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Framework to evaluate quality performance of green building delivery: construction and operational stage

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ABSTRACT

Quality performance in construction is the degree of compliance with the specifications against which the work was executed. Green buildings extend the compliance to sustainability-related aspects to ensure that the energy and water consumption is conserved, promote a healthy indoor environmental quality and reducing the detrimental impacts of the construction activities on the environment. The operational stage reflects the construction workmanship and the effectiveness of the design solution to achieve the sustainability requirements through the overall building performance. Procedures for maintenance and overhauling extend the longevity of buildings. Green buildings exhibit underperformance caused by inadequate construction practices and a lack of understanding of the operations and maintenance practices. This research serves to tackle this problem through a comprehensive and forward-looking framework to depict construction- and operation-related quality activities through an integrated definition for the function modeling (IDEF0) process model. Semi-structured interviews and a focus group validate the framework's suitability and its implementation offered revelations from industry practitioners on the factors affecting quality procedures from assigned metrics, liaison of staff from different project lifecycle stages, green building technologies, commissioning and retro-commissioning and impact of project delivery systems adopted especially in isolating operational liaison. The contributions of this work reinforce the impact of quality on the sustainability objectives that a green building is envisioned to serve, and through capturing the pre-, during, and post-construction lifecycle, the compliance and performance quality aspects are combined in a more integrated manner.

KEYWORDS

Green buildings; quality performance; project delivery systems; sustainability; construction quality; operational quality

Introduction

The heavy burdens that a project's construction phase imposes on the environment and society include exploiting natural materials for building stock, such as cement, timber, steel and glass, which eventually becomes landfill waste (Kennedy et al. 2007; Augiseau and Barles 2017), dust migration and particulate emissions from earthmoving and truck loading along with direct impacts on human and animal respiratory systems (Muleski et al. 2005), noise nuisances from construction machinery (Lee et al. 2019), and traffic and access restrictions (Çelik et al. 2017). Most of the 21% of global CO_2 emissions are a result of the energy required in products and services for construction operations. The subsequent operational phase is responsible for 80% of the energy used, which is predominantly from primary energy sources (Huang et al. 2018). The global domestic water consumption was found to be 3.6% of the total water usage (this proportion is dwarfed by agricultural consumption at 92%, but is still appreciable considering that industrial production accounts for 4.4% of consumption) (Hoekstra and Mekonnen 2012), and varies depending on climate conditions and building type (i.e., commercial or industrial buildings).

The construction phase inherently alters the nature of the environment and any delay in its completion further exacerbates its damaging effects. Love et al. (2018) explained that reworks occurring for quality conformance are a cause of further delays, which prolong the exposure of the environment to construction effects. Once detected, poor quality in construction leads to reworks that have consequences in terms of increased cost and schedule overruns to rectify the mistakes (Mills et al. 2009). Such reactive response to a problem already manifested that could have been appraised and avoided through proactive procedures. Assaf et al. (1996) inferred that construction inspection defects, such as a lack of inspections or weakness of respecting the rule to rectify nonconformance by a constructor, most severely affect the maintenance contractors overall. Thus, any compromises in the construction will have implications on operations.

The construction of building stock remains a requirement for advancing society, and the industry is attempting to tackle its detrimental effects through green buildings, that exhibit superior performance in energy, indoor environmental quality (IEQ), water consumption, and environmentally conscious considerations for material usage. This entails reducing the energy consumption through passive heating and cooling design, metering and efficient heating, ventilation and air conditioning (HVAC) systems; reduce water consumption with the admission of fixtures, metering and considering alternative sources of water (rainwater and greywater); conscious decision-making on enhanced building materials containing recycled content and

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rapidly renewable sources with reduced environmental impact; and finally, improved IEQ through acoustic, thermal and visual comfort. Legislative frameworks are already implemented in many countries to slow down the climate change process from the built environment (Tam et al. 2019). However, on a micro-level, faults HVAC systems are commonplace, even in traditional buildings, and can have consequences of higher than required energy consumption or unstable air flow rates that impact indoor air quality (Zhang and Hong 2017). In a literature review, Alencastro et al. (2018) diagnosed how quality defects cause buildings to fall short in thermal energy performance compared to their designs, and found that poor installation of insulating elements such as in cavity closers, jambs, and sills, discontinuities of insulation layers, punctured or missing vapor/air barriers, discontinuities in structural elements services thermal bridging and malfunctions of mechanical ventilation. Abdul-Rahman et al. (2014) reported that the most common defects in affordable housing are the total failure of water systems and the leakage of pipes. Green buildings have lower lenience to such shortcomings faced in conventional buildings, because of the greater necessity to conform to the more rigorous designs to meet multiple sustainability objectives, and thus pose a greater challenge for the construction industry to overcome. Raouf and Al-Ghamdi (2018) collated several studies that report such challenges including construction complexities, contractors' inexperience and their conservative behavior that impedes innovation, and scarcity of products complying with design standards (Denzer and Hedges 2011; Ozorhon 2013; Hwang et al. 2015; Chan et al. 2017). From an operational aspect, the energy performance levels of green buildings did not match up to the certification level the building acquired (Newsham et al. 2009; Tilton 2014; Geng et al. 2019). Kubba (2016) reported that IEQ litigation issues are on the rise in an apparent chain-reaction manner across building occupants to owners, contractors, design consultants, and product manufacturers because of heavy mold infestation. Coombs et al. (2017) corroborated this in evaluating the potential health risks from the type of fungal microbiomes that infest green and non-green building materials when damaged by water. This raises questions of how effective green buildings are delivered in meeting the expectations set out and conforming in execution to their designs in an environmentally and socially conscious manner. Such effectiveness and conformance falls under the periphery of the quality domain and was argued to be a significant driver for construction companies to have a competitive edge in delivery (Haupt and Whiteman 2003).

Quality in green building construction and operation

Gransberg and Molenaar (2004) define quality in the construction phase as procedures, policies, and programs implemented to achieve confidence in meeting the desired characteristics and that the project will function as intended over its design life. Yu et al. (2017) propose conformance quality, which deals with the project's quality standards and reducing defects, and performance quality, which concerns the fitness for use, operational, and functional characteristics of a building, and to which end-user satisfaction is highly attributable. From construction and operational standpoints, both types of quality definitions are important to consider when evaluating the overall green building quality level, especially as the level of quality delivered in construction will have a direct impact on the operational performance. The construction phase is more related to the degree of conformance to designs and having the building end-product being free of construction defects, whereas the operational phase is more performance-based in sustainability measures and considers the end-user satisfaction in its metrics.

The mechanisms for quality performance are quality control and assurance, of which the first involves activities to appraise and adjust production and construction processes to meet a level of quality for the end product, and the latter involves systematic actions needed to provide a level of confidence that the building components will perform satisfactorily in service (Koch and Molenaar 2010). Green buildings experience more frequent inspections in the construction phase that ensure the components installed to conform with the design team's intent (Azouz and Kim 2015). The construction phase also has a thorough materials quality control and assurance program to verify the conformity of the materials to the project standards. The design stage establishes the specifications, physical characteristics, manufacturing methods, and test requirements against which the on-site quality assurance cross-examines to determine whether the materials are to be accepted or replaced. Green buildings have greater requirements for material conformance by the material suppliers to fully disclose any potential chemicals of environmental or health concern through Environmental and Health Product Declarations. In addition, adherence to environmental metrics is more pronounced in green buildings such as construction waste reduction and IEQ monitoring during construction. Operation-wise, the quality of design and construction is put to the test, along withmechanisms to maintain the building integrity and prolong its life expectancy in performing as it was designed for. This had led to presence of certification systems strictly for operation and maintenance.

Commissioning is a unique quality assurance mechanism in green buildings, which may be considered as a quality bridge between the construction and operational phases. The mechanism consists of a series of tests and adjustments on the electrical, mechanical, and plumbing systems to ensure that the building components perform according to the intended design goals. In green buildings, the commissioning process is well established from the design phase and is led by an independent commissioning agent (Baxter et al. 2002; Kubba 2016). The agent is also involved in the building operations through liaising with the operations and maintenance staff and occupants to resolve issues after one year from the project completion. The process is a greater challenge for green buildings because of the low-energy HVAC systems, innovative renewable energy sources (such as wind or solar power), raised floor ventilation systems (or natural ventilation through passive design strategies), and evaporative cooling systems (Baxter et al. 2002). There is also a greater scope for seasonal variabilities, such as functional testing of heating and cooling equipment in winter and summer.

Project delivery systems' impact on construction and operational quality

Love and Edwards (2004) attributed the quality deviations in the construction industry to the antagonistic relationships between the stakeholders due to their lack of communication and mutual liaison. Owners require quality to be achieved for the intended function of the building facility without incurring extra costs. Designers however wish to pursue a reputation of achieving a high-quality and satisfactory structure without excess cost increases from the design. Constructors on the other hand, at a fixed cost, want to meet the quality expectations at a bare minimum, with less intention to exceed the quality expectations

(Barrie and Paulson 1992). Richerzhagen et al. (2008) found that important actors (architects, developers, and workers) lack the knowledge and capabilities required for energy-efficient technologies, which had stimulated some actors to establish training and quality management programs to improve professionals' skills and the product quality. The involvement of different stakeholders in quality calls for a re-examination of how project delivery systems (PDSs) perform against one another in the quality domain. Different delivery system arrangements enable the owner to choose the extent of delegating responsibilities or retaining control. The degree of delegating responsibilities becomes a fiduciary responsibility for the parties, which in turn affects the level of quality (ASCE 2012). Koch and Molenaar (2010) indicated that in PDSs, the vast majority of quality control and assurance activities remain the same, but the difference is in which party is responsible for performing the activities. Raouf and Al Ghamdi (2019b) explored how PDSs for green buildings harness an environment for value engineering, improved procurement programming of materials and enable better forward thinking on the overall construction process.

Koch and Gransberg (2010) explain that Design-Bid-Build (DBB) contracts have the construction procedures and methods provided in greater detail. Design-Build (DB) contracts consider the contractors using their own specific construction means to distinguish themselves from other bidders and find areas of efficiencies, which may be risky concerning quality. The authors assert the necessity for the owner to specify the flexibility of the DB project in terms of construction methods. There is also a tendency for owners to adopt a DBB mentality when opting for a DB project and is reflected in the request for proposal (RFP) documentation, which is the owner's control mechanism, and often lacks a quality management plan before a DB contract is awarded. Construction Management Agency (CMA) or Agency at Risk (CMAR) strikes a balance, such that a professional construction manager sets the standards of quality as a third-party independent agent, which satisfy regulations while maintaining economy of cost in the quality performance through alignment with project goals (Barrie and Paulson 1992). The independent agent party also provides objectivity in ensuring conformance in construction through inspection regimes. Owners establishing a project's quality management system before awarding a contract enables them to ask the bidders to improve their quality management plans if needed before finally awarding the works (Gransberg and Molenaar 2004).

Construction contractors find green buildings to comprise more innovations, with greater associated risks (Azouz and Kim 2015). Conventional PDSs may not be suitable for this in their tendency to penalize professionals for errors, thus causing them to adhere to traditional methods rather than exploring innovations (Leoto and Lizarralde 2019). The Integrated Project Delivery (IPD) system countered this by providing contractual arrangements with reward pools to incentivize innovation. The multiple parties in IPD engage as a single entity in decision-making with shared risk responsibility. El Asmar et al. (2013) found IPD projects to have fewer deficiency issues and punch list items than conventional projects.

Research motivation and objectives

This study addresses the construction and operational phases as processes that can be measured and improved based on quality performance. Both phases are the most cost-consuming project lifecycle stages, with the first having a consequential impact on the latter if discrepancies are not caught before handover. The authors made a systematic review on the effectiveness of PDSs in green building delivery, and deduced that such systems were not evaluated for quality performance to the same extent as cost and schedule metrics (Raouf and Al Ghamdi 2019c). The United States Green Building Council (USGBC) highlighted the need to increase the design and construction outcomes predictability and blamed the poor performance record due to poor construction practices, insufficient building commissioning and a lack of understanding on operations and maintenance practices (USGBC Research Committee 2007).

Therefore, the work motivation is to address this research gap and thereby fulfill the objectives of: (1) developing a clear and comprehensive construction and operational quality process model for green buildings; (2) refine the framework model through semi-structured interviews with green building practitioners to be more aligned to the construction and operational practice; (3) determine from the responses the shortcomings in the construction and operational process that had implications on constructing and operating green buildings; and (4) validate the framework model through the focus group study. The complete capture of the quality activities involved in building construction and operation will enable decision-makers to determine the best strategies to tackle a complex green building project effectively in a forward-thinking manner and select the most suitable PDS for such an undertaking. All the participants in the interviews were based in the State of Qatar.

Research methodology and paper organization

Figure 1 below illustrates the overall research methodology, which extends from earlier research done on the subject as Step 4: content analysis, semi-structured interviews and a focus group study:

Step 1 was a systematic literature review on the obstacles and challenges faced in green building delivery, which inferenced the design and construction complexities, compliance to superior performances and operational performances mismatching what the buildings were designed against (Raouf and Al-Ghamdi 2018). Also, it was established that project delivery systems held a significant role in impacting the success of green building but there was a research gap in studies evaluating the quality performance of project delivery systems in green building projects (Raouf and Al Ghamdi 2019c). To test the findings into practice, Step 3 involved a questionnaire survey was then distributed to managerial practitioners to determine whether sustainability traits of a green building can be affected by quality performance and it was concluded that such traits are embedded in key performance indicators related to quality performance (Raouf and Al Ghamdi 2020).

After establishing the importance of quality performance in a green building context, it was decided that a framework model would be needed to map out all the quality activities involved in a green building project lifecycle to enable for gauging the activities for projects (Step 4).

Step 4 A was a content analysis of peer-reviewed literature to identify the important activities that occur in the construction and operation stages and the associated quality procedures to ensure such activities are executed effectively. Quality management plans from projects were also reviewed for the same purpose, and to deduce the key performance indicators that are adopted in the quality management process. The results in Stage 4A were then combined to produce an overall map of all the

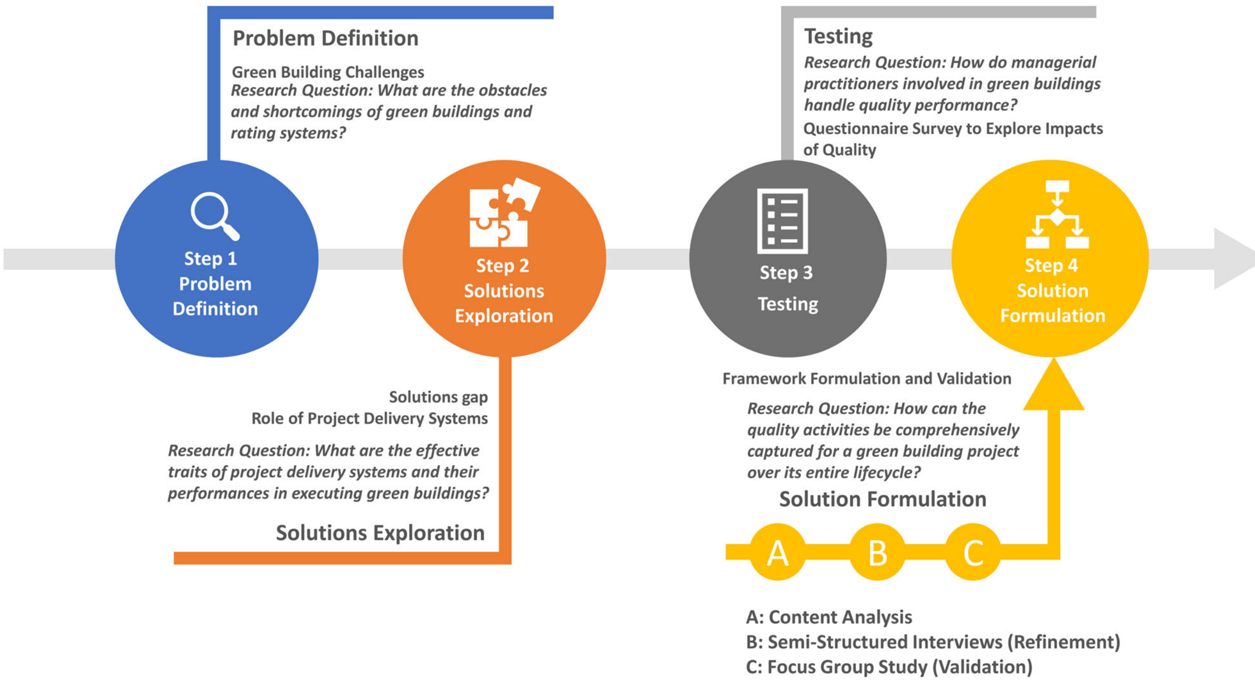

Figure 1. Framework methodology.

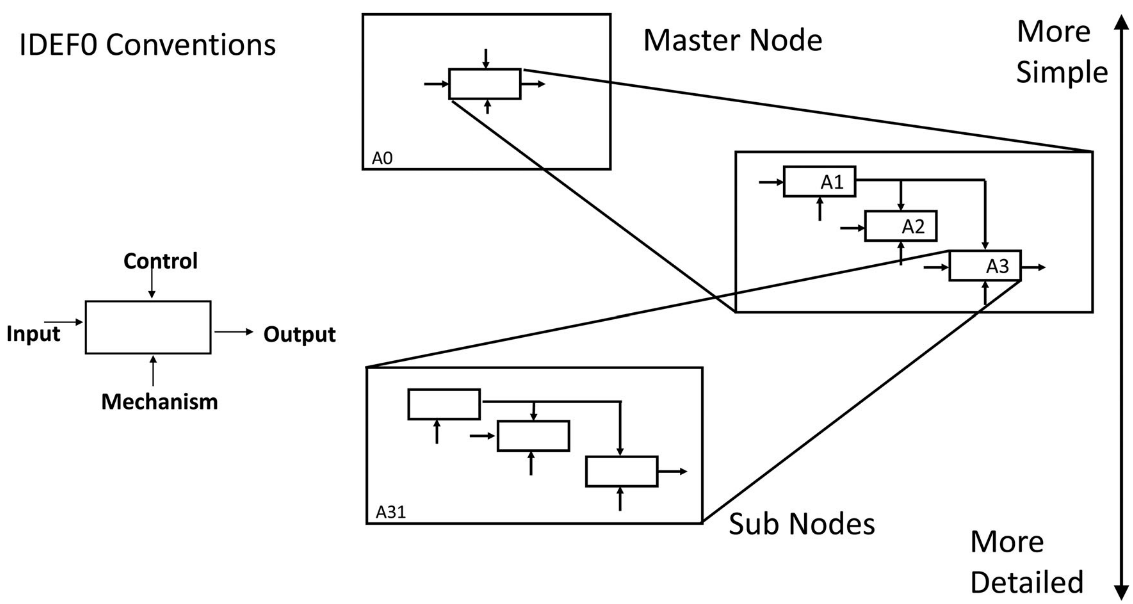

Figure 2. IDEF model conventions.

activities using an industry process model (IDEF$_0$). IDEF$_0$ was found to be the most suitable to capture the activities while maintaining the intricacies of each process. The activity of each lifecycle stage is represented by a box with left, right, top, and bottom arrows representing the input, output, control, and mechanisms, respectively (presented in Figure 2). The IDEF$_0$ model has been previously used for construction industry research (Shin et al. 2018; Papajohn et al. 2020). The logic for selecting and sequencing the activities was based on the Preventative-Appraisal-Failure (PAF) model, which several authors have used for assessing the Cost of Quality (CoQ) of a project (Kazaz et al. 2005; Abdelsalam and Gad 2009; Heravi and Jafari 2014; Raouf and Al Ghamdi 2019a). Preventative activities are proactive measures to ensure the desired quality is achieved. Appraisal activities are gauging and auditing measures to determine that the activity is within conformance to the established quality levels. Failure activities are those that rectify nonconformance to restore the works acceptable quality levels. The construction stage has greater opportunities for preventative and appraisal activities compared with the operational stage, although certain preventative maintenance procedures are conducted.

Step 4 involved conducting semi-structured interviews and a focus group study to gain more thorough insights into the procedures and issues faced by green building construction and operational quality activities. The basis used for producing the questions was the draft IDEF0 model produced from Step 4A.

Table 1. Participant profiles.

Number	Title	Green Accreditation	Experience Level	Entity Representing	Stage	Project Type	Certification Level	Participation
1	Environmental Engineer	GSAS CGP	25	Owner Representative	Construction	School	LEED Gold	Interview
2	QAQC Manager	LEED AP	15	Owner Representative	Construction	School	LEED Gold	Interview
3	Sustainability Consultant	LEED AP, GSAS CGP	25	Independent Consultant	Construction	Commercial	GSAS 4 Star	Interview and Focus Group
4	Sustainability Consultant	LEED AP, GSAS CGP	10	Independent Party Consultant	Construction	Outdoor Sports Venue	GSAS 4 Star	Interview and Focus Group
5 LEED Gold	Operations Manager Interview	LEED AP	10	Owner Representative	Operations	Student		Accommodation
6 LEED Gold	Mechanical Engineer Interview	LEED GA	10	Owner Representative	Operations	Student		Accommodation
7	Operations Manager	LEED AP, Greenstar	15	FM Contractor	Operations	Outdoor Sports Venue	LEED Gold	Interview and Focus Group
8	Commissioning Agent	LEED AP	15	Owner Representative	Construction		GSAS 4 Star	Interview and Focus Group
9	Commissioning Agent	LEED AP, GSAS CGP	15	Commissioning Consultant	Design and Construction	Commercial	LEED Gold	Interview
10 LEED	Operations Manager Platinum	LEED GA Interview and Focus Group	20	Owner Representative	Operations	Student		Accommodation
11	Project Manager	GSAS CGP	20+	Owner Representative	Construction	Outdoor Sports Venue	GSAS 4 Star	Interview
12	Environmental Manager	GSAS CGP	20	Design and Supervision Consultant	Construction	Outdoor Sports Venue	GSAS 4 Star	Interview
13	Commissioning Agent	LEED AP	15	Supervision Consultant	Construction	Offices	LEED Platinum	Interview
14	Sustainability Consultant	LEED AP	20+	Sustainability Consultant	Construction	Commercial	LEED Platinum	Interview and Focus Group
15	Operations Manager	LEED GA	15	Owner Representative	Operations	Residential	LEED Gold	Interview
16	Sustainability Consultant	GSAS CGP	15	Supervision Consultant	Construction	Offices	GSAS 4 Star	Interview
17	Operations Strategist	GSAS CGP	15	Council Approval Authority	Operations	Commercial	GSAS 4 Star	Interview
18	Construction	GSAS CGP	15	Council Approval Authority	Construction	Residential/ Commercial	GSAS 4 Star	Interview
19 LEED	Mechanical Engineer Platinum	LEED GA Interview	25	Owner Representative	Operations	Student		Accommodation
20	Sustainability Consultant	LEED AP	15	Sustainability Consultant	Construction and Operations	Outdoor Sports Venue	GSAS 4 Star	Focus Group
21	Construction Manager	LEED AP and GSAS CGP	15	Supervision Consultant	Construction	Commercial	GSAS 4 Star	Focus Group
22	Sustainability Consultant	GSAS CGP	20	Supervision Consultant	Construction	Outdoor Sports Venue	GSAS 4 Star	Focus Group
23	Environmental Manager	GSAS CGP	20	Supervision Consultant	Construction	Resort	GSAS 3 Star	Focus Group
24	Project Coordinator	LEED AP	20	Sustainability Consultant	Construction	Outdoor Sports Venue	GSAS 4 Star	Focus Group
25	Sustainability Consultant	LEED AP, WELL AP	15	Sustainability Consultant	Construction	Resort	GSAS 3 Star	Focus Group

An application was submitted to the institutional review board (IRB) to ensure that the interview questions complied with local codes of conduct and ethics, as well as ensuring that information of the interviewer profiles and companies remained confidential. The pre-designed set of open-ended questions was submitted and approved by the IRB, with the objectives of capturing qualitative data from participants on the construction and operational processes, compliance with sustainability requirements, as well as their views on PDSs and their impact on quality based on their experiences. Such a technique to gain an in-depth understanding of the topic is common in construction management studies (Liu and Wilkinson 2015; Yang and Shen 2015; Sadiqi et al. 2017; Lestari et al. 2019). Before engaging with the participants, the questions were given to two professionals to ask for a review if the questions would be effective enough in getting responses. For example, the use of the term "lessons learnt" was more acceptable to use in determining defects or reworks happening in projects. The participants were purposively selected based on satisfying the criteria of having more than 10 years of experience in green and conventional buildings, recently involved in a green building project, holding a green accreditation, as well as sound knowledge and an understanding of PDSs (as determined from the initial introductory questions in the interview). In total, 19 participants took part in the interview (12 from construction and 7 from operations). The number of participants was relatively comparable to other construction management studies that used semi-structured interviews and focus groups (Fernandes et al. 2015; Shehu and Akintoye 2010). The profiles of the participants are shown in Table 1. The interviews lasted between 40 and 90 minutes and were conducted face to face, except for one interview, which was done by telephone. The sampling method used to select the participants consisted of purposive sampling by initially approaching the local green building council to ask for potential participants with more than 10 years of experience in green and conventional building projects, hold a green accreditation, and making sure to obtain the a diverse representation of entities and the green building project types they were in charge of. A content analysis was then used to synthesize meaning from the interviews and to deduce any commonalities and differences in the information provided, as well as potential reasons for such differences (Fellows and Liu 2015). The participants predominantly worked on projects pursuing Leadership in Energy and Environmental Design (LEED) or Global Sustainability Assessment System (GSAS) certification, which are international green building rating systems. The framework was also refined in case of certain activities or mechanisms were omitted that were then mentioned in the semi-structured interviews. The results of the interviews were then given to a focus group to validate the statements made in the semi-structured interviews. This involved a group discussion in which a mediator would encourage the participants to exchange ideas and express their opinions to a set of questions on a certain topic in a permissive, non-judgmental environment (Krueger and Casey 2015). An invitation was sent to 14 participants involved in green building construction and operations from which 12 accepted to attend. Before commencing the focus group study, the mediator briefed the interviewers about the research, its rationale and the purpose of the framework model. Statements were made to the participants from semi-structured interview results regarding commissioning and retro-commissioning, material and construction methodology compliance, green building technologies, liaison between design construction and operations and project delivery systems to stimulate discussions among them on the various topics.

Finally, Step 4C involved using the same focus group to evaluate the appropriateness, comprehensiveness, relevance and effectiveness of the framework in solving the quality performance issues faced with green buildings using the method of (Shin et al. 2018). The degree of agreement for each evaluation metric was calculated using Equation (1) below where a value close to 1 reflects a greater agreement level. Q_3, Q_1 and M_{dn} are the upper and lower quartiles and the median values of the dataset.

$$Agreement = 1 - \frac{Q_3 - Q_1}{M_{dn}}$$

Results and discussion

Framework development through content analysis

The framework context diagram is shown under the A0 page with the overall client aspirations and desires being transformed into a green building and meeting its sustainability requirements. The master A0 node itself decomposes into four lower-level functions, which are the lifecycle stages. Each node then further decomposes into the respective detailed nodes that represent the main function. The inputs, control, outputs, and mechanisms are preserved in the decomposition of the master node (A0 in this case) (Beude 2000). The breakdown of the master node A0 into the lifecycle nodes A1–A4 is shown in Figure 3. The scope of this study however is only limited to the construction (A3) and operation (A4) nodes (shown respectively in Figure 4 and Figure 5). Project Brief (A1) and Design (A2) are explained in another accompanying study (Raouf and Al Ghamdi (Under Review)). The sub-modes of Node A3 in Figure 4 are color-coded as yellow for pre-construction and blue for during construction. The project phase delineations for A1 to A4 are collated from notable book references and industry standards (ASHRAE 2018; RIBA 2013), as well as academic studies (Magent et al. 2005; Bayraktar and Owens 2010; Parrish and Regnier 2013).

Tables 2 and 3 provide explanations of what the nodes represent and their associated mechanisms. A further elaboration with the referencing sources for the information is provided in Supplementary material.

Insights from semi-structured interviews and focus group

The interviews and focus group results for the themes of material and construction methodology conformity, green building technologies quality issues, commissioning and retro-commissioning, liaison between design, construction and operations and PDSs impacts for construction and operations are presented in this section. Cross-referencing on the process model components are mentioned within the text as to what elements were mentioned in the interviews and focus group (for example, responses to mentioning on ensuring material conformance are tagged to the respective node activity A35 from Figure 3). Components for the mechanism to do with Project Brief and Design stage are also cross-referenced. The full narrative of the interview and focus group results as well as the framework models for Project Brief and Design are presented in Supplementary material.

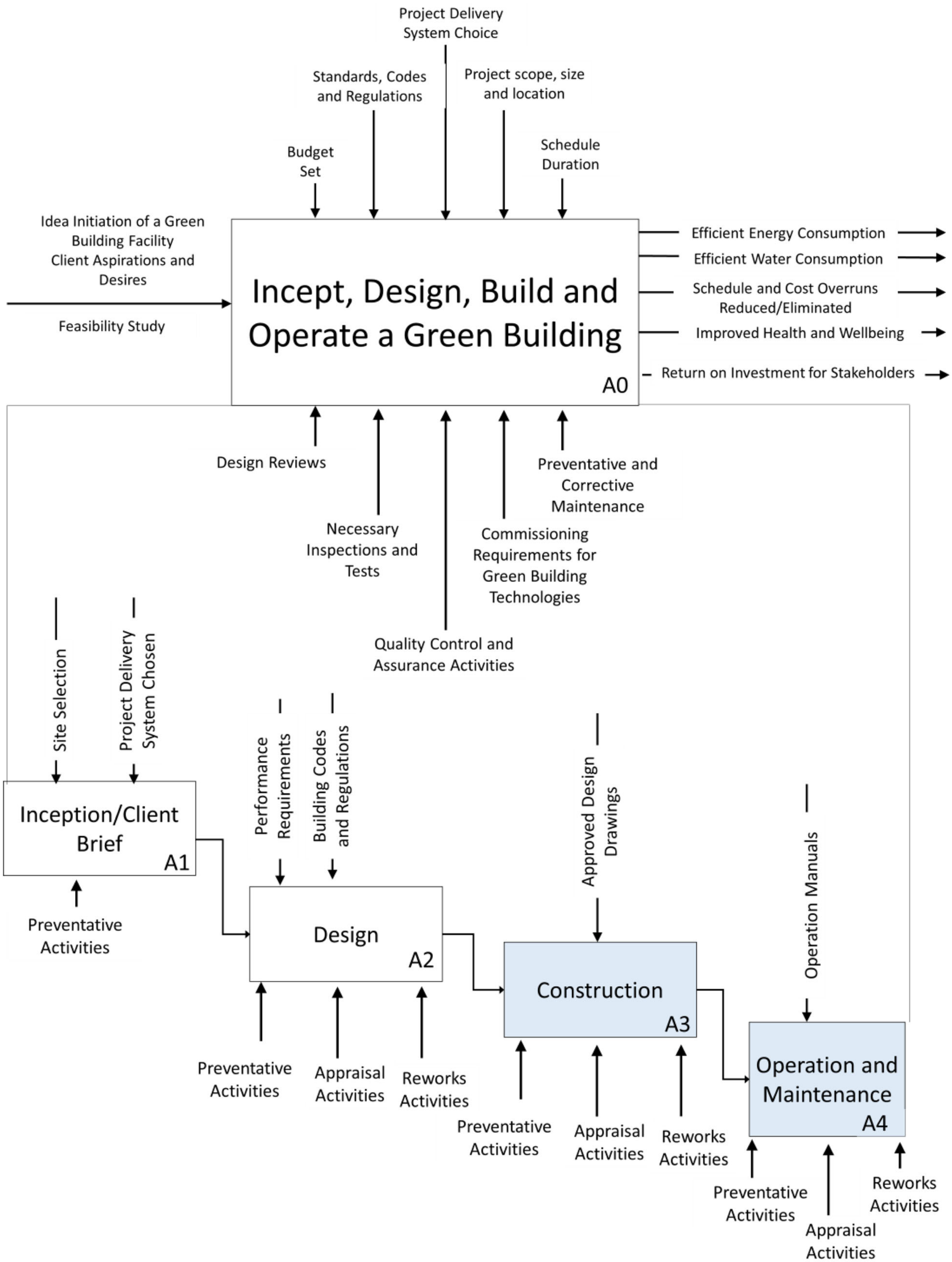

Figure 3. IDEF A0 master node expanding into nodes A3 construction and A4 operations.

Material and construction methodology conformity

Material conformity was found to be more challenging for a green building setting compared to conventional settings because of the extra documentation required that is not readily available (e.g., chain of custody, forestry stewardship certification) causing material submittals to undergo several revisions (A35 and M43). Also, testing facilities to verify technical information for quality assurance are not available (in particular for U-values and Solar

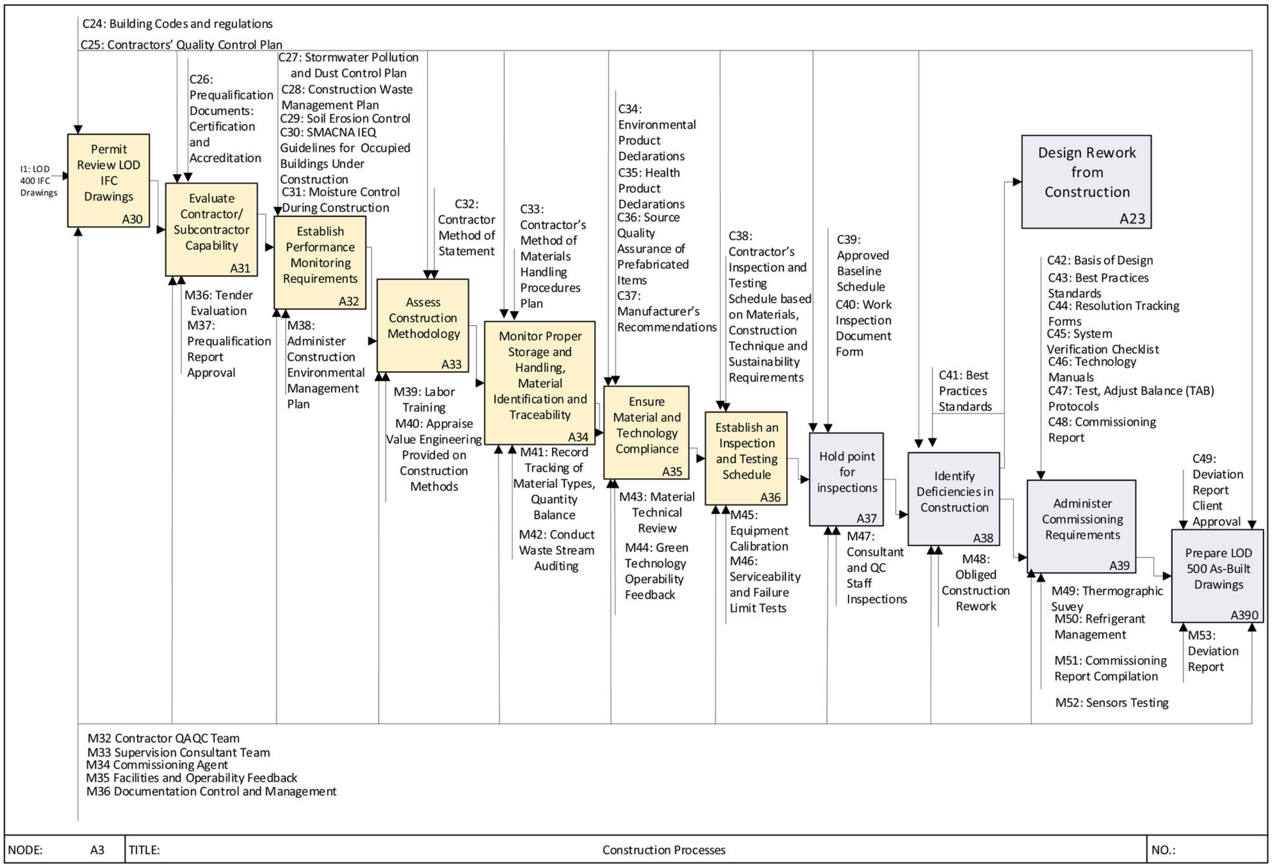

Figure 4. Construction phase nodes: nodes in yellow indicate activities in pre-construction and nodes in blue indicate activities during construction.

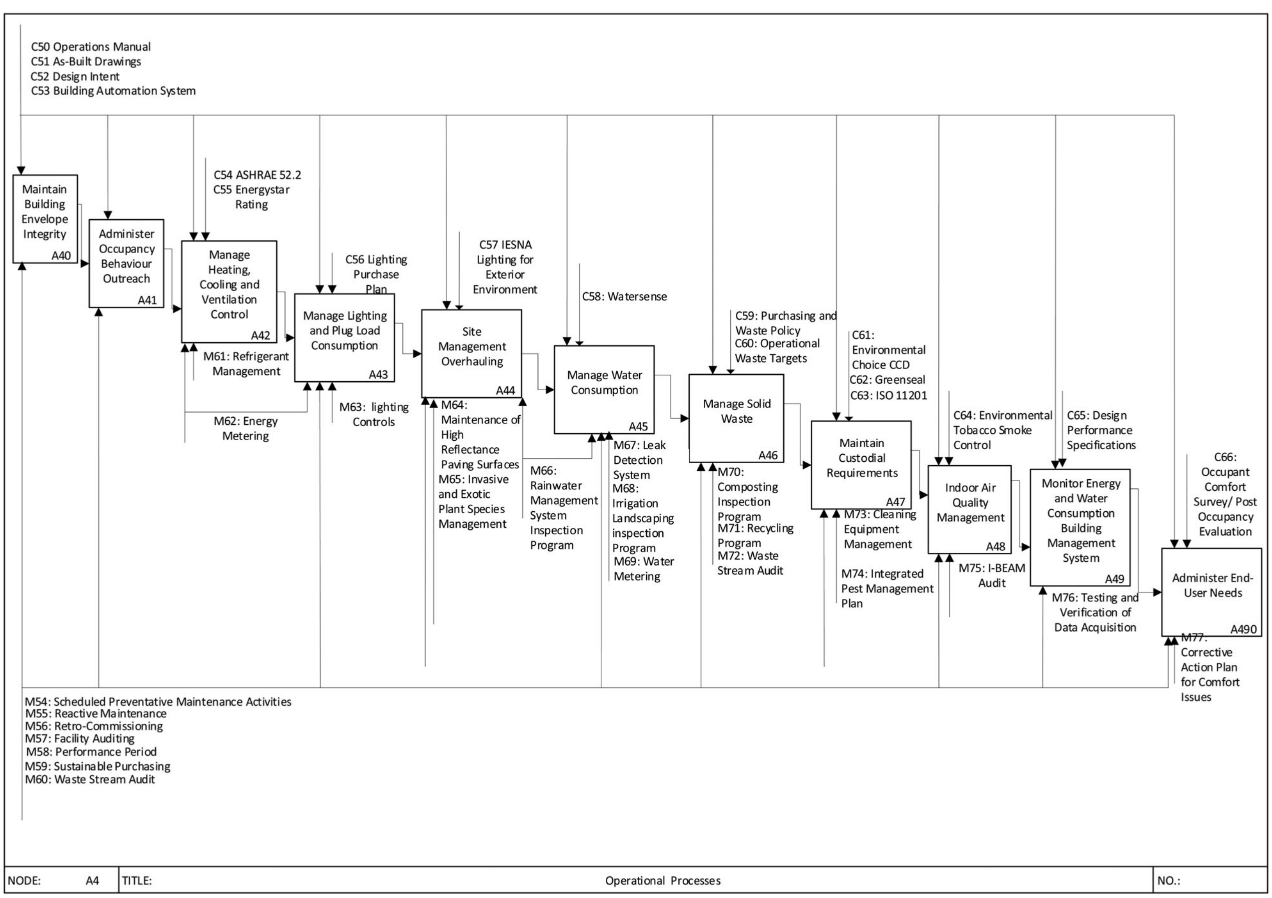

Figure 5. Operational Nodes.

Table 2. Explanation of construction nodes A30 to A35.

A30: Review on LOD 400 Issued for Construction Drawings for Building Permit	A31: Evaluate Contractor's/ Subcontractor's Capability	A32: Assess Construction Methodology	A33: Establish Performance Monitoring Requirements	A34: Monitor Proper Storage, Handling, Material Identification, and Traceability	A35: Ensure Material Compliance
Authorities review the drawings and issue an authority approval indicating the drawings are approved for construction commencing.	Contractors and subcontractors are chosen with delegated responsibilities assigned based on the PDS chosen for the project.	Production of a Method of Statement (MoS) that indicates the procedures and logical sequence of work sequence. Health, safety, and environmental risks with corresponding mitigation actions provided.	Sustainability and construction team liaise to establish performance monitoring requirements. Produce execution plans for: soil erosion management dust control stormwater runoff management indoor environmental quality during construction	Materials are tracked and traced into a record system. Recording for materials consumed and remaining balance. Recording of material waste.	Review of material and equipment specifications from suppliers against technical specifications set in the project specifications and construction drawings.
	M6: Tender evaluation	*M8: Labor training*		*M10: Record tracking of material types, quantity balance*	*M12: Material technical review in complying with project specifications*
	M7: Prequalification report approval	*M9: Appraise value engineering provided on construction methods*		*M11: Conduct waste stream auditing*	

Mechanisms Covering all Nodes:
M1: Contractor's QAQC team: Administers and executes the quality supervision on the construction team through tests and inspections.
M2: Supervision consultant team: Approving authority for material submittals, inspection requests, and construction drawings, responsible for notifying of any nonconformances in works.
M3: Commissioning agent: Administers commissioning plan provided from design or prepares an early commissioning plan in Node A33.
M4: Facilities representative: Reviews approved drawings and provides operability feedback to construction team on any discrepancies faced.
M5: Documentation control and management: Records for document transmittals for inspections, material submittals, drawings, minutes of meeting records, and test reports are organized with information provided as per ISO9001 standards.

Table 2. Continued: explanation of construction nodes A36 to A390.

A36: Establish Inspection and Testing Schedule	A37: Hold Point for Inspections	A38: Identify Construction Deficiencies	A39: Administer Commissioning Requirements	A390: Prepare LOD 500 As-Built Drawings
Inspection and testing regime formulated in the design phase is revised further in the construction stage. Inspection and testing plan included in construction schedule as part of the baseline schedule submission.	Administer hold points to seize the work progress to allow for a third party to appraise workmanship of a certain construction activity before proceeding to the next activity.	Capturing and documenting construction deficiencies. Classifying deficiency and preparing a corrective action to rectify the deficiency.	Appraisal of building components (envelope, lighting, HVAC, MEP fixtures, management control systems) to ensure compliance with design intent documents.	Preparation of drawings of the completed building components. Collate deviations into a deviation report for owner representatives to review and appraise.
M13: Equipment calibration M14: Serviceability and failure limit testing	*M15: QC team and consultant inspections of work activity adherence to specifications*	*M16: Nonconformance report is submitted and rectification procedure to be executed.*	*M17: Thermographic survey M18: Refrigerant management M19: Commissioning reporting compilation for functional and verification tests done. M20: Sensor testing for all data acquisition systems (including meters, sensors)*	*M21: Submit deviation report to associated parties to appraise the necessity for rework or accept deviations.*

Mechanisms Covering all Nodes:
M1: Contractor's QAQC team: administers and executes the quality supervision on the construction team through tests and inspections.
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M3: Commissioning agent: Administers commissioning plan provided from design or prepares an early commissioning plan in Node A33.
M4: Facilities representative: Reviews approved drawings and provides operability feedback to the construction team on any discrepancies faced.
M5: Documentation control and management: Records for document transmittals for inspections, material submittals, drawings, minutes of meeting records, and test reports are organized with the information provided as per ISO9001 standards.

Reflective Index parameters). There are views that the designer needs to hold greater responsibility for carrying material specifications in terms of market availability and testing capability, which should also be part of the constructability review in the design process (M18 and M30). Otherwise, the risks of materials related to sustainability conformance can cause green building credits to be denounced because the specifications need long lead items to be procured and is a challenge

Table 3. Explanation of operation nodes A40 to A45.

Node A40 Maintain Building Envelope Integrity	Node A41 Administer Occupancy Behavior Outreach Node	Node A42 Manage Heating, Cooling, and Ventilation Control Systems	Node A43 Manage Lighting and Plug Load Consumption	Node A44 Site Management Overhauling	Node A45 Manage Water Consumption (Including Process Water)
Regular checks to ensure building envelope does not contain any leaks or moisture intrusions that can cause mold growth or permit pests.	Awareness and activity program for end-users to contribute to sustainability requirements through behavioral changes.	Diagnosis of any noise, poor ventilation rates, insufficient cooling and heating.	Established lighting levels that the building follows are monitored. Photosensors periodically checked for functionality.	Reporting on dilapidated materials. Maintenance of permeable surfaces.	Periodic flow and pressure tests ensure that the plumbing fixtures and fittings comply with the flow and volume rates prescribed for the components. Water budgeting is done and compared to baseline models.
		M6: Refrigerant management: Elimination or reduction	*M8: Calibration and verification of photosensors and automatic lighting controls*	*M9: High-reflectance paving surfaces maintenance: recoating of surfaces to maintain SRI levels M10: Invasive and exotic plant management: Prevent growth of weeds that are consume water at the expense of indigenous plants.*	*M12: Leak detection system M13: Irrigation landscaping inspection program M14: Water metering*
		Mechanism covering Node A42 and A43 *M7: Energy metering: Periodic check on calibration and functioning of meters and termination with the energy-consuming components.*		***Mechanism covering Node A44 and A45*** *M11: Rainwater management system inspection program: Ensure all rainwater-harvesting components (collection, conveyance, and filtration) are well maintained.*	

Mechanisms covering all nodes:
M1: Preventative maintenance: Periodic inspections, adjustments, lubrication, cleaning, and performance testing intended to extend the service life of a building component.
M2: Predictive maintenance: Maintenance done based on statistical estimations on potential for building component deterioration.
M3: Reactive maintenance: Service repairs to restore building components or make them more efficient.
M4: Retro-commissioning/recommissioning: Third party commissioning agent appraises building components in complying with their design intent specifications through calibration of control system instrumentation and optimizing HVAC performance.
M5: Sustainable purchasing: Purchasing policies across all themes are adhered to ensure compliance with green building requirements.

Table 3. Continued explanation of operation nodes A46 to A4490.

Node A46 Manage Solid Waste	Node A47 Maintain Custodial Requirements	Node A48 Indoor Air Quality Management	Node A49 Monitor Energy and Water Consumption Building Management Systems	Node A490 Administer End-User Needs
Responsible purchasing plan to eliminate hazardous waste sources. Segregation and recycling of solid waste. Periodic waste stream audits for ongoing waste and toxins.	Periodic cleaning with approved green cleaning chemicals. Proper disposal of hazardous waste.	Measuring air quality metrics such as CO_2, PM10 and 2.5, SOX and NOX, temperature and humidity. Diagnosing air quality problems.	Building management system monitored for functionality. Meters, submeters, and other data acquisition systems are periodically calibrated for accurate measurements.	Needs of end-user for work orders and maintenance requests to be done promptly to ensure the occupants are satisfied with the building itself. Post occupancy evaluation (POE) to get feedback on occupant satisfaction for environmental, energy, and water performance.
M15: Composting inspection program M16: Recycling program: Administer the waste recycling strategies implemented. M17: Waste stream audit: Periodic audits on waste streams to verify end-disposals.	*M18: Cleaning equipment management M19: Integrated pest management plan*	*M20: I-BEAM audit*	*M21: Testing and verification of data acquisition systems and accuracy of information received in the building management system.*	*M22: Corrective action plan for comfort issues*

Mechanisms covering all nodes:
M1: Preventative maintenance: Periodic inspections, adjustments, lubrication, cleaning, and performance testing intended to extend the service life of a building component.
M2: Predictive maintenance: Maintenance done based on statistical estimations on the potential for building component deterioration.
M3: Reactive maintenance: Service repairs to restore building components or make them more efficient.
M4: Retro-commissioning/recommissioning: Third-party commissioning agent appraises building components in complying with their design intent specifications through calibration of control system instrumentation and optimizing HVAC performance.
M5: Sustainable purchasing: Purchasing policies across all themes are adhered to ensure compliance with green building requirements.

for a time-compressed construction schedule. This also extends to lighting fixtures and energy-saving motors of fan coil units.

A Method of Statement (MoS): declares the sequencing of works to be followed; contains health, safety, and environmental risk concerns inherent in the execution (A33 and C32). Successful projects had schedule sequencing that included durations for inspection activities for proper green building certifications (A36, A37, C38 and C39), but such effective sequencing depended on the knowledge and competence of the client in enforcing that the schedule (A37). A sustainability consultant faced challenges that an independent schedule for sustainability requirements is usually not streamlined in their schedule, which leads to conflicts and bypassing sustainability-related testing (C38). The MoS was found not to formalize environmental concerns at the same level as health and safety (M38). Recommendations are made for greater adherence to environmental requirements for a green building context. Furthermore, there was weak administration of the Construction Environmental Management Plan (CEMP), which was perceived as a "checklist documentation to attain certification."

Green building technology quality issues

Building Management Systems (BMS) are sensitive green building technology for monitoring and controlling building performance. Most of the systems provided by a single manufacturer and even when a contractor provided a different BMS supplier with full warranties on its integrity and seamless connectivity, it was rejected by them. Meters and submeters connected with the BMS system can fall short from short life expectancy, lack of batteries that can compensate for power outages and the inability of built-in data logging. Besides, the outdoor meters were not compatible with the hot weather conditions (M44).

Sustainable urban drainage systems (SUDS)

Technologies that are more aligned with the rainfall amounts and frequencies of temperate climates and not the arid climate of Qatar. Higher frequency of rain periods will have fewer contaminants accumulating in the area, whereas rare rainfall events in a desert climate caused environmental authorities to reject SUDS systems owing to the contaminants collected from roads onto the bioswales introduced. There are to be more filters and oil interceptors embedded in the SUDS systems, but such possibilities are restricted in certain cases, such as parking areas (M44).

Rainwater and greywater systems

Buildings not fully occupied or in scarcity of rainwater cause greywater treatment systems (GTS) and rainwater harvesting systems (RHS) to malfunction. Designers do not make correct calculations to address the system feasibility, and because the costs of smaller systems are high, designers instead opt for larger systems to cover the whole building. The tanks' filtration systems require a constant supply of water to keep them well maintained. Although there are alternatives such as recirculating condensates produced from air handling units into the systems, designers are apprehensive to implement such innovations, because they are not widespread in the design practice.

Feasibility assessment

Renewable energy technology sources need their feasibility studies on how much is being saved for operations (M27). These should not be limited to energy production, but rather in comparison to the opportunity costs of remaining with conventional energy sources and the associated repair and labor costs needed. Another example concerns photovoltaic technologies that fall short in the storage of energy produced because batteries are expensive and have a short lifetime. Instead, P10 requires an emphasis on the demand side of energy and water consumption to be reduced before adopting supply sources. Moreover, a building with a standalone reverse osmosis unit has a high running cost to produce 1 m^3 of water. Overall, there was a consensus that hot and humid climate in Qatar cannot depend solely on passive strategies to achieve energy and IEQ-related performance, but rather requires conjunctive use of green building technologies to attain the required performance. The participants warned against green building technologies that have not undergone committee and laboratory approvals for assuring that these were tested and tried and that it was important for the commissioning agent to review such requirements before execution.

Commissioning and retro-commissioning

Commissioning agents were found to be vital in reviewing construction drawings to identify discrepancies that were overlooked by the designer and contractor because they provide a commissionability and operability lens in reviewing such drawings (M17 and M34). A particular example was in integrating energy and water metering devices and other extra-low voltage (ELV) systems with a centralized building management system (BMS). Commissioning scope is limited to only the energy, water and IEQ aspects of the building in the electrical and mechanical scope (air conditioning, ventilation circulation, pressurization, and air balancing), lighting performance, flow rate of water fixtures, water filtration accuracy for greywater and stormwater systems but not as pronounced for the architectural scope. The latter more effectively covers passive design strategies (apart from U-values of building envelope components). The participants ideally preferred the commissioning authority (CxA) to commence from the project beginning to fine-tune the owner's project requirements (OPR) (M2 and M12). OPR can be contradicting and not cost-feasible (for example, owner requires fresh air increase and reduced energy efficiency). The CxA has extensive experience throughout the whole project lifecycle and so can provide vital feedback to the OPR through establishing construction checklists, conducting verification checks on the MEP systems, and checking the material submittals against the basis of design (BOD) and OPR (M12). Several participants expressed dissatisfaction from the commissioning process in which an independent third party was hired only in the end of construction and was compensated through in-house commissioning to reduce cost and only satisfy the paperwork necessary for commissioning credits. The lack of early CxA engagement caused severe consequences of abortive works in the execution because the energy performance requirements discovered may not match the specifications. Examples include the temperature levels of air conditioning that lead to reopening the ceilings and replacing the ducts with others of appropriate size or in the fan positioning for fan coil units (M55).

Several participants underscored the operational value of commissioning after construction, as there will always be misalignments or system challenges that do not comply with performances that can ultimately reduce the life expectancy of building components (M56). Effective commissioning would avoid additional costs from being incurred in the future through an extended life period for the building components. Any retro-commissioning to reap extended life benefits were non-existent in the project, but some operations teams compensated by following manufacturers' recommendations in the operation manuals and corrective works were performed.

Liaison between design, construction and operations

Participants underscored the importance for liaison between the lifecycle stages because projects attaining a green certificate in design stage were approved based on incorrect assumptions, and that construction circumstances can cause contractors to suffer in complying with sustainability. Some expressed the lack of mechanism set in place from the client to allow for operational feedback to the designers on the requirement of the operations team because of the urgency of delivering the project on time (M19). The LEED Design and Construction (D + C) was found to be not as effective as LEED Operations and Maintenance (O + M) certification inallowing for formal operational feedback. This was due to the owner will be inclined to add technologies with high operating costs needing 24-hour active labor engagement that are not centralized to serve a cluster of buildings (M27).

The liaison done with the design team to reduce construction waste in providing feedback for construction waste of 5% as a contingency for designers to find streams for reducing or reusing waste in the construction practice from the materials specified in the design (M18). Additionally, the construction waste that would usually get produced (e.g., cardboard material, concrete debris, glass waste) is reported to the designer to report how such materials are salvaged into factories for manufacturing from recycled materials instead of virgin raw materials. An extra monitoring check on the DB contractor during design through reviewing drawings and checking the materials specified to comply with the performance of a 4 Star GSAS certification level.

Rare liaison with operations team as a sustainability consultant but appreciate the huge benefits of liaison (M19). By being aware of what happens in the design and construction, the facilities management can commence preparing a more realistic and attainable facilities management plan (M54). It was stressed that designers do not have the efficient facility management experience to make effective spacing arrangements in the building layout that would consider aspects for waste hauling and access panel availability for maintenance (M19). Designing for LEED Gold is a difficult but attainable task and there can be overconfidence in assuming a top level of LEED Gold being achieved. For achieving a LEED Platinum certification, there should be involvement from the operations team for opportunities of extra points through designing for operations that happened in providing custodial and pest control-related design contributions.

Efficient sub-metering at a higher resolution was not achieved in the project and prevented useful comparisons against the baseline energy models to determine the energy and water performance efficiency (M19). The significance of sub-metering as an operational contribution in the design process was emphasized because it is not a common practice for designers to efficiently design for sub-metering with all the major systems for energy (air handling units, lighting, plug loads) and water (for irrigation and domestic usages) sub-metered, especially at a higher resolution to capture any irregularities rather than having one submeter for the whole floor. Examples included misinterpretations that CO_2 metering is only to be done in basements and not as per LEED requirements on floor levels holding certain occupant densities.

Leak detection devices are also commonly overlooked in designs and would ultimately impact the efficient control of deficiencies (C25). Furthermore, the sub-meters connected to a building management automation system were specified by designers for monitoring only, and not control (M17 and M34). It is common practice in design precertification to specify for cooling conservation efficiency to use variable air volume systems and variable frequency HVAC systems and for the designers to set an unoccupied setpoint temperature to be 27 °C. This was based on previous auditing experience that air conditioning temperatures were set at 23 °C throughout the 24-hour duration even when the building is unoccupied because of high humidity and pressurization conditions. Recommendations to modulate the air handling unit capacities by installing CO_2 sensors to optimize for the volume of occupants inside the building. In addition, lighting control management systems would have additional photocells and light-dimming controls in glazed areas where daylight becomes prevalent and regulate the artificial lighting to operate at partial capacity.

Significance of project delivery systems and quality performance

Material submittals. Some participants preferred DBB because the contract given to the building contractor is more thorough in material specification requirements, recommendations of the contractor in the project specification, as well as the performance level (A20-A23). For example, the contractor is given a "Preferred Vendors List," which means that the designer has given greater forethought in specifying the materials and from which vendor the materials are available. Therefore, the successfully awarded contractor would have material submittals expected to be compliant. DB, however, does not have the same regiment and the contractor as a designer specifies his own materials based on what is found to be suitable to their own preference.

Accommodating for volatile market conditions and design freeze. Difficulty in DBB project in not accommodating for circumstances when design stage had taken a prolonged period and becomes outdated owing to volatile market conditions, and particularly for MEP equipment needing compliance with new performance criteria for green buildings. The economic embargo that Qatar experienced made it impossible to import MEP equipment from neighboring countries at affordable rates. Other circumstances could include the owner ordering a design freeze from budgetary concerns and commencing after five years.

A DB contractual arrangement would reduce the periodic gap consequences between design and construction to enable a more current design complying with market conditions. A DB arrangement has more flexibility through the avenue of a direct meeting with the designer to readjust the specifications to fit the market availability.

Adherence to inspection hold points. Only on a case-by-case basis, such that DB contractors are overconfident in the construction execution and bypass hold points for inspection in the construction sequence with the supervision teams because of time-pressure circumstances (A37 and A38). DB was more prone to abortive works, especially as the contractor executes the civil works without fully designing the MEP works (A38). Some view that respecting hold points depends on the professionalism of the contractor and the ability to gain the trust of the supervision consultant, irrespective of the PDS setup.

Cost-cutting versus value engineering. The main DB issues were cost-cutting through value engineering (A20 and M25 being established in the preliminary design stage to prevent inappropriate cost cutting), especially if the DB contractor is engaged in schematic design. There was discouragement for having DB contracts with contractor commencing in later design stages because the design solutions have already been formulated. Others contested on quality difference between DB and DBB delivery, as it is not part of the operational periphery to consider how the project was procured. This indicates a lack of facility management involvement in the project inception. For contracting post-construction expansions for buildings and facilities, there were fewer unknown parameters in the design and it is safer to go for a DB contract as owner representatives unless the expansion would involve a large, complex building, in which case it is preferred to choose DBB.

Operational feedback. PDS dictates the liaison between design and construction but does not cover the operational phase (M19). For example, DB provides monitoring and feedback in design, even when there is a specific green building design consultant. Although DB contracts have coordination provided between the designer and constructor, operational coordination was difficult to achieve as the design and construction activities were happening in parallel.

The operational participants found noticeable quality differences with DBB being favored for workmanship in the execution but DB in terms of the solution quality for sustainability, creativity, and innovation. The greater the integration that the PDS includes (for example, design-build-operate (DBO)), the more guaranteed would be the quality of the project. A single entity would also be solely responsible for the operational quality and would consider from the design stage how to improve the overall lifecycle quality performance. Additionally, the DBO contractor retains the right of their own solutions for efficient operations rather than falling into a trap of more costly requirements from the owners to comply with.

Framework validation

A focus group study was organized in which professionals working in the construction and operations stages. The experts were expected to provide credible evaluations and thorough opinions on possible improvements because they had worked over the last 20 years in the construction and operational stages. The process model was evaluated based on its applicability, comprehensiveness, relevance and effectiveness. The reliability of the participants' results were evaluated using the level of agreement method as what was done by (Shin et al. 2018). A value close to 1 indicates that the answers are valid. The results shown in Table 4 indicate an overall average of 7.61 out of 10.

Table 4. Framework evaluation results.

Category	Average	Level of Agreement
Appropriateness	7.95	0.90625
Comprehensiveness	7.7	0.8125
Relevance	7.8	0.75
Effectiveness	7	0.6875

The level of agreement on Effectiveness was lower than the other evaluation metrics and this is attributed to one of the respondents suggesting to further expand Node A37 in green building sensitive cases where Hold points have not been adhered to. Some respondents suggested feedback loops to also be included to enable iterations in the processes, especially for Nodes A37 and A38, and what would ultimately happen if there is no quality conformance compliance (which is where C49: Client Approval for Deviation Report comes in place). From the professionals' evaluation, it can be concluded that the quality performance process model to be appropriate, comprehensive, relevance and effective for compliance to construction and operational performance of a green building project.

Conclusion

The quality performance of a green building project in the construction and operational stages requires the procedures to be undertaken to be mapped out to diagnose and improve the overall execution. To this end, an $IDEF_0$ model was adopted which allowed defining the construction and operational processes' inputs, controls, and mechanisms. The elements were obtained from a literature review and semi-structured interviews with practitioners involved in green building construction and operational stages and validated through a focus group study. It was imperative to consider the impact of the PDSs on the overall process because they dictate the timing of engagement of multiple entities involved, particularly in the construction phase. The PDS impact was found to be more pronounced in the construction phase compared to the operational phase. This raises a limitation of the study that there were no green building projects delivered using PDSs that engage operational entities in the overall project execution.

The quality domains that the interviews revealed showed culpability toward compliance with the material attributes specified in design; sequencing of works; labor quality in execution; feedback on the incorporated green building technologies; liaison between design, construction, and operational teams; and commissioning and retro-commissioning effectiveness and shortcomings. The research provided the following insights from the construction and operational practice. First, although operational feedback proved beneficial for the design and construction team, the liaison of the operational entity was not common because the PDSs did not encourage this, nor did the nature of the certification systems stimulate the entities to engage with operational staff. Second, both DBB and DB systems have their particular advantages for a green building setting that can allow for a hybrid delivery system to adopt both of their traits to achieve a more coordinated delivery system with fewer risks of opportunism and cost-cutting under the pretext of value engineering at the expense of sustainability traits. Third, commissioning is not as effective when done in a later stage during construction and has consequences, especially for the control and monitoring of the BMS with the various components related to energy, water, and IEQ. Fourth, buildings in aggressive climates cannot depend only on passive strategies and require conjunctive use of green technologies to achieve the necessary efficient performance levels. However, there were issues with several types of technologies for which the designers had not given proper forethought in terms of specifying the maintenance costs, availability of competent labor to operate, and their vulnerability to failures leading to the purchase of long-lead items that are not commonly available on the market.

The study asserts on the need for recognizing the role of adhering to quality for achieving green building performance, and through a framework model, it enabled a diagnosis to determine the hidden impacts of the processes the construction and operations industry that have consequential impacts leading to poor quality. The poor quality can jeopardize the green building's sustainability performance characteristics and thus is vital to tackle to protect the sustainability performance. The contribution of this research is a green building construction and operational quality process model validated by the industry. It will support owners, architectural programmers, and designers involved in green building projects to synthesize in a more comprehensive lifecycle approach the importance of integrating constructability and operability into designs rather than strictly focusing on performance specifications as far as quality in execution and operation is concerned. The process model enabled to decipher key sensitive issues in the construction and operational stages that can jeopardize the conformance and performance quality of a green building. Both the semi-structured interviews and focus group study acknowledged that the current practices are lacking in certain quality performance activities to meet green building certification estimations. Such a model is different from existing models or practices because it is based on quality performance in a green building context and provides a connection between all the project lifecycle stages under the quality domain to better pursue the quality outcomes. The study supplements work on previous studies that pursue having a more efficient construction performance through using Building-Information Modelling (BIM) in pre-project planning and decision making by revealing the later construction and operational stage challenges that may be obscure for planners and designers (Crowther and Ajayi 2019; Fazeli et al. 2019; Najjar et al. 2019). Future research will involve examining certain mechanisms for opportunities of expansion as well as associating costs with the activities based on building components for preventative, appraisal, and potential rework costs in BIM modeling software.

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Data availability

All data, models, and code generated or used during the study appear in the submitted article.

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