (2008), Chua et al. (1999), Clarke, A. (1999)
	Planning Effort	Chan et al. (2004), Lam et al. (2008), Jergeas and Van der Put (2001), Chua et al. (1999)
	QA/QC	Chan et al. (2004), Chua et al. (1999), Sanvido et al. (1992), Lam et al. (2008)
	Overall Management Actions	Chan et al. (2004), Lam et al. (2008), Chua et al. (1999)
Human-Related	Project Participant's Experience	Chan et al. (2004), Lam et al. (2008), Belassi and Tukel (1996), Sanvido et al. (1992)
	Owner's Ability to Brief	Chan et al. (2004), Yu et al. (2006)
	Owner's Ability to Make Decisions	Chan et al. (2004), Lam et al. (2008), Chua et al. (1999)
	Project Leader's Early and Continued Involvement in the Project	Chan et al. (2004), Chua et al. (1999)
	Overall Team Cohesiveness	Lam et al. (2008), Chua et al. (1999), Larson, E. (1995), Sanvido et al. (1992)
	Learning from Previous Projects	Gambatese (2007), O'Connor, Larimore et al. (1986)
Design	Standardization	Poh and Chen (1998), Low (2001), Jergeas and Van der Put (2001), Clarke, A. (1999)
	Simplicity	Poh and Chen (1998), Low (2001), Jergeas and Van der Put (2001)
	Single-Integrated Elements	Poh and Chen (1998), Low (2001), Jergeas and Van der Put (2001)

The human related category includes six factors that are critical to the success of an NZE home. This category is important because it involves all the key people that are directly related to the success of the project (Chan, Scott et al. 2004). The factors that are included in this category are *project participant's experience*, *owner's ability to brief*, *owner's ability to make decisions*, *project team leader's early and continued involvement in the project*, *overall team cohesiveness*, and *learning from previous projects*. The experience level of the project participants is a crucial element of success since experience gives participants the necessary competence, skills, and tools to implement the technical details involved with this home. Competence and skills of team members are key characteristics during all implementation stages to reach a successful completion of a project (Belassi and Tukel 1996). A high-level of home building competency is required to transfer the complex details from the design stages to the field. The owner's ability to brief is critical to ensure that directions and details are communicated to all participants to reduce issues and inefficient use of time and materials. Briefing involves frequent interaction between owner and project team to convey the complex details and large magnitude of information that is involved in a project (Yu, Shen et al. 2006). Owner's

ability to make decisions is extremely imperative in the effort to limit issues and increase efficiency. Establishing a mechanism to ensure that problems can be dealt with promptly and efficiently is an important objective (Chua, Kog et al. 1999). The owner must be present to make decisions and not leave tradesmen who are not as familiar with the technology to guess on how activities should be executed. Project team leader's early and continued involvement is critical to project success being that the project leader's competency and authority should influence a successful outcome (Chua, Kog et al. 1999). Overall team cohesiveness is another factor that has been developed out of necessity limiting issues during construction of a net-zero energy home. Larson (1995) proposed that project success is influenced by owner-contractor relationships that employ a partnering approach. Project partnering as a method of developing a cohesive project team suggest that team cohesiveness should be broadened to include all project participants. Learning from previous projects is critical to the level of production and efficiency of construction. If the project participants take time to evaluate the success and failures of past projects they are able to avoid repetition of mistakes.

The design factors are based on the Singapore Buildable Design Appraisal System (BDAS), a system developed to quantify constructability. The BDAS gives a score to each construction project; the higher the BDAS score, the higher the constructability of the project. According to multiple sources, the BDAS score has a high correlation with productivity (Poh and Jundong 1998; Low 2001). The theoretical foundation for the BDAS is the 3S system—*Standardization, Simplicity, and Single-Integrated Elements*. These three elements form the design CSFs. Standardization is the repetition of components throughout a project, and the use of standardization decreases construction time and makes fabrication easier (Low 2001). Simplicity refers to choosing particular designs or methods in order to provide the greatest ease of installation and construction. Single-integrated elements are pre-fabricated construction elements that consist of smaller individual components, which are easier to install on-site and thus save valuable construction time (Low 2001).

There are many drawbacks to the BDAS system, one of the most notable being an exclusion of mechanical and electrical systems from consideration. However, a project that utilizes the 3S approach is likely to have higher levels of productivity in constructability; this is particularly true in residential construction (Poh and Jundong 1998). Despite this fact, as Jergeas and Van der Put note (2001), there is a notable lack of these principles in current construction practices.

## METHODS

The approach used for this research was the following: (1) identify major success factors that are used in the building industry were identified; (2) collect and analyze data to determine which success factors were critical to limiting constructability issues of NZE homes. Process mapping and observational research techniques were used during the selection process.

Literature review produced a list of success factors that have been widely used in the building industry, together with constructability issues that occur during traditional residential construction, and observational research techniques.

Review of observational research techniques resulted in four possible quantitative data collection approaches: phenomenology, ethnography, grounded theory, and case study (Johnson 2004). The case study approach to qualitative data collection is research that involves the study and analysis of one or multiple cases (Johnson 2004). Researchers examine one or more

cases to collect data to answer questions regarding the case. There are three types of case studies: intrinsic, instrumental, and collective. The intrinsic case study method provides a case study design for understanding a specific case while the instrumental case study allows the research to develop a more general understanding of the case than a specific outcome. The collective case study design involves studying multiple case studies for one research study (Johnson 2004). An instrumental case study approach was selected due to the nature of this research.

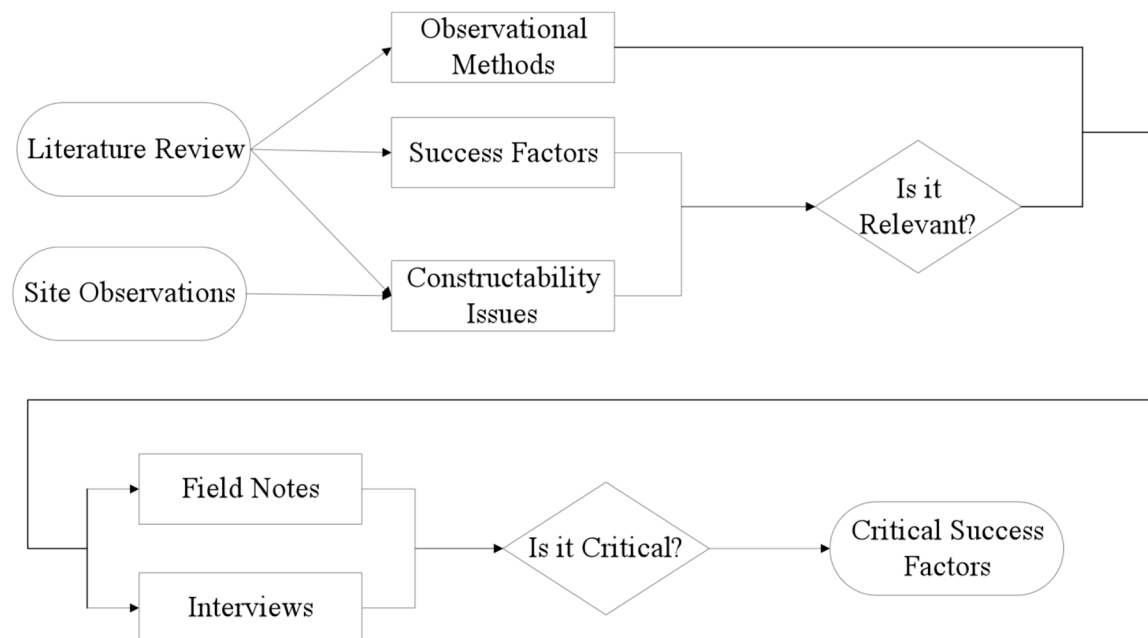
Site observations took place to understand what constructability issues were occurring during the construction of a net-zero energy home and to eliminate success factors that were not relevant to the study. Activities that occurred as part of site observations included watching trades implement specialty technologies, recording and documenting field work, and questioning project managers, supervisors, and tradesmen to learn about their experiences during construction. Observational research techniques were applied to identify the relevance and importance of CSFs to the success of the project.

The process map given in Figure 2 illustrates the research approach. The order and relationship of the activities that took place during selection of CSFs are shown.

Due to the nature of the research, observational techniques for collecting qualitative data were employed. The case study method was chosen for the qualitative approach for the project due to the science-based origin of the study as compared to more experience-based methods. More specifically, an instrumental case study approach was taken to collect the qualitative data needed to determine the CSFs for a net-zero energy home. The instrumental case study approach was chosen since the desired outcome of the study was to derive a general conclusion of CSFs that can be applied to more projects involving net-zero energy homes (Johnson 2004).

Data for this study was gathered through observation of work events, structured conversations with individuals from a variety of roles including project managers from the designer and

**FIGURE 2.** Process Map of Research Approach



builder, subcontractors, and tradesmen, and through analysis of documents. Triangulation was used to check the veracity of study findings. CSFs that were consistently identifiable through data sources were reported in the study. Triangulation is a useful strategy when trying to ensure that all issues of high relevance to a study have been identified. In general terms, if investigators remain properly open-ended during data collection, and no longer record anything substantially new, it is likely that they have identified the full range of issues (Friedman 2006).

## **ANALYSIS AND DISCUSSION**

The NZE critical success factors are grouped into three categories: Project Management Actions, Human-Related Factors, and Design Factors. Each factor is defined, its importance to a NZE home is explained, and evidence from the case study on the net-zero energy home is presented in order to demonstrate the importance of each factor to the success of an NZE home project.

### ***Project Management Actions***

#### ***Communication***

Communication refers to exchange of information, either formal or informal, among project participants. Lack of communication between designers and builders is a primary barrier to constructability. While effective communication is important on any construction project, it is of paramount importance on an NZE home. Since a NZE home requires advanced technology and unconventional practices, the project manager must develop clear and effective lines of communication with all parties involved in the project. On the NZE home project, much effort was put into communication.

IBACOS and S&A Homes had meetings at least once a week leading up to the project, and the lead project manager from S&A was in daily contact with the team leader from IBACOS throughout the construction phase. Additionally, both S&A Homes and IBACOS were involved in much more communication with sub-contractors than they would be on an equivalent traditional project. The project manager was reported to have been in contact with sub-contractors at least three times more often as would have been on a traditional home project. Several of the sub-contractors noted that this increased communication was essential to their understanding of the project, and thus was essential to project success.

#### ***Planning Effort***

Planning effort is the work done by the project manager and design team to prepare for the construction phase of the project, and is one of the most important aspects of sustainable construction. On a NZE home, extensive planning is needed to ensure that home will be able to meet energy and quality standards with minimal increases to cost, construction time, and company resources. IBACOS was observed to spend more effort in planning the NZE home when compared to a traditional residential construction project. Their team met with each sub-contractors working on the home, reviewed the required techniques for the home and received feedback from the tradesmen. The benefits of this planning effort are inherently difficult to quantify. Measuring a ratio of planning hours to work hours is proposed to analyze whether the planning effort yields a greater chance of project success. The proposed ratio serves as a basis of comparison for multiple systems in a NZE home.

### ***Quality Assurance/Quality Control (QA/QC)***

Quality assurance and quality control (QA/QC) are critical components of all building projects to ensure that quality and safety are maintained throughout the entire building process. The importance of a well-planned and executed QA/QC program on an NZE home is to guarantee that the home is being built to the complex specifications and that the high energy efficiency strategy is being met. Even with an adequate amount of briefing and explanations prior to field implementation, mistakes occur during construction. Therefore, it is up to the manager to make sure QA/QC is being properly carried out to identify the mistakes and fix errors before they become costly or jeopardize the project's success. QA/QC had a high priority on the net zero home project.

An example to QA/QC on the NZE home came during the backfill of the basement walls. The excavator operator accidentally damaged several pipes for the ground source heat pump (GSHP). Instead of informing the project manager, he simply ignored the problem, hoping that it would go unnoticed. The IBACOS team leader was on-site to check over the work after the tradesmen were finished for the day and discovered the damaged pipes. If the mistake had not been caught, the energy goal for the home would have been jeopardized, therefore directly affecting the outcome of project success.

### ***Overall Management Actions***

The project leader must be a skilled and effective manager who is extremely knowledgeable about the technology being implemented in order for a net-zero energy project to be successful. These skills include, but are not limited to, technical ability, experience, adaptability, organization, and the ability to develop strong working relationships. One of the most effective ways of assessing managerial ability on a construction project is through input from sub-contractors. Structured conversation with multiple sub-contractors who worked on the home construction provided valuable feedback regarding management on the project.

Generally, sub-contractors commented that the project management was very effective. None of the sub-contractors had ever worked on a house with similar levels of energy efficiency, so the project manager played a crucial role in project success. There was also agreement that the management team on the project had a much greater presence than that seen on a traditional home project. The sub-contractors also gave several recommendations for improvement for future projects. One of the most common recommendations was more efficient scheduling. Taking these recommendations into consideration, IBACOS and S&A will be able to continue to improve their project management techniques to achieve greater success on future NZE home projects.

### ***Human-Related Factors***

#### ***Project Participants' Experience***

Project participants' experience refers to the level of ability of team members in construction practice. In order to excel at building a technologically advanced home such as an NZE home, all project participants must be experienced and competent in building traditional homes. Because of these issues, IBACOS and S&A Homes went through an extensive process to select the most experienced and capable sub-contractors for the project. Instead of having a bid process, the project management team first sought out a sub-contractor base that was not only competent but also interested in the project and willing to learn about the technologies and practices being utilized. The crew members that were involved in the framing of the home had

a minimum of 15 years of experience in the home building industry; this was typical of many of the other sub-contractors as well. The experience of the crew allowed them to have confidence in implementing the uncommon construction practices and gave them the foresight to identify potential problems and the ability to ask the right questions to avoid potential issues.

### ***Owner's Ability to Brief***

All project participants must be fully aware of the construction plan at all times in order to achieve project success. On a net-zero energy home, this takes on an even greater level of importance. Not only is there a great deal of complexity in the construction details of the home but there is likely a significant increase in the number of details in the design. On the home project, briefing was an area that could have been improved.

In a meeting with the project manager from IBACOS, he noted that as many as 90% of the issues that arose during construction of the home occurred because of tradesmen reading the plans incorrectly. Despite this fact, IBACOS and S&A Homes did not implement a formal daily briefing program. While the design team went to great lengths to discuss the specific details for the home in numerous pre-construction meetings and the project managers stayed involved in active communication throughout the construction phase, these efforts did not alleviate the need for daily briefings. Though it may be uncommon in traditional residential construction, it was noted that a formal briefing plan could have helped the team to avoid some of the constructability issues that occurred on the project, thus achieving greater project success.

### ***Owner's Ability to Make Decisions***

Most of the labor force is unfamiliar with the practices required for a net-zero energy home; so more of the onus of decision-making is placed upon the owner. Since IBACOS had put such a high level of planning and detail into all of the specifications and plans for the home, sub-contractors were more prone to asking questions on areas of even minor confusion.

On a traditional construction project, a contractor could simply use his/her best judgment in determining the necessary configuration for minor problems. However, since IBACOS had very specific plans for the home, their input was requested at every stage. The availability of IBACOS team members and their ability to make effective decisions quickly was crucial to the success of the project.

### ***Project Team Leader's Early and Continued Involvement in the Project***

The project team leader's early and continued involvement in the project is a success factor of particular importance to an NZE home. Unlike traditional home construction, where tradesmen are given more latitude and a project manager can oversee multiple sites at once, a net-zero energy home requires the oversight of an individual or group of individuals to ensure success.

For the NZE home project, IBACOS assigned their own team leader who was able to focus solely on the NZE home. The team leader proved to be indispensable on many occasions. Though the role of a team leader seems impractical for a production builder, it is initially necessary for the success of net-zero energy homes. With more experience over time, the workforce will become acquainted with high-energy performance techniques and practices and the team leader's role will eventually diminish.

### ***Overall Team Cohesiveness***

Overall team cohesiveness refers to the integration of all project participants, including both designers and builders, into a unified team to bring about a more successful result.

The benefits of involving construction personnel early in the design process has been widely noted (Gambatese et al. 2007, Jergeas 2001). Involving builders throughout the entire construction process will help to minimize constructability issues as well as build a positive team environment conducive to project success. On a net-zero energy home this is highly important; in order to truly have a successful endeavor, all project participants must believe in the principles of high-energy performance construction. On the NZE home project, the foundation of team cohesiveness came from the relationship between IBACOS and S&A Homes. The two companies had worked together on previous high-energy performance projects and were able to initiate planning of the NZE home from a position of mutual trust. During the design phase, the project manager from S&A met with IBACOS's team weekly, adding his construction input to their design efforts in order to minimize constructability issues and maximize success. This team cohesiveness carried over to the construction phase, creating a work environment conducive to satisfaction, productivity, and quality.

### ***Learning from Previous Projects***

The ability to learn from previous projects and to incorporate lessons learned is of vital importance to the success of any company. A home builder working on a NZE home can help avoid many constructability issues and greatly improve the success of the project by using lessons learned from previous projects. For IBACOS, this NZE home project represents the beginning of a formal lessons learned program. Realizing the potential benefits of such a program, IBACOS is focusing strongly on documenting the NZE home in order to create a database of lessons learned. They have been documenting every phase of planning and construction of the house and conducting formal post-construction structured conversation with tradesmen. The results of this effort are expected to yield benefits to IBACOS, their Alliance partners, and the residential construction industry in general.

### ***Design Factors***

#### ***Standardization***

In the 3S system, standardization refers to the repetition of components on a project. Standardization can increase constructability by taking advantage of a learning curve; if components are the same throughout a project, workers will likely become more efficient at installing those components with practice. Since NZE homes typically require practices and components which tradesmen are unfamiliar with, standardization of design is critical to overall project success.

One key example is in the floor system that consists of wooden open-web trusses. These trusses are beneficial in that they provide plenty of space for the mechanical systems to run through the floor. The initial design had different depths for the two floors; however, after consultation with the HVAC contractor, the floors were redesigned to a common dimension, which was noted to simplify layout and installation of the HVAC system.

#### ***Simplicity***

Simplicity in design is the commitment to using components and practices that will provide construction personnel with the greatest ease of installation. It is the integration of constructability concepts into the design of a project. Since the workforce is unfamiliar with some of the practices and techniques involved in NZE constructing, simplification of the design is important for limiting constructability issues. When choosing components for a NZE home,

designers must balance ease of construction with cost and technical performance. IBACOS constructed several full-scale samples for wall assemblies, sheathing, insulation, and light fixtures to test various components for performance and ease of construction.

The use of simplicity in design saves both time and money. While such extensive research may not be feasible for a production builder, simplicity can still be incorporated over time by learning from previous projects and utilizing the ground work from groups such as the Best Practices Research Alliance.

### ***Single-Integrated Elements***

Single-integrated elements are preassembled components manufactured off-site to provide greater ease of installation for workers. The goal behind single-integrated elements is to save time by allowing workers to install one larger component instead of multiple small components. As the NZE home market grows, the widespread use of single-integrated elements will be an important tool for reducing constructability issues. Since a net-zero energy home typically necessitates non-traditional features, the manufacture of these features into integrated units will help to avoid costly on-site construction issues.

The IBACOS NZE home utilized single-integrated elements to construct the above-grade walls. The unique panels, designed by the IBACOS team, greatly aided the tradesmen installing the walls by alleviating the need to construct the wall using unfamiliar techniques, saving time and money.

## **CONCLUSION**

The objective of this research was to develop a list of CSFs that would serve as a framework to limit constructability issues and aid in the project success of a net-zero energy home. A list of thirteen CSFs were developed and organized into three categories: Project Management Actions, Human Related Factors, and Design Factors. The CSFs were derived from a combination of literature review and observational research done in the field during the construction of a net-zero energy home. A case study method was used to collect the qualitative data which included field notes, structured conversation with project participants, and audiovisual materials. The data that was collected aided in the final determination of which predefined success factors that were gathered during literature review, were critical to the success of the project. This framework will act as a guide to new or on-going participants in the high-energy performance building market to increase constructability while maintaining a focus on quality. Furthermore, these CSFs will assist the residential sector's continued effort to reduce energy use and propel conservation through supporting net-zero energy residential construction.

Additional case studies that involve quantitative data and include the influence of external factors would be beneficial to further limiting constructability issues for net zero energy homes. Another suggestion is to analyze another building type such as an office structure, or multiple residential buildings to observe the effect of identified CSFs to the final success of the project. One of the criteria for project success was to meet occupant performance expectations from the residential home. However, the NZE home studied within the project is to be monitored for three years, only after which will be put on the market. The monitoring period was not completed when the article was sent for publication. As with most sustainability efforts and studies, adding a temporal scale and revisiting the performance of the NZE home would present valuable information on achieved project goals and validity of identified CSFs.

The United States' rapid consumption of energy cannot be sustained by future generations. The research and construction of high-performance homes is one way that current generations can reduce their resource consumption and overall environmental impact. This particular home was designed to limit the average family's energy consumption. If design and research outcomes from the NZE home can be implemented on a production scale, the United States has the ability to greatly reduce its energy consumption. In order to implement the high-performance home technology on a large scale, the benefits associated with the home must outweigh the costs. Currently, construction of a high-performance home that maintains the comfort of the occupants may be more expensive compared to conventional homes. The costs associated with the construction of a high-performance home are due to the level of engineering to complete the design, materials, and constructability issues during the implementation of the new technology. Current research conducted to develop CSFs for a net-zero energy home will aid in the elimination of constructability issues, and thus a portion of the costs, and will ultimately lead to high-performance homes becoming an economical option for buyers.

## ACKNOWLEDGEMENT

We thankfully acknowledge IBACOS and MCSI.

## REFERENCES

- Construction Industry Institute (1986). *Constructability: A Primer*, University of Texas, Austin, TX.
- U.S. Energy Information Administration (2008). *Annual Energy Report 2008*, U.S. Department of Energy, Washington, D.C.
- S&A Homes (2010). A Residence For: Cobble Stone Lab Home. Lab Home Floor Plans.
- Arditi, D., Elhassan, A., Toklu, YC. (2002). "Constructability analysis in the design firm." *Journal of Construction Engineering and Management* **128**(2): 117–126.
- Belassi, W. and O. I. Tukul (1996). "A new framework for determining critical success/failure factors in projects." *International Journal of Project Management* **14**(3): 141–151.
- Chan, A. P. C., D. Scott, et al. (2004). "Factors Affecting the Success of a Construction Project." *Journal of Construction Engineering and Management* **130**(1): 153–155.
- Chua, D. K. H., Y. C. Kog, et al. (1999). "Critical Success Factors for Different Project Objectives." *Journal of Construction Engineering and Management* **125**(3): 142–150.
- Clarke, A. (1999). "A practical use of key success factors to improve the effectiveness of project management." *International Journal of Project Management* **17**(3): 139–145.
- Friedman, C., Wyatt, JC. (2006). *Evaluation Methods in Biomedical Informatics*, Springer Science.
- Gambatese, J. A., Pocock, J. B., Dunston, P. S., Ed. (2007). *Constructability: Concepts and Practice*. Reston, VA, American Society of Civil Engineers.
- Hlad, K. (2009). SUSTAINABLE PRACTICES IN RESIDENTIAL PROJECTS. *Building Construction*, University of Florida. **M.S.**
- Jergeas, G. and J. Van der Put (2001). "Benefits of Constructability on Construction Projects." *Journal of Construction Engineering and Management* **127**(4): 281–290.
- Johnson, B., and Larry B. Christensen (2004). *Educational Research: Quantitative, Qualitative, and Mixed Approaches*. Boston ; Montréal, Pearson/A and B.
- Lam, P., Wong, FWH. (2009). "Improving building project performance: how buildability benchmarking can help." *Construction Management and Economics* **27**(1): 41–52.
- Lam, P., Wong, FWH., Chan, APC., Shea, WCYLau, JWS. (2012). "A scheme design buildability assessment model for building projects." *Construction Innovation: Information, Process, Management* **12**(2): 216–238.
- Larson, E. (1995). "Project Partnering: Results of study of 280 construction projects." *Journal of Construction Engineering and Management* **11**(2): 30–35.

- Low, S. P. (2001). "Quantifying the Relationships Between Buildability, Structural Quality and Productivity in Construction." *Structural Survey* **19**(2): 106–112.
- Marszal, A., Heiselberg, P., Bourrelle, J.S., Musall, E., Voss, K., Sartori, I., Napolitano, A. (2011). "Zero Energy Building – A review of definitions and calculation methodologies." *Energy and Buildings* **43**(4): 971–979.
- NCDC (2012). "National Climatic Data Center." 2012, from <http://www.ncdc.noaa.gov/oa/ncdc.html>.
- Ng, S., Tang, Z. (2010). "Labour-intensive construction sub-contractors: Their critical success factors." *International Journal of Project Management* **28**(7): 732–740.
- Poh, P. S. H. and C. Jundong (1998). "The Singapore Buildable Design Appraisal System: A Preliminary Review of the Relationship Between Buildability, Site Productivity and Cost." *Construction Management & Economics* **16**(6): 681.
- Saghatforoush, E., Hasim, S., Jaafar, M.S., Kadir, M.R.A. (2009). "Constructability Implementation Among Malaysian Building Contractors." *European Journal of Scientific Research* **29**(4): 518–532.
- Sanvido, V., F. Grobler, et al. (1992). "Critical Success Factors for Construction Projects." *Journal of Construction Engineering and Management* **118**(1): 94–111.
- Uhlik, F. T. and G. V. Lores (1998). "Assessment of Constructability Practices among General Contractors." *Journal of Architectural Engineering* **4**(3): 113–123.
- Wong, F. W. H., P. T. I. Lam, et al. (2007). "A Study of Measures to Improve Constructability." *International Journal of Quality and Reliability Management* **24**(6): 586–601.
- Yu, A. T. W., Q. Shen, et al. (2006). "Investigation of Critical Success Factors in Construction Project Briefing by Way of Content Analysis." *Journal of Construction Engineering and Management* **132**(11): 1178–1186.
- Zwikael, O., Globerson, S. (2006). "From Critical Success Factors to Critical Success Processes." *International Journal of Production Research* **44**(17): 3433–3449.