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Development of an integrative commissioning methodology for new-building construction

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DEVELOPMENT OF AN INTEGRATIVE COMMISSIONING METHODOLOGY FOR NEW-BUILDING CONSTRUCTION

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ABSTRACT

Commissioning (Cx) is a quality process for building construction used to verify that the owner's project requirements (OPR) are being met by the final design, construction, and operations and maintenance. The goal is to confirm that each phase of the project is linked back to the OPR through quality assurance methods. Leadership in Energy and Environmental Design (LEED) certification is an OPR which contributes to difficulties within the design and construction (D&C) process. Though LEED certification is only part of the OPR, too often the design drifts from the OPR and simply focuses on meeting the LEED certification.

Quality function deployment (QFD) has been successfully used in product development to capture the voice of the customer (VOC) and translate it into engineering characteristics. QFD then carries these parameters into production and service to ensure the VOC is being met with the final product. The House of Quality (HOQ), a tool within QFD, can provide a means for comparison of OPR and the proposed design, along with identifying how the design decisions impact the LEED scorecard. QFD can effectively link the project phases through design and construction and into operations and maintenance to ensure the OPR is met with the final building.

The primary objective of this research is to develop an integrative and systematic methodology that utilizes the QFD four-phase model in the commissioning process of new-building construction to ensure the OPR is met. The purpose is to provide practitioners the steps to take the QFD four-phase model through the entire Cx process to use as a means to oversee the entire design and construction quality process.

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We have finally finished …but now the really important work begins. Roll On!

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NOMENCLATURE

Symbol	Description
A/E	Architect/Engineering
ACG	AABC Commissioning Group
ACP	Associate Commissioning Professional
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BAS	Building automation system
BCA	Building Commissioning Association
BIM	Building Information Management
BoD	Basis of Design
CCC	California Commissioning Collaborative
CCP	Certified Commissioning Professional
CM	Construction Manager
CO	Change Order
CPMP	Commissioning Process Management Professional
Cx	Commissioning
CxA	Certified Commissioning Authority (certification from ACG)
CxA	Commissioning Authority (General term used for Cx provider)
CxAP	Commissioning Process Authority Provider
D/B	Design-Build
D/B/B	Design-Bid-Build
EA	Energy and Atmosphere

ECBCS	Energy Conservation in Building and Community Systems
GBCI	Green Building Certification Institute
GED	General Education Development (high school equivalency exam)
GSA	General Services Association
HOQ	House of Quality
HVAC	Heating, ventilating and air-conditioning
HVAC&R	Heating, ventilating, air-conditioning, and refrigeration
ID	Innovation in Design
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IgCC	International Green Construction Code
LEED	Leadership in Energy and Environmental Design
LEED AP	LEED Accredited Professional
LEED-NC	LEED for New Construction
MR	Materials and Resources
NBI	New Building Institute
NEBB	National Environmental Balancing Bureau
NIBS	National Institute for Building Sciences
O&M	Operations and maintenance
OPR	Owner's Project Requirements
PACRAT	Performance And Continuous Re-Commissioning Analysis Tool
PM	Project Manager
QCxP	Qualified Commissioning Process Provider
QFD	Quality Function Deployment
RFI	Request for Information

RFQ	Request for Qualifications
ROI	Return on investment
RP	Regional Priority
SM	Systems manual
SS	Sustainable Sites
TABB	Testing Adjusting and Balancing Bureau
USGBC	U.S. Green Building Council
VAV	Variable Air Volume
VOC	Voice of the Customer
WBD	Whole Building Diagnostician
WE	Water Efficiency
WO	Work order

1. INTRODUCTION

1.1. RESEARCH OBJECTIVE

The construction of a new non-residential building can represent one of the largest investments any business will face. With most investments, it is desired to maximize value and minimize cost and this of course holds for most new building construction. Trends are driving building designs and construction methods that are considered "sustainable" and/or "green:" however, the benefits of going sustainable/green vary greatly depending on the needs of each potential building owner. Along with these new design trends are more complex building systems, higher first-cost of construction, and greater risk of not meeting the owner's expectations.

For a traditional design-bid-build project delivery method, the owner contracts with multiple parties in order to bring the vision of a new building to completion. The owner first contracts with an architect who will design the building. The required engineering teams will be contracted by the architect and the architect will coordinate the engineering efforts. The coordination among the engineering design teams is often less than optimal as each design discipline works on their specific part of the project. It is expected that the architect/engineering (A/E) team will be designing towards the owner's project requirements (OPR). Once the design is complete, the project is put out for bid and the winner is awarded a contract for construction. Primary responsibility for future project deliverables and meeting the OPR then passes to the general contractor.

To ensure receipt of their expected value at project completion, the owner often contracts a third-party commissioning authority (CxA) to act as technical advisor and to oversee the quality of the design and construction. Major activities of the commissioning (Cx) process have been developed to ensure the final design and construction meet the OPR. Many of the activities have solid methods developed for their application, but significant gaps in the process need to be addressed. Two key activities that need to be addressed include, verify the basis of design (BoD) meets the OPR and verify the final design meets the OPR. Several Cx consulting firms were asked how they would accomplish these activities in a formal request for qualifications (RFQ) and none responded with any method. Either they had no method or they did not want to respond. This is seen as a weakness in the Cx process and motivation for this research.

Additional difficulties arise when project owners are seeking Leadership in Energy and Environmental Design (LEED) certification. Many potential building owners have opted for LEED-certification as proof that their building is “green” and has added value. There is no guarantee that LEED-certification will provide added value. Value will largely depend on the owner’s project requirements and whether those requirements have been met by the finished project. Achieving LEED-certification at any of its four levels may not ensure added value in the eyes of the owner. There are many combinations of credits that can be utilized to accomplish an owner’s LEED-certification goal, but which combination best fits the OPR and the owner’s definition of value is a question that must be answered early.

The LEED certification system offers numerous point opportunities that span the full range of design disciplines. It is difficult to quickly understand how a design decision made by one discipline impacts another discipline’s goal(s) for maximizing LEED points in their perspective areas. LEED certification is part of the OPR, but too often the design drifts from the OPR and simply focuses on meeting the LEED certification.

The goal of this research is to develop a new integrative methodology that utilizes the QFD four-phase model in the Cx process for new-building construction and also includes a methodology for the development of a stand-alone HOQ for use with those projects seeking LEED certification. The QFD model will provide an effective method for linking each of the Cx activities to assist the CxA in managing the quality process and ensuring the OPR is achieved. The LEED HOQ will provide a method for identifying the impact each LEED credit has on the others as a means to improve the design decisions and ensure the LEED credits pursued meet the OPR.

1.2. BACKGROUND ON COMMISSIONING

The commissioning process consists of several steps throughout the design and construction process; then extends into building occupancy and beyond. The steps include developing the owner's project requirements, develop the Cx plan, verify that the basis of design meets the OPR, design review, develop Cx specifications, submittal review and site visits during the construction phase, record drawing review, operations and maintenance (O&M) document review, training review, functional performance testing, Cx report, seasonal testing, warranty review, and lessons learned. Figure 1.1 illustrates a simplified flow chart of the major Cx activities in the process proposed in American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) Guideline 0-2005: The Commissioning Process. These activities should be expected by any owner requesting Cx services.

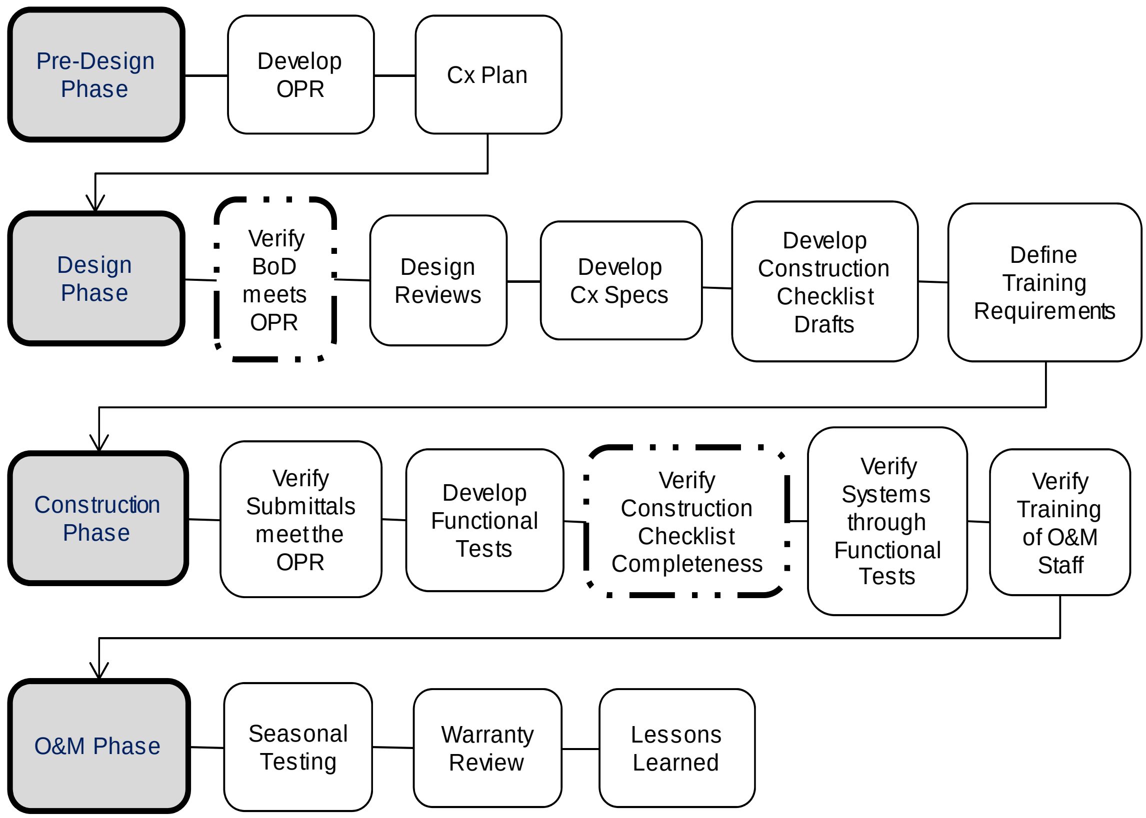


Figure 1.1. Flow Chart of Major Cx Activities

The following organizations have developed guidelines and best practices for the commissioning process:

- American Society of Heating, Refrigeration and Air-Conditioning Engineers
- ACG – AABC Commissioning Group (ACG)
- U.S. General Services Administration (GSA)
- California Commissioning Collaborative (CCC)
- Building Commissioning Association (BCA)

Each has a slightly varying approach to the Cx process, but each aligns its definition of commissioning with that provided in ASHRAE Guideline 0-2005: "A quality-focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all of its systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the Owner's Project Requirements." [ASHRAE, 2005]

The definition is generally for new-building construction. Other Cx processes for purposes outside of new construction are defined by ASHRAE Guideline 0-2005 as:

- Re-Commissioning: "An application of the Commissioning Process requirements to a project that has been delivered using the Commissioning Process. This may be a scheduled re-commissioning developed as part of an *Ongoing Commissioning Process*, or it may be triggered by use change, operations problems, or other needs."
- Retro-Commissioning: "The Commissioning Process applied to an existing facility that was not previously commissioned."
- Ongoing Commissioning Process: "A continuation of the Commissioning Process well into the Occupancy and Operations Phase to verify that a project continues to meet current and evolving Owner's Project Requirements. Ongoing Commissioning Process activities occur throughout the life of the facility; some of these will be close to continuous in implementation, and others will be either scheduled or unscheduled (as needed). Also see Continuous Commissioning Process."
- Continuous Commissioning Process**:** "A continuation of the Commissioning Process well into the Occupancy and Operations Phase to verify that a project continues to meet current and evolving Owner's

> Project Requirements. Continuous Commissioning Process activities are ongoing for the life of the facility. Also see Ongoing Commissioning Process." [ASHRAE, 2005]

In different terms, re-commissioning is a process conducted on buildings that were commissioned during the original construction. This process may be scheduled to be conducted every three years for example. The goal is to bring the building systems back to optimal operating conditions.

Retro-commissioning is a process for buildings that were never commissioned. The goal is to discover the deficiencies a building has, whether it be degraded equipment, calibration problems, failed sensors, sequence of operations and controls issues, or the multitude of other possibilities, and recommend the necessary corrections for the building to be brought up to its optimal operating condition.

Ongoing commissioning is similar to re-commissioning as it is a continuation of Cx and extends through the life of the building, but may occur at any time, not necessarily at predetermined intervals. The goal is to identify system degradation or changes sooner than re-commissioning for quicker resolution.

Continuous commissioning is nearly identical to ongoing commissioning, but takes advantage of technology for metering and monitoring of the systems such that changes in system performance are identified quickly and can be remedied immediately. This is expected to keep repair and energy costs at a minimum.

Having an understanding of these other Cx processes is important, as they are all conducted on existing buildings. The original new-building Cx as discussed in this research, provides the baseline for future implementation of the other Cx processes.

In order to deliver a successful project the OPR must be met. This requires that the owner's needs be well documented from the start. Documenting the OPR closely parallels writing the scope of a typical project. If the scope is not well defined it is difficult to achieve success at the end of the project. The CxA will verify that the design presented by the team meets the OPR.

1.3. BACKGROUND ON LEED

With energy costs rising and the increasing need for energy efficiency and environmental protection the U.S. Green Building Council (USGBC) developed and implemented a program to define and measure green buildings. This program known as Leadership in Energy and Environmental Design is a rating system that building owners must utilize to qualify their projects for registration as LEED certified with the Green Building Certification Institute (GBCI). LEED 2009 has several areas of certification, which include: New Construction, Existing Buildings, Commercial Interiors, Core & Shell, Schools, Retail, Health Care, Homes, and Neighborhood Development. The focus of this research is limited to LEED 2009 for New Construction (LEED-NC). All of the certification areas use a point system with 100 base points and 10 bonus points. Certification levels and point requirements are:

Certified	40 - 49
Silver	50 - 59
Gold	60 - 79
Platinum	80 and above

The certification credits and the corresponding points are then divided among seven categories (Table 1.1).

Table 1.1. LEED Scoring by Category [USGBC, 2009]

Topic	Available Points
Sustainable Sites (SS)	26
Water Efficiency (WE)	10
Energy and Atmosphere (EA)	35
Materials and Resources (MR)	14
Indoor Environmental Quality (IEQ)	15
Base Points	**100**
Innovation in Design (ID)	6
Regional Priority (RP)	4
Bonus Points	**10**
Total Points	**110**

Many potential building owners have opted for LEED certification as proof that their building is "green" and has added value. There is no guarantee that LEED certification will provide added value. Value will largely depend on the owner's project requirements and whether those requirements have been met by the finished project. It is also important to note that what is valuable for one construction project may not be valuable for another. Achieving LEED certification at any of the four levels may not ensure added value in the eyes of the owner. There are many combinations of credits that can be utilized to accomplish an owner's LEED certification goal, but which combination best fits the OPR and the owner's definition of value is a question that must be answered early in the design process or preferably in pre-design.

Each of the categories listed in Table 1.1 contain prerequisites that must be met prior to any points being awarded and each prerequisite must be met by any project applying for certification. Each LEED certified building will have the prerequisites in common, but how the certification points are accomplished is left to the owner, architect, and engineering teams to determine. Two additional consulting groups who are added to the team on many LEED projects are a LEED Accredited Professional (LEED AP) and a Commissioning Authority.

To deliver a successful LEED project to the building owner the team must meet LEED certification requirements, provide a building that meets the OPR, and be within the owner's budget. The LEED AP will assist the owner and design team in determining the best path to take for a particular LEED level by providing assistance in understanding and implementing the LEED scoring system. The design team will work towards delivering designs capable of achieving the LEED points expected from each of their respective areas of expertise. The CxA will assist the owner in verifying that the design and construction meet the OPR. This is a complicated process which requires much coordination, cooperation, and communication.

1.4. ECONOMIC ASPECTS

The construction of a new non-residential building can represent one of the largest investments any business will face. With most investments, it is desired to maximize value and minimize cost. This also holds for most new building construction. Trends are driving building designs and construction methods that are considered “sustainable” and or “green.” The benefits of going sustainable or green vary greatly depending on the needs of each potential building owner.

In a study investigating the cost-effectiveness of commercial-building commissioning, Mills et al. [2004] established a database of the largest available collection of standardized information on commissioning of actual buildings. They explain that building Cx was first developed in the 1980s as a way to reduce litigation. Building owners used Cx as a quality control method to ensure they received what they paid for. It was found that heating, ventilation, and air conditioning (HVAC) operating and controls systems had the most frequently found problems during Cx. The study determined the energy saving potential of Cx commercial buildings was in the range of $18 billion per year in the United States alone. It was estimated in the late 1990s that less than 5% of newly constructed buildings were commissioned when built. The LEED certification process is now the single most driver of new-construction Cx.

In a final report to the USGBC, the New Building Institute (NBI) gathered and analyzed data with regard to the “Energy Performance of LEED for New Construction Buildings” [Turner and Frankel, 2008]. At the time of the study (2006), 552 buildings had been certified under LEED-NC. All were invited to participate with the stipulation that building owners would provide one year post-occupancy energy data. 121 building owners participated and provided the necessary information. Findings indicate that, on average, LEED certified buildings do reap the benefit of energy savings. Buildings with higher LEED certification, on average, had higher energy efficiency. A troubling note is that half of the buildings had performance that significantly deviated from the design intent. 25% had performance that was lower than intended. The cause of the poor performance was not investigated.

As a follow up to the Turner and Frankel [2008] report, Newsham et al. [2009] took a more rigorous approach to analyzing the NBI data. A full statistical analysis comparing the LEED buildings to carefully matched non-LEED buildings produced the same results, that energy performance is improved for LEED certified buildings and, on average, LEED buildings use 18-39% less energy per floor area than conventional buildings. Newsham et al. [2009] also tested energy performance versus the LEED energy credits received and energy performance versus additional Cx and measurement and verification credits and found that neither correlated. The study shows that as the certification level of these building increased so did the credits obtained in the energy areas. However, the additional effort and funds to obtain these credits had no effect on energy performance. The authors suggested that this could be caused by the fact that the energy data provided by the building owners was for the first year. This is typically the period when the "bugs" are worked out of the system. They also questioned whether the Cx process was properly conducted, but did not provide an answer.

The proposed QFD methodology developed in this research provides a more focused emphasis on the development of the OPR and verifying the alignment of the BoD to the OPR which reduces late design changes, therefore, reducing cost and saving time.

1.5. CX AND LEED

When the team, including the owner, meets to determine which LEED credits to target, they typically refer to the list provided in Table 1.2 and discuss whether each credit is worth attempting. Much of what is discussed is cost, impact to project budget, and whether it is even achievable. For example, if a new piece of property is purchased in a rural area it is very unlikely Sustainable Sites, Credit 2, Development Density and Community Connectivity will be achievable. However, this purchase may provide an excellent opportunity to achieve Sustainable Sites, Credit 5.1, Site Development - Protect and Restore Habitat. There are trade-offs to be made. Another example might be questioning the higher cost for achieving Sustainable Sites, Credit 7.2, Heat Island Effect – Roof, which could be accomplished by installing a vegetative or "green" roof.

Table 1.2. LEED Credits and Associated Points [USGBC, 2009]

Sustainable Sites (SS)		**26 Points**
SS Prerequisite 1	Construction Activity Pollution Prevention	Required
SS Credit 1	Site Selection	1
SS Credit 2	Development Density and Community Connectivity	5
SS Credit 3	Brownfield Redevelopment	1
SS Credit 4.1	Alternative Transportation – Public Transportation Access	6
SS Credit 4.2	Alternative Transportation – Bicycle Storage and Changing Rooms	1
SS Credit 4.3	Alternative Transportation – Low-Emitting and Fuel Efficient Vehicles	3
SS Credit 4.4	Alternative Transportation – Parking Capacity	2
SS Credit 5.1	Site Development – Protect and Restore Habitat	1
SS Credit 5.2	Site Development – Maximize Open Space	1
SS Credit 6.1	Stormwater Design – Quantity Control	1
SS Credit 6.2	Stormwater Design – Quality Control	1
SS Credit 7.1	Heat Island Effect – Nonroof	1
SS Credit 7.2	Heat Island Effect – Roof	1
SS Credit 8	Light Pollution Reduction	1
Water Efficiency (WE)		**10 Points**
WE Prerequisite 1	Water Use Reduction	Required
WE Credit 1	Water-Efficient Landscaping	2 to 4
WE Credit 2	Innovative Wastewater Technologies	2
WE Credit 3	Water Use Reduction	2 to 4

Table 1.2. LEED Credits and Associated Points (cont.)

Energy and Atmosphere (EA)		**35 Points**
EA Prerequisite 1	Fundamental Commissioning of Building Energy Systems	Required
EA Prerequisite 2	Minimum Energy Performance	Required
EA Prerequisite 3	Fundamental Refrigerant Management	Required
EA Credit 1	Optimize Energy Performance	1 to 19
EA Credit 2	On-Site Renewable Energy	1 to 7
EA Credit 3	Enhanced Commissioning	2
EA Credit 4	Enhanced Refrigerant Management	2
EA Credit 5	Measurement and Verification	3
EA Credit 6	Green Power	2
Materials and Resources (MR)		**14 Points**
MR Prerequisite 1	Storage and Collection of Recyclables	Required
MR Credit 1.1	Building Reuse – Maintain Existing Walls, Floors, and Roof	1 to 3
MR Credit 1.2	Building Reuse – Maintain Interior Nonstructural Elements	1
MR Credit 2	Construction Waste Management	1 to 2
MR Credit 3	Materials Reuse	1 to 2
MR Credit 4	Recycled Content	1 to 2
MR Credit 5	Regional Materials	1 to 2
MR Credit 6	Rapidly Renewable Materials	1
MR Credit 7	Certified Wood	1
Indoor Environmental Quality (IEQ)		**15 Points**
IEQ Prerequisite 1	Minimum Indoor Air Quality	Required
IEQ Prerequisite 2	Environmental Tobacco Smoke (ETS) Control	Required
IEQ Credit 1	Outdoor Air Delivery Monitoring	1
IEQ Credit 2	Increased Ventilation	1
IEQ Credit 3.1	Construction Indoor Air Quality Management Plan – During Construction	1
IEQ Credit 3.2	Construction Indoor Air Quality – Before Occupancy	1
IEQ Credit 4.1	Low-Emitting Materials – Adhesives and Sealants	1
IEQ Credit 4.2	Low-Emitting Materials – Paints and Coatings	1
IEQ Credit 4.3	Low-Emitting Materials – Flooring Systems	1
IEQ Credit 4.4	Low-Emitting Materials – Composite Wood and Agrifiber Products	1
IEQ Credit 5	Indoor Chemical and Pollutant Source Control	1
IEQ Credit 6.1	Controllability of Systems – Lights	1
IEQ Credit 6.2	Controllability of Systems – Thermal Comfort	1
IEQ Credit 7.1	Thermal Comfort – Design	1
IEQ Credit 8.1	Daylight and Views – Daylight	1
IEQ Credit 8.2	Daylight and Views – Views	1

Table 1.2. LEED Credits and Associated Points (cont.)

Innovation in Design (ID)		**6 Points**
ID Credit 1	Innovation in Design	1 to 5
ID Credit 2	LEED Accredited Professional	1
Regional Priority (RP)		**4 Points**
RP Credit 1	Regional Priority	1 to 4

What is not always clear during these discussions is the total impact of one choice, based on either the ease of obtaining the credit or cost, on the entire project or other credits. Many credits can have a positive or negative impact on other credits and budget. To illustrate, consider the information provided in the studies previously mentioned. Based on that research, it can be seen that the Cx process does provide energy savings and that many building owners have not realized the investment made in a LEED certified building with respect to energy savings. The question of whether to attempt the enhanced Cx credits must be discussed in new-building construction and based on findings of the research many owners would decline spending the money. What is not fully understood is what this means to the other credits and life-cycle cost if enhanced Cx is not pursued.

Within the Energy and Atmosphere category is EA Prerequisite 1, Fundamental Commissioning of Building Energy Systems. Commissioning affects numerous LEED credits and a total of 48% of the possible base points. These credits and points are shown in Table 1.3. A significant portion of the construction budget will be allocated to these areas.

Table 1.3 Credits and Points affected by the Cx Process [USGBC, 2009]

Credit	Title	Available Points
SS Credit 8	Light Pollution Reduction	1
WE Credit 1	Water Efficient Landscaping	2 to 4
WE Credit 2	Innovative Wastewater Technologies	2
WE Credit 3	Water Use Reduction	2 to 4
EA Credit 1	Optimize Energy Performance	1 to 19
EA Credit 2	On-Site Renewable Energy	1 to 7
EA Credit 5	Measurement and Verification	3
IEQ Prerequisite 1	Minimum Indoor Air Quality Performance	--------
IEQ Credit 1	Outdoor Air Delivery Monitoring	1
IEQ Credit 2	Increased Ventilation	1
IEQ Credit 5	Indoor Chemical and Pollutant Source Control	1
IEQ Credit 6	Controllability of Systems	2
IEQ Credit 7	Thermal Comfort	2
	Total Possible Points	**48**

A CxA is a technical representative of the owner, and in most cases not an employee of the owner but rather a contracted third-party consulting firm. For LEED projects, the CxA is responsible for ensuring the systems within the EA and IEQ credit categories are designed, constructed, and operating as specified, along with developing the Cx plan, Cx requirements, and completing the Cx report. “Commissioning process activities must be completed for the following energy-related systems, at a minimum:

- Heating, ventilating, air-conditioning and refrigeration (HVAC&R) systems (mechanical and passive) and associated controls,
- Lighting and daylighting controls,
- Domestic hot water systems, and
- Renewable energy systems (e.g. wind, solar).” [USGBC, 2009]

Those systems will be commissioned for every LEED project under the EA prerequisite 1.

The CxA has the responsibility of ensuring the owner's definition of value is realized. When the systems are designed and installed as specified, as well as operating as intended, commissioning optimizes the energy efficiency of those systems. "Properly executed commissioning can substantially reduce costs for maintenance, repairs, and resource consumption, and higher indoor environmental quality can enhance occupants' productivity." [USGBC, 2009]

EA Credit 3, Enhanced Commissioning, is worth two additional points; it places additional responsibility and requirements on the CxA, but not without additional cost to the owner. Cx processes will be expanded to include:

- Documenting the commissioning review process
- Reviewing contractor submittals
- Developing the systems manual
- Verifying the training of operations personnel
- Reviewing building operation after final acceptance
  [USGBC, 2009]

1.6. DESIGN-BID-BUILD

There are multiple project delivery methods for building construction. The focus of the proposed methodology in this research will be on the design-bid-build (D/B/B) approach. This is the traditional method and most widely used. The D/B/B approach has distinct phases which include the design phase, bidding phase, and construction phase.

The owner typically contracts with an architect, who then retains any necessary engineering teams, to produce the design and complete construction documents. The construction documents can then be put out for construction bids. The general contractor winning the bid is also contracted by the owner to construct the building.

The D/B/B is in contrast with another popular project delivery method, Design-Build (D/B). With this method the owner would contract with a design-build contractor who would take responsibility for contracting with the architect and engineers as well as all construction responsibilities. This method places all project fault responsibility on the D/B contractor.

1.7. OBSTACLES

There are several possible obstacles for the proposed methodology. The greatest is likely the additional time that will be required of the Cx process to construct the QFD four-phase model. A major part of the Cx workload would be shifted to the pre-design phase while assisting the owner with the OPR development and investigating the alignment of the BoD with the OPR. Significant time would then be required to identify the system, sub-system, and components required to populate the design-phase of the model. With this additional time would come additional cost. It is likely that the CxA would need additional personnel to handle the upfront work.

An obstacle that may be as significant as the time factor for the CxA is the amount of owner time and support that will be required in the early phases. The goal of the Cx process and this proposed methodology is to provide the owner with what is expected at project end; however, without the owner’s input and support this is not likely to be as successful. The owner may feel their time should not be spent since they are paying the design team and CxA to handle it for them. It may take some salesmanship on the part of the CxA to convince the owner that their early support will pay dividends later in the project.

The methodology may be opposed by many Cx practitioners who feel they already have solid methods in place for delivering the process. With that, it may be difficult to get the Cx practitioners to use the methodology so further research can be conducted.

As the methodology is designed to bridge the gaps of the current Cx activities the general contractor and subcontractors should not see any additional effort and should not present an obstacle to the methodology.

1.8. BENEFITS OF CX AND LEED

Cx and LEED certification can benefit any building project and provide additional value to the owner if both processes are administered properly. LEED certification can improve building efficiency if the proper credits related to energy efficiency are achieved. This will only happen if the owner has determined that (1) a particular level of efficiency is the goal, (2) the budget will allow it, and (3) the design and construction follow through on those requirements. If the LEED credits to be achieved are identified early, preferably in pre-design, and are determined to not conflict with each other and jeopardize the certification level, Cx can improve the opportunity to achieve the desired LEED certification level and expected efficiencies.

A form of Cx is required as a prerequisite in the LEED certification system and enhanced Cx is an optional credit which may provide an additional two points toward certification; however, neither of these can ensure the owner will receive additional value. The owner will specify what level of value is to be obtained through the OPR. If the owner is pursuing LEED and Cx, the project will certainly have an improved opportunity to achieve the required value. Both LEED certification and Cx have obstacles, but these obstacles can be overcome by utilizing the proposed QFD four-phase model and the LEED HOQ methodologies which link the design and construction activities and verify that each meets the OPR by taking into consideration the design impacts of the LEED credits. With each activity linked, any late design proposals can also be traced back to the OPR and LEED credits to understand how the proposed design may impact the other OPR and LEED credits.

2. REVIEW OF RELEVANT LITERATURE

2.1. INTRODUCTION

> "Design is a team effort, but how do marketing and engineering talk to each other?" [Hauser and Clausing, 1988]

The question of how to communicate is critical in product development and manufacturing. Capturing what a customer desires from a product is the first obstacle, but once those desires are known they must get transferred to the engineering team so the product parameters can be developed. This is not an easy task. Quality function deployment is a system used in product development and manufacturing. QFD takes the customer needs and benefits or voice of the customer (VOC) and provides a prioritized list of product features and service characteristics to the engineering team. The engineering team can then create with those features and characteristics in mind. The entire QFD process will translate the voice of the customer to engineering, manufacturing, and service.

The design and construction of a new building follows a similar process to product development and manufacturing and similar communication issues are present. As with product development, gathering the customer's desires or owner's project requirements in a construction project has obstacles. Once the owner's project requirements are known, they must be transferred to the design team in an understandable format, so each of the requirements can be effectively addressed by the design. Though the design team has responsibility to provide a design that meets the OPR, the owner will often contract a commissioning authority to apply a quality process to the project with the goal of ensuring that the design and construction meet the OPR. The current commissioning methods have gaps that need to be filled. There is a need for (1) improved communication among the responsible teams of each project phase, (2) the transfer of knowledge from phase to phase through documentation, (3) a method for tracing proposed design changes back through the phases to understand the impact of the change to the project whole, and (4) traceability of issues back through the phases to identify the root cause for continuous improvement.

QFD can fill the gaps and needs for improvement in the Cx process just as it has for product development and manufacturing. This research proposes a new methodology for commissioning new-building construction which utilizes the QFD four-phase model to the entire Cx process. This research will utilize the existing Cx activities as defined in ASHRAE Guideline 0-2005: The Commissioning Process, and effectively bridge these activities using the four-phase model to improve communication and knowledge transfer between phases and to provide a means of tracing proposed design changes and issues back through the phases.

Some specific modifications to the model will be made to accomplish this. First, a roof will be added to the OPR as a second correlation matrix used to identify conflicting OPR. This will be particularly useful for LEED projects. Now as the owner and design team try to bring the OPR and BoD into alignment each party can identify how proposed changes will affect either document. This will allow greater opportunity to keep the OPR in true alignment with the owner's vision. Second is the addition of a roof on the design phase HOQ. This will be used to identify potential coordination problems among equipment installations that may occur during construction.

LEED certification creates additional difficulties when translating the OPR to the design team. Many LEED credits conflict with each other and can have a negative impact on opportunities for achieving other credits. These impacts must be understood when expressing to the design team what LEED certification level and credits to attempt.

Previous literature provided a methodology for assisting the owner in determining the optimal LEED certification level and which credits to attempt based on cost analysis. This research will develop a methodology to set up the HOQ for use in capturing the LEED scoring system and identifying the design impacts among the LEED credits. The purpose is to quickly identify negative impacts on the overall LEED certification level and possible value to the owner if any additional LEED credits are proposed late in design.

The review of relevant literature covers the areas of commissioning, LEED, QFD in construction, and QFD in commissioning. As LEED requires Cx there is some overlap between the two areas.

2.2. COMMISSIONING

Altwies [2002] explains the requirements of commissioning within the LEED rating system. Two levels of commissioning are possible, one as a prerequisite that must be accomplished by every LEED-certified project, and a second level, enhanced commissioning, which can provide additional LEED points if accomplished. Altwies also details the intent of each commissioning level and the requirements for achievement.

Akashi et al. [2004] created a glossary of commissioning terms and definitions for international use. The work was produced for the International Energy Agency (IEA)/Energy Conservation in Building and Community Systems (ECBCS). The glossary covers terms for four types of commissioning; initial commissioning, re-commissioning, retro-commissioning, and on-going commissioning. Definitions of these four commissioning types are also included.

Hamilton [2006] answered the question of why commissioning is important with a simple example of HVAC equipment sizing. Explaining that because of standard materials and equipment sizing within the industry the designers purposely design ducts and equipment larger than is actually necessary but provide means, such as balancing dampers, to provide adjustability to the system which can account for the oversized equipment. The commissioning effort will ensure the system has been balanced properly so the owner will know the system is running at its highest efficiency.

Tseng [2005] explains issues the commissioning industry was experiencing at the time. These include additional fees required for the commissioning services, concern that the quality of commissioning was deteriorating, untrained staff, too few commissioning professionals, and a shortage of experience. The additional fees were forcing Cx providers and owners to limit the scope of the Cx service to keep fees at a minimum, which, in turn, reduced the effectiveness of the service. This led to concerns that the quality of Cx was deteriorating. It is likely that the quality of what was provided was not deteriorating, but rather owners were not receiving all that they should. With the rapidly growing industry the need for qualified practitioners was also in demand and supply was not keeping up with that demand.

Tseng also explains three key attributes of commissioning; Cx is a process, meaning there is a flow of tasks with each supporting the previous, it is about quality, and finally, the focus is on performance. With a focus on building performance, Tseng discusses the interrelated nature of each building system into one complex system. The interdependence of these systems needs to be understood by the Cx team because one deficiency can affect the entire building. If the deficiencies are remedied the owner might expect to see improvements in the following areas: occupant comfort and productivity, energy and operating cost, indoor environmental quality, system and equipment reliability, building operation and maintenance, worker productivity, and market resale value.

To improve the quality of LEED projects, Tseng expresses that any LEED credits to be pursued for a project must be integrated into the owner's project requirements to allow the design team an early opportunity to incorporate LEED goals into a design that will meet the OPR.

A paper titled *Simplifying the Commissioning Process*, originally submitted in the *Proceedings of the World Energy Engineering Congress 2006*, was published in three parts in *Energy Engineering* [Doty, 2007a,b,c]. The three parts are: Part 1 - What is Commissioning?, Part 2 – Tips for Applying Commissioning, and Part 3 – Quantifying the Commissioning Benefits.

Part 1 – What is Commissioning? explains what the commissioning process is and why it is important to the project owner. The explanation is presented in a format which is directed towards helping the CxA answer typical questions an owner might ask about Cx. The key points made include (1) owner support of the process is essential for success; (2) Cx protects the owner's interest at each stage; and (3) Cx fills gaps left from cost pressures in the design and construction methods. The core concepts of Cx are (1) identify the intent of the work and how the goals will be met; (2) early detection and intervention; (3) operations staff training; prepare maintenance activities for sustainability; and (4) quantify the Cx benefits. The goal is to detect issues early using sampling techniques with a primary purpose of correcting systemic problems which would become long-term and costly.

Doty makes it clear that the CxA must be able to "change hats" between the design and construction phases when the focus moves from reviewing the design for quality and alignment with the OPR to construction where the design must be implemented and defended. To assist any new Cx in understanding what is involved with each of the project disciplines a series of questions are presented. These questions can be useful not only for the CxA but for any of the disciplines to have a chance to put on the shoes of the other. If each discipline knows what the others require the deliverables to each successive phase can be improved. This is described as an exercise in empathy.

The final sections of Part 1 discuss typical aspects that the CxA will be looking for during each phase of design and construction. Emphasis is placed on early detection of systemic issues and focuses on quality deliverables to the future phases, with many of the deliverables being documentation to the operations and maintenance staff.

Part 2 – Tips for Applying Commissioning begins with tips for what to look for in a CxA. The CxA is described as a partner to the owner. Some basic personality focused attributes suggested include strong communication skills, a cooperative nature, willingness to compromise and listen, positive attitude, and pays attention. A list of technical experience required is provided. Some of which, but not limited to, are five years of experience in Cx work, HVAC and controls design, system analysis and monitoring, and indoor air quality knowledge. Doty also points out that this experience may require a team rather than one individual. The CxA or team will act as a third-party representative of the owner with no other connection to the architect/engineering or construction contractor.

The success of the Cx effort requires that the owner provides continuous support to the CxA throughout the project. This will help align the Cx activities with the design and construction timelines. Prompt and accurate communication is required. Additional tips to assist the owner in determining the level of Cx required and the expected fees are offered.

Doty also explains what Cx can and can not do for the owner. Cx can protect the owner's investment, reduce risks, provide another set of eyes on the project, improve quality, provide early detection of systemic and coordination issues, improves coordination among teams, identifies and protects the OPR, reduces change orders and requests for information and therefore construction delays, smoothes the turnover of the running building, and reduces warranty issues. Cx does not provide the above benefits automatically if the Cx fee is paid, replace the designer's and general contractor's quality control efforts, or provide 100 percent review and testing of drawings and systems. The paper closes with tips for the Cx to use for overcoming resistance. Much of this is focused on communication methods used to avoid demoralizing the design and construction teams during reviews and site visits if deficiencies are identified.

Part 3 – Quantifying Commissioning Benefits is focused on the value of the Cx process. Methods for identifying commissioning savings are presented with an emphasis of using business investment terms for improved communication to the owner. Major sources of savings are identified as first cost avoidance, future repair or replacement cost(s) of a defect, and reduced maintenance and energy cost(s). These savings are typically realized by identifying and protecting (from proposed changes) the OPR and early detection and correction of issues. Examples of design and construction issues that might be identified and corrected are presented along with the basis of savings. Additional examples for those issues which are more difficult to quantify the savings, even when the benefits are obvious, are also presented.

Wilkinson [2012] describes the Cx provisions provided within the new International Green Construction Code (IgCC). The IgCC was implemented in the Spring of 2012 and is the first international code for high-performance buildings. IgCC requires Cx and attempts to define basic and advanced facets of Cx. Cx is a quality-assurance process primarily, but is also the first step in preventive maintenance. The IgCC lacks the provision that the CxA provide a third-party review of the bid documents, but does require Cx specifications be added to the bid package. The CxA will provide a design review against the OPR and also a submittal review during construction. This constant verification builds quality into the project. IgCC also expresses the requirements of the systems manual, which should include systems narrative, sequences of operations, control diagrams, and the set points recorded during functional testing. Wilkinson explains that this systems manual requirement is not sufficient and should also include the building description, strategies for operations and control, maintenance procedures, and any metering locations. Finally, the need to better define an issues log required to keep the team informed of project progress, with a minimum of weekly distribution.

Enke [2010] expresses the need for a holistic approach to Cx. Research suggests that 25% of buildings certified under LEED do not demonstrate the energy savings predicted by their designs. Several potential reasons are provided, including not having a well-defined OPR, uncoordinated design, poor construction, and improper operation and maintenance. The proposed holistic approach begins with full implementation of ASHRAE Guideline 0-2005 and places additional emphasis on OPR and BoD development, as well as the review(s) to verify these two align. Enke points out that the BoD requirement is often overlooked in contracts with the A/E and without this critical information it is nearly impossible to know the OPR has been met. High performance buildings have two key elements: maintainability and measurability. This places emphasis on ensuring that all equipment requiring maintenance has the ability to be maintained within the design, meaning if it requires access that it has access or it may not be maintained as needed.

The ability to measure the system functions is critical to understanding when the system is not performing properly. Provisions for maintainability and measurability need to be addressed in the OPR and BoD. The design phase Cx will carry the long-term measures required through the entire process well into the operations and maintenance phase. Enke states that in his experience the design phase Cx provides "…clear and concise construction documents that typically reduce project risk significantly and contingency used for change orders, tighter contract bids, a more maintainable facility, and the systems and procedures necessary to achieve and maintain facility performance."

If the building is well-commissioned the operator can focus on preventive maintenance rather than eliminating complaints.

Ellis [2008] describes Cx as a multi-stage process which does not end at building occupancy. Verifying the building systems are performing as they were designed and expected by the OPR is only the first step in long-term success. Once the building is successfully commissioned, and complete and accurate documentation is provided, as well as proper systems training for the O&M staff, the building can go to the next level of performance. Cx is performed on a building that is not occupied and to the originally anticipated design conditions. These conditions will never happen again once the building is occupied. The owner being provided with all of the final products mentioned provides a baseline for continuous improvement. The O&M staff can now work towards optimizing the systems.

Ellis [2009a] expresses that simply commissioning a building does not ensure that all of the owner's energy goals will be met. Scenarios which can cause this phenomenon are presented. One example involves a submittal review process in which a design team member approved a submittal and was either not aware or did not remember aspects of the design that would require rejecting the product submitted. A requisite communications interface was sited as a core issue for the incorrect approval. A diligent CxA can be helpful in identifying these issues.

Ellis [2009b] discusses the relationship between commissioning and energy conservation, stating that one does not necessarily guarantee the other. The owner must express their energy conservation goals in a quantifiable measure for the design team and CxA to utilize. Even with this many owners will not expend the project funds for energy modeling and the design team is forced to choose energy efficient equipment based on experience rather than a proven model. Often this does not produce the expected results. LEED projects require a specified energy conservation measure above an industry baseline and energy modeling. This provides a solid base for design and verification. Ellis points out that energy consumption is out of the design and construction teams' hands after occupancy. Much depends on the occupancy and the skills, tools, and available time of the O&M staff to maintain proper system operations.

Ellis [2009c] describes a noticed trend of design documents being issued for bid prior to design being complete. It is explained that no design is perfect and the design and construction process has methods in place for dealing with the imperfections, but imperfect and incomplete are completely different issues. The main reasons for this occurrence include the design team's belief that some incomplete designs can be finished later without affecting progress or budget, the owner's inability to express project requirements, and to not delay the construction start date. Cx can identify the incomplete design aspects and clearly state to the owner what appears to be missing and the impact or risks involved with not waiting for a complete design prior to bidding. The goal is full transparency for all involved.

Ellis [2011] provides insight into problems that can occur at the end of construction if the owner's expectations are not met. Specifically looking at the expectations of the operations and maintenance staff when they were involved early in design and then their expectations are not realized in the final design and construction. Some O&M staff have actually stated that as soon as they take possession of the building they intend on changing how the building operates. Most often this involves the sequence of operations and system controls. The question asked of the CxA is should these changes be made prior to the functional testing and final Cx or complete the process per design and allow the O&M staff to make changes later. It is preferred to have this resolved prior to turnover and is a strong justification for review during the design phase.

Barber [2008] explains the necessary evil of three key commissioning documents, the OPR, BoD, and systems manual (SM). These documents are often seen as expensive and not necessary; therefore, these invaluable tools are under used. The documents facilitate effective Cx and also provide critical information to the O&M staff. Documenting the OPR has many valuable attributes, one of which is to minimize conflicting owner directives. Design teams often receive different priorities and expectations from groups within the owner's organization. The fully developed OPR requires the different groups to come to agreement on common functional requirements. The BoD is the confirmation that the OPR is understood and provides a description of how the requirements will be met with the design. The SM is likely the least understood and possibly the most important document. The SM focuses on the system operations and is intended to provide the functional intent, BoD, configuration, sequences of operation, and operating characteristics of the as-built systems. This is the document that will guide the O&M staff towards long-term sustainability.

Xaio and Wang [2009] investigated the need and progress of automatic commissioning of HVAC systems as a means for ongoing or continuous Cx. An overview of traditional Cx is provided to illustrate the labor, time, and cost requirements of a non-automated process. Currently the manual method of Cx dominates the industry but research in automated methods is increasing. For building systems to be properly commissioned systematic step-by-step guidelines are necessary. Many guidelines have been produced, but the manual methods are time-consuming. Automatic Cx can provide a better means for ongoing Cx. Automatic Cx cannot be realized without technology. Building automation systems (BAS) are being installed regularly as a means to monitor and control building systems, which therefore can reduce energy usage. The BAS can be used for data collection. A computer-based information management system should be used to maintain all system documentation traditionally found in varying formats. Functional performance tests can be automated to provide monitoring and feedback. Performance and fault diagnostics are also being investigated. This will provide direction to the O&M staff if the system degrades.

Ye and Rahman [2011] explain the benefits and necessity of Cx and present reasons why buildings do not perform as intended. Of the reasons, the research focused on faulty construction and loss of information between the project phases. Loss of information is caused by inconsistencies between the parties at phase changes and can result in project delays, poor quality, and increased cost. They suggest a need for research which looks at the project from the end backwards, meaning from the occupancy phase upstream to construction and beyond. It is expressed that a high level of interaction between all parties is essential through the life-cycle of the project. It is also suggested that this backwards looking approach is similar to the 'V-model' in systems engineering.

Nicholson and Molenaar [2000] explain the commissioning process, with key points being that the process should start in pre-design to reduce costs associated with late changes and the process requires much documentation throughout. It is pointed out that there is no clear method for documenting the process and no method for comparing the cost versus savings ratio. Communication and documentation between the owner and designers is essential for Cx to work and the CxA facilitates both. Numerous benefits of Cx are listed and the cost of the process is typically justified by the energy savings expected by a more efficiently operating building. Finally, Cx stems from the fact that new modern buildings contain many complex systems which require specialized expertise to verify they are all functioning properly together. With the need for these buildings to be delivered faster and cheaper the life-cycle analysis is frequently overlooked.

Driver [2010] investigated the fault detection differences between ongoing and retroactive commissioning. The primary purpose of the study was to determine the differences, or fault detection capabilities of each Cx method, and from that develop a method for expressing the energy savings associated with each as a return on investment (ROI) that owners can understand. Driver expressed that commissioning could be a much larger industry if CxAs were able to sell the process better. Return on investment (ROI) would provide a solid selling point for any CxA to use while discussing options with owners.

Turkaslan [2006] explains the building commissioning process for new buildings and the definitions of the three other common Cx types, which include re-commissioning, retro-commissioning, and continuous commissioning. A new method called embedded commissioning is proposed. The goal is to provide a computational method of Cx. Software applications offered for Cx are evaluated. (Performance And Continuous Re-Commissioning Analysis Tool (PACRAT) is used to monitor existing building performance and Whole Building Diagnostician (WBD) is used to monitor energy usage. Both are used on completed buildings after occupancy. Turkaslan automated the verification of performance criteria and performance measurement. For the model to be expanded there is a need for continuous data through all phases, standardized processes that all CxAs will use, and computational support to manage Cx information.

Shakoorian [2006] performed a performance assessment of the building commissioning process to determine which method of delivery would provide the best results. The delivery options were owner-led or designer-led. Each method was evaluated for design/bid/build and design/build construction options. Five major performance factors that were identified for the research are communication, validation, collaboration, integration, and integrity. A panel of experts was surveyed using a Delphi study. The owner-led option rated highest in four of the five measures. The study pointed out that the communication performance measure was very poor for each delivery method. The cause of the low communication scores was investigated. Causes of communication breakdown are explained and the communication interdependencies for the Cx process are mapped. Shakoorian suggests a more rigorous investigation into the communication issues to improve communication within Cx.

2.3. LEED

Castro-Lacouture et al. [2009a] designed an optimization model for selecting building materials based on the LEED rating system. The model allows user input of material and material properties, available budget (for materials), LEED requirements, material cost, and design parameters. With these inputs the model will determine the materials to use and the quantity to use while maximizing the LEED points accomplished and minimizing cost within budget. Sensitivity analysis will allow variations in maximizing LEED points with regard to budget, inflationary impact based on a percent increase in material cost, and material availability issues. Information regarding the model is available in Castro-Lacouture et al. [2009b]. Castro-Lacouture et al. explain that the model could be expanded to include other portions of the LEED rating system.

Bayraktar and Owens [2010] developed a LEED implementation guide to be used by construction practitioners. The guide utilized data collected from survey questionnaires answered by architects, engineers, commissioning authorities, general contractors, construction managers, and facilities managers who all held LEED AP credentials. The implementation guide offers a step-by-step procedure for start-to-finish development and implementation of LEED-certified new construction projects. The guide is broken down into phases, the first of which is “Program.” The sub-phases of “Program” are Owner’s Project Requirements, Scope Verification and Design Charette. Each sub-phase is designed to aid the team in developing the OPR, determining the LEED certification requirements and generating a LEED action plan. The purpose of the LEED action plan is to verify all prerequisites are, or will be, achieved and to provide a comparison of LEED credits and cost so design alternatives can be developed. The “Design Phase” includes guidance for developing and executing the commissioning plan.

Lapinski et al. [2006] evaluated a LEED-certified construction project conducted by Toyota. The purpose of the evaluation was to identify critical activities and capabilities utilized by Toyota to bring the project to realization at a cost equal to the cost of a conventional, non-LEED, building of similar size. Toyota’s office complex, built in southern California, attained LEED Gold certification. The industry average to deliver a LEED-certified building came at a cost premium of 5-10%. The primary focus of Toyota was to provide value in terms of the customer. If the customer's requirements were met then value had been added. By mapping the delivery process it was determined that Toyota's Production System and lean principles, used for designing the building, did not necessarily reduce waste, but key aspects of success were identified. The top five are (1) early evaluation and adoption of environmental of environmental considerations, (2) aligning the project budgets with sustainable goals, (3) sustainable capabilities, (4) early selection of team members with sustainable experience, and (5) alignment of team members goals with project goals. An early decision to seek sustainable design and incorporation of this goal into the entire process is critical to LEED success without incurring additional cost.

Enche-Pommer and Horman [2009] focused their research on green building within the healthcare industry and the opportunity for improvement within the built environment. Building "green" can lower operating costs, energy consumption, and reduce water use. The examination of the project delivery process, greening strategies and lean principles included, but was not limited to, transparency in relation to green outcomes, the owner's commitment, early adoption of "green," and the commissioning process. Four cases were evaluated and compared using process mapping analysis to understand the delivery process. Key outcomes of the study were that owner commitment to sustainability leads to better project planning, early decisions to go green allow for a more well defined scope, and that the commitment to Cx needs to be early with a on the specification phase.

2.4. QFD IN THE CONSTRUCTION INDUSTRY

Ahmed et al. [2003] investigated the application of Quality Function Deployment (QFD) to the planning and design stage for civil engineering projects. Due to the complexity and extended timelines required for civil engineering capital projects the study utilized two existing projects to test the use of QFD. Both projects had progressed through the Project Requirement and Feasibility Study phases and were now in the Preliminary Design phase, each by the traditional process without the use of QFD. As such, the process flow of the QFD model was modified for use of existing data. Modifications are (1) the only source of initial client's objectives is the data in the Project Requirement phase, (2) instead of using the output from a House of Quality (HOQ) as an input for the corresponding phase to produce the phase deliverables, data from the phase deliverables are input into the "how" section of the corresponding HOQ, (3) there is no looping of the process due to changes. Two levels of HOQ are generated for the back-analysis and a logic test is used to verify if the following are accomplished, (1) the client's initial requirements are fully addressed, (2) all output is traceable from its origin and can be checked for any distortion throughout the project planning process, (3) each target value is logical by itself. After conducting this back-analysis on the two projects the verification led Ahmed et al. to believe the QFD model was valid and could be used to enhance the project planning process.

Mallon and Mulligan [1993] present quality function deployment as a means for meeting the customers' requirements in construction projects. The QFD methodology can be used to prioritize conflicting needs and provide a tool for making more accurate decisions. This in turn will allow the design team to create while aligning with the customers' needs and reduce future changes. Mallon and Mulligan define the customer and explain how QFD should be utilized throughout the project to meet the needs of changing customers. Each is a customer of the previous and each must consider the next. An example of applying QFD to construction is presented using a minor renovation of a computer workroom as an example. Initial needs of the customer are determined and are prioritized by importance to the customer. These needs are then compared to competitor's workrooms and sales points for each are assigned. Finally, this data is entered into matrices, weighted and evaluated to determine how to accomplish each need. Conclusion of the study was the accuracy of the design concepts can be seen immediately.

Lee and Arditi [2006] developed a methodology for applying QFD as a qualification system for ranking/selecting Design/Build firms for construction projects. As part of the development of the methodology several tables of information were created and presented. These tables include the components and definitions for Service Quality Factors, Corporate Quality Management System, Project Quality Management System, Building Quality Factors, and Building Performance Factors. Data for the study was gathered using survey questionnaires. One such questionnaire was administered to 50 architecture students and was used to collect data with regard to building quality factors and building performance factors. Data from this survey is presented in a matrix and used to demonstrate how to determine the maximum level of performance in the area of question.

Eldin and Hikle [2003] conducted a pilot study to determine the effectiveness of using QFD in construction projects. The study focused on the feasibility of QFD being used as a project management tool for the early engineering designs of a large classroom. This would include identifying the customers' needs, organization of the customers' requirements, building the House of Quality, and investigating the preliminary designs. The paper explains the QFD process and provides step-by-step instructions for implementation and the building of the HOQ. The aspects of QFD that are explained include QFD team, QFD tools, focus groups (further broken down to: selection of participants, session moderator, session rules, and session questionnaires), affinity diagram, tree diagram, and HOQ. The conclusions are that QFD improved communication and the early critical design decisions. Difficulties experienced by the design team during the process included refining the WHAT and HOW to something manageable, agreeing on the evaluation ratings, and determining which items were critical and therefore should be included in the HOQ. Eldin and Hikle also offered that QFD should be successful on larger construction projects and the process can minimize construction delays.

2.5. QFD IN COMMISSIONING

No literature for the use of QFD in the Cx industry was identified.

2.6. SUMMARY

The primary objective of this research is to develop a methodology that will bridge the gaps in the Cx process. In this research, an integrative methodology is developed which utilizes the QFD four-phase model to effectively bridge the gaps in the

Cx process. Little research has been conducted on the use of QFD in construction and no research currently exists in the literature for using QFD in the Cx process.

From the previous research and literature some common themes appear. First, the Cx process is most effective if it begins in the pre-design phase. This provides an opportunity for the CxA to assist with the OPR development. The OPR is considered critical to a smooth project. The Cx goal is to ensure the OPR is met by design and construction and that all systems are functioning as expected. Energy savings is a selling point for the process but the savings are not always achieved. This is often due to the O&M staff not receiving the required training and documentation at building turnover.

The focus of the literature appears to be at the front and back ends of the project. A common complaint is poor communication across all phases of the project. A standard methodology for connecting each of the Cx activities within the process back to the OPR is needed and can be provided by QFD.

The proposed methodology will provide (1) improved communication among the responsible teams of each project phase, (2) the transfer of knowledge from phase to phase through documentation, (3) a method for tracing proposed design changes back through the phases to understand the impact of the change to the project whole, and (4) to trace issues back through the phases to identify the root cause for continuous improvement.

No research was found which provides a means to identify the design impacts among the credits of the LEED certification program. There was also no literature found utilizing the HOQ in any manner in the LEED program. The methodology for developing the LEED HOQ is a completely new approach to managing the LEED scoring system from an owner or designer perspective.

3. QFD AND THE HOQ

3.1. INTRODUCTION

In the case of a traditional design/bid/build construction process there are distinct phases in the building lifecycle. During each phase certain groups have responsibility for deliverables and those are generally structured as follows: Pre-design phase – owner and architect (and often the engineers); Design phase – architect and engineers with owner feedback at design reviews; Construction phase – general and sub-contractors with oversight by the owner's construction manager (CM); and Operations & Maintenance phase – the maintenance team assigned to the building. Typically the owner's project manager (PM) will be involved from pre-design through occupancy; however, the PM may have minimal involvement other than schedule and budget concerns once construction begins and the CM is involved. It is unlikely the PM will be involved with the project after occupancy, which leaves sole responsibility of the O&M phase to the O&M staff. If a building is to be sustainable, project emphasis must continue beyond construction into the O&M phase of the building's lifecycle. This becomes difficult when project oversight is relinquished at turnover.

Cx is an owner initiated process that is expected to bridge all phases, including the O&M phase, by verifying that D&C meets the OPR. As each team hands off to the next, the CxA will confirm that the preceding team is providing the following team with the necessary information to complete their responsibilities in a manner that meets the OPR. This begins with the owner, meaning the OPR needs to be as detailed and complete as possible so the designers understand what they are to provide.

Next, the designers must produce construction documents that are adequate for the contractor to build what is designed. The contractor must provide submittals for the materials and equipment, which confirm the selections meet the drawings and specifications. Then the construction must be completed as specified in the construction documents.

Finally, the training and documentation provided to the O&M staff must provide a clear picture of what they will be operating, how it was designed to operate, why it was designed that way, and how it should be operated and maintained. Without the O&M staff having this knowledge it is unlikely the building will be sustainable. The O&M staff is left with what is turned over to them when construction is complete. If the process of linking all activities back to the OPR fails in any previous phase it is unlikely they will be able to operate the building as expected.

As there is a handoff of responsibilities at each phase, the CxA is now given responsibility to ensure and verify that each handoff is sufficient to meet the OPR. Though building commissioning is not a new concept and is the focus of much work by Cx organizations and practitioners, there are still weaknesses in the process that can be addressed.

As a preliminary step of the research, a formal request for qualifications (RFQ) for Cx services was sent to several Cx consulting firms. The purpose was to identify potential firms for future needs. Thirteen formal responses were received. One key question asked within the RFQ was: “How will the basis of design be verified with regard to the owner’s project requirements?” None responded with any type of process for how they would accomplish this, simply that it would be done. An assumption made was that they either did not have a formal method or they did not wish to disclose. Regardless, there is no published methodology for this process and firms or persons entering the field are left to figure it out as they go.

This is seen as a weakness in the process and serves as a key motivation for this research. The reason for contracting a third-party representative, the CxA, is for the owner to get some hard documentation that all of the verification is being accomplished and is sufficient. Without some type of method used by the CxA, the owner is left with the same uncertainty as would be if they simply took the word of the Architect/Engineer (A/E) team and contractors. And the question remains – "when this project is completed, will I get all that I asked for and am expecting?"

3.2. QFD

QFD has traditionally been used by companies for product development and manufacturing to determine the best design options, manufacturing processes, costs, and level of quality among others. Hauser and Clausing [1988] asked, "Design is a team effort, but how do marketing and engineering talk to each other?" This is a question that many in the manufacturing industry might answer, "not well." A similar question could be asked within the construction industry, "Design is a team effort, but how does the owner and A/E team talk to each other?" Many in the construction industry might answer the same way, "not well." This is no fault of either party as they typically do not speak the same language. Many owners do not understand the technical jargon of architects and engineers. With product development, marketing is typically adept at determining what the customer might want in a product. With building design, the architect typically has the first contact with the owner. Most architects are proficient with the programming effort required to determine what the building should be; however, much can be missed when it comes to the building systems. Hauser and Clausing [1998] illustrate how quality function deployment and the House of Quality can provide a solid method of communication between marketing and engineering, and follows downstream to the manufacturing and quality assurance activities. A similar method using the HOQ can be adapted to the D&C process.

QFD has been proven within product development and manufacturing but little work has been done to move QFD to the construction industry. Two papers have addressed the use of QFD and the HOQ in the new-building construction industry. Mallon and Mulligan [1993] present QFD as a means for meeting the customers' requirements in construction projects. They illustrate how the QFD methodology can be used to prioritize conflicting needs and provide a tool for making more accurate decisions. This will allow the design team to be creative with their design concepts, while aligning with the customers' needs and reduce future changes. Eldin and Hikle [2003] conducted a pilot study, using the design of a classroom as a case, to determine the effectiveness of using QFD as a means of developing conceptual designs in the preliminary phase of construction projects. This included identifying the customers' needs, organization of the customers' requirements, building the HOQ, and investigating the preliminary designs. The study concluded that QFD provided a means to keep the project moving forward, could eliminate the need to backtrack for design corrections, and should be successful on larger construction projects.

The objective here is not to regenerate how QFD could be used by a design team within the construction industry as a means to improve their final product (design only), rather to provide a new methodology using the QFD as a means for the CxA to link each of the D&C phases, to oversee the entire quality process, and ensure the OPR are met.

To continue the discussion regarding how QFD can assist the CxA a few key terms used in Cx need to be understood. The terms as defined in ASHRAE Guideline 0-2005 are:

- Commissioning Process**:** "A quality-focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all of its systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the Owner's Project Requirements." [ASHRAE, 2005]
- Owner's Project Requirements: "A written document that details the functional requirements of a project and the expectations of how it will be used and operated. These include project goals, measureable performance criteria, cost considerations, benchmarks, success criteria, and supporting information." [ASHRAE, 2005]
- Basis of Design (BoD): "A document that records the concepts, calculations, decisions, and product selections used to meet the Owner's Project Requirements and to satisfy applicable regulatory requirements, standards, and guidelines. The document includes both narrative descriptions and lists of individual items that support the design process." [ASHRAE, 2005]

The OPR is considered a living document and is subject to change throughout the design and build. Changes may occur at any time during the project and any changes must be approved by the owner and be updated by the CxA. The BoD is also a living document and will very likely change as the design progresses and should also be updated as needed.

The Cx process consists of several steps that span the design, construction, and operations and maintenance phases. These steps include, but are not limited to: *Pre-Design Phase:* develop owner's project requirements, develop the Cx plan; *Design Phase:* verify the basis of design meets the OPR, develop construction checklists, develop Cx specifications, establish training requirements of the O&M staff, verify design submittals from the A/E team meet the OPR and BoD, update OPR and BoD as necessary; *Construction Phase:* verify submittals, develop functional test procedures, site visits to verify construction meets the final design and OPR, verify training activities, witness functional tests, and document results; *Occupancy and Operations Phase:* warranty review, lessons-learned meeting, and seasonal testing. The CxA will have the responsibility of ensuring these activities are realized and that each meets the expectations of the OPR.

The CxA is contracted by the owner to conduct this quality process for the D&C activities from pre-design through occupancy and O&M. It is assumed that each member of the A/E team, as well as the construction contractors, will have their own internal quality processes and will strive to provide the owner with a quality end product, but the CxA represents the owner specifically and applies a blanket quality process to the entire project. This is expected to benefit all involved, including the A/E and contractors, by reducing late changes and rework, therefore saving time and resources. The ultimate goal is to have a satisfied owner at building occupancy and continue through O&M, as well as the design team and contractors completing the project with a profit.

3.3. HOQ

The HOQ is a tool within the QFD process which provides a means of matching the product's design with the voice of the costumer or customer requirements. Figure 3.1 illustrates the basic HOQ. Customer requirements are *what* the customer desires of a particular product based on marketing studies. The design response is *how* the designers will meet the needs of the customer. Design correlations are used as a means of understanding if one design response has an impact on another design response. The body of the matrix holds the relationships, or how well each design response addresses the customer requirements. The marketing matrix and design data matrix are used by the marketing and design teams for developing and prioritizing the whats and hows. In short, QFD is designed to gather the customer's needs and desires of a product, weigh those needs and desires against the needs and desires of the company, verify that engineering designs the product to those requirements, and verify that manufacturing can produce the product as designed. The goal is a product that will appeal to as many customers as possible.

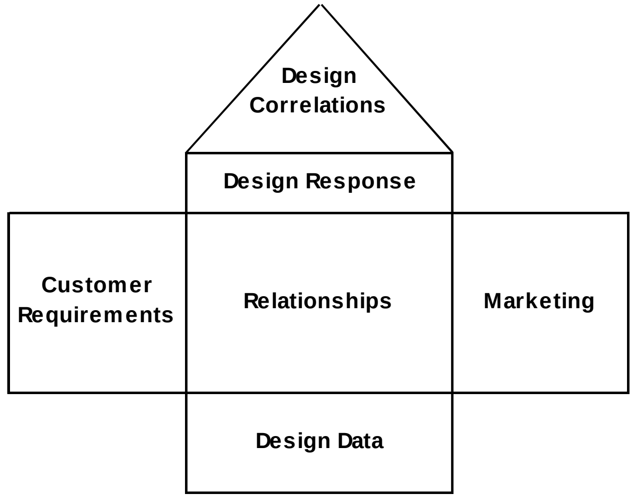


Figure 3.1. HOQ Model

3.4. BUILDING THE HOQ

The first step in the Cx process is developing the OPR. There are many methods for assisting the owner in developing the OPR, some of which might include workshops with key stakeholders, questionnaires, group meetings, or nominal group technique. Based on the focus of this research, these methods will not be discussed here with the exception of those OPR that include LEED certification.

Information gathered from the OPR development workshops will be entered into the marketing matrix and whats sections simultaneously. This will provide an opportunity to prioritize the OPR based on importance to the owner. Once the OPR has been established, prioritized, and approved by the owner the information is finalized in the whats area of the house. The approved OPR along with the priorities should also be provided to the A/E team for use as a reference and compliment to their programming and design effort.

The BoD, based on the approved OPR, will be generated by the A/E typically during their schematic design phase and will be provided to the owner and CxA. The BoD is entered into the hows area of the house. Figure 3.2 (rotated 90 degrees CCW to fit the page) represents the customer requirements (whats), design response (hows), and the relationships portions of the Pre-Design HOQ.

Each project will have a different OPR and BoD; therefore, Figure 3.2 has been kept as generic as possible by populating with a list of items that ASHRAE Guideline 0-2005 states should be addressed or identified within the OPR and BoD (the OPR has been abbreviated). One specific addition here is the LEED requirement. In this example, ‘LEED-Silver’ in Row 7 of the OPR and ‘LEED credits to attempt’ in Column 10 of the BoD has been added. The LEED requirements and how to deal with them will be discussed later.

Row Number	Relative Weight	Column Number → / Owner's Project Requirements (OPR) a.k.a. What's \ Basis of Design (BoD) a.k.a. How's	1 Specific codes, standards, and guidelines considered during design of the facility and designer interpretations of such requirements	2 Information regarding ambient conditions (climatic, geologic, structural, existing construction) used during design.	3 Assumptions regarding the usage of the buildings	4 Expectations regarding system operation and maintenance	5 Performance criteria that the system was designed to meet - linked to Owner's Project Requirements.	6 Specific design methods, techniques, software used in design.	7 A narrative statement of design - that verbally describes how the designer intends to meet the Owner's Project Requirements.	8 A narrative statement of operation - that verbally details how the facility is expected to operate under various situations (such as normal operation,	9 A listing of specific manufacturer makes, and models used as the basis for drawings and specifications.	10 LEED Credits to attempt
1	0.20	Project schedule and budget	.	.	.							
2	0.10	Energy efficiency goals		9								
3	0.10	Environmental and sustainability goals	3	3								
4	0.06	User requirements			9		3					
5	0.02	Commissioning Process scope and budget										
6	0.03	Owner directives		1								
7	0.10	LEED - Silver			.							9
8	0.04	Restrictions and limitations										
9	0.02	Community requirements										
10	0.04	Occupancy requirements and schedules										
11		⋮										

Figure 3.2. Pre-Design (HOQ)

The body of the matrix will be used by the CxA during the review of the BoD to verify it meets or addresses each of the OPR. Using a numbering scheme of 9 (strong relationship), 3 (medium), and 1 (weak) in each cell to specify how well each BoD meets a particular OPR will be used. A "**.**" is used to populate a cell in which the combination has been reviewed and found to have no relationship. This is meant to reduce the duplication of work which may occur if the cell is left blank.

It is important to understand that these entries are the professional opinion of the CxA and are not intended to be a critique of the design per se, rather to identify points of discussion between the owner and design team if it appears some OPR are not well represented in the design. The values in each row and column will be summed to identify which OPR are well addressed by the BoD and how well each BoD is addressing the OPR as a whole.

The design correlations area (roof) of the HOQ is used to understand the impact, negative or positive, one design criteria has on another. The methodology for the roof will be explained for the LEED HOQ.

The number of owners seeking LEED certification is growing at a rapid rate and within its rating system is a prerequisite which requires a fundamental level of Cx. The fundamental Cx prerequisite is an abbreviated version of the total building Cx process proposed by most practitioners but the LEED requirement, however small, is contributing to the growth of the Cx industry and should be considered.

4. LEED HOQ

4.1. INTRODUCTION

The complex system of LEED credits requires the design disciplines to coordinate, cooperate, and communicate if the required LEED certification level is to be achieved. There are many combinations of credits that can be utilized to accomplish an owner's LEED certification goal, but determining the combination that best fits the OPR can be a difficult task and must be accomplished early in the project.

The four certification levels of LEED, each progressively more difficult to achieve, offer numerous point opportunities and configurations that span the full range of design disciplines. Too often the design simply focuses on meeting the LEED certification. It is necessary to quickly understand how a design decision made by one discipline will impact the goal(s) of another discipline for maximizing LEED points in their respective areas. LEED certification level and the credits to be attempted credits are part of the OPR and need to be maintained as such. Any requested deviation from the LEED credits specified in the OPR needs to be evaluated as to how the deviation will impact the point opportunities of the other credits.

Bayraktar and Owens [2010] developed a LEED implementation guide to be used by construction practitioners. The guide utilized data collected from survey questionnaires answered by architects, engineers, commissioning authorities, general contractors, construction managers, and facilities managers who all held LEED Accredited Professional credentials. The guide is broken down into phases, the first of which is "Program" with sub-phases of OPR, scope verification, and design charette.

Each sub-phase is designed to aid the team in developing the OPR and determining the LEED certification requirements. Information gathered during the “Program” phase of this implementation guide could be one method of populating the LEED HOQ.

The recommendation here is to build a stand-alone HOQ to examine the LEED certification requirements of the OPR and BoD. In a general sense, the LEED certification level desired will become an OPR. A building owner may require a LEED certification level of Silver, for example, and the design team will work towards meeting that goal; however, in many cases the credits attempted are not approved by the certification authority (the GBCI) and a lower level is actually achieved or the project is not capable of meeting the certification level because of other conflicting OPR.

4.2. BUILDING THE LEED HOQ

At this point all of the certification levels and the required points are added as OPR, as the final level that will be achieved is not known this early in the process. The LEED credits will now be added as BoD responses. Figure 4.1 represents an abbreviated LEED HOQ. The remaining credits would be entered in the same manner, but are not able to be displayed in the format of this document. Therefore, an abbreviated version is provided. The associated points for each credit are added to the target value (LEED Points) row above the credits categories. LEED categories and credits along with the associated points can now be quickly referenced.

The row above the target value is used to symbolically represent whether the target value should be maximized or is the target. Many credits only offer one point level (all or nothing) while others offer a range of points. If the points are “all or nothing” a

"×" is used to indicate this is the target. If the points are a range a "▲" is used to identify that the goal is to maximize points. The next row above is used to represent the difficulty of achieving the target or goal.

Row Number	Relative Weight		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
		Column Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
		Difficulty of Accomplishment (0 = Easy , 10 = Hard)	10	6	10	6	2	2		4	6	3	10	8	5	3	3		4	4	8	4	6	
		Maximize (▲) or Target (×)	×	×	×	×	×	×	...	▲	×	▲	▲	▲	×	×	×	...	×	▲	×	×	×	...
		Target Value (LEED Points)	1	5	1	6	1	3		4	2	4	19	7	2	2	3		3	1	2	2	3	
		LEED Catergory	SUSTAINABLE SITES							WATER EFFICIENCY			ENERGY & ATMOSPHERE						MATERIAL RESOURCES					
		Basis of Design (BoD) ***LEED Credits Only*** / Owner's Project Requirements (OPR) ***LEED Only***	SSc1 Site Selection	SSc2 Development Density and Community Connectivity	SSc3 Brownfield Redevelopment	SSc4.1 Public Transportation Access	SSc4.2 Bicycle Storage and Changing Rooms	SSc4.3 Low-Emitting and Fuel-Efficient Vehicles	...	WEc1 Water Efficient Landscaping	WEc2 Innovative Wastewater Technologies	WEc3 Water Use Reduction	EAc1 Optimize Energy Performance	EAc2 On-site Renewable Energy	EAc3 Enhanced Commissioning	EAc4 Enhanced Refrigerant Management	EAc5 Measurement and Verification	...	MRc1.1 Building Reuse-Maintain Existing Walls, Floors, and	MRc1.2 Building Reuse-Maintain Interior Nonstructural	MRc2 Construction Waste Management	MRc3 Materials Reuse	MRc4 Recycled Content	...
1	0.10	LEED-Certified (40-49)	9	1	1	3	1	3		3	1	3	9	1	3	1	3		1	1	3	3	3	
2	0.50	LEED-Silver (50-59)	9	3	1	3	1	3		3	1	3	9	3	9	3	3		1	1	3	3	3	
3	0.25	LEED-Gold (60-79)	9	9	1	9	3	3		9	3	9	9	3	9	3	9		1	1	3	3	3	
4	0.15	LEED-Platinum (80-110)	9	9	1	9	9	9		9	9	9	9	9	9	9	9		1	1	9	9	9	

Figure 4.1. LEED HOQ

In this case the CxA's experience in the D&C fields would be used to rank the difficulty of each credit from 0 – 10, with 10 representing "extremely difficult." These values are not critical to the process, but can be a valuable tool for generating talking points during meetings between the CxA and the owner. Primarily the difficulty represents the level of cost, time, and resources required to accomplish the associated LEED points. The matrix between the OPR and BoD is now populated. This can only be completed with some understanding of the LEED process and the requirements for achieving the LEED credit points. Generally though, without that knowledge, it can easily be seen that in order to achieve LEED Platinum, which requires a minimum of 80 points from the available 110, attempting most of the credits will be necessary. Achieving 80 points is not an easy accomplishment.

The same numbering scheme of 9 (high), 3 (medium), and 1 (low) will be used to populate the relationships matrix, but are now used to indicate how important it might be for this credit to be attempted in order to meet the level of certification. Again analyzing the opportunities or necessities for LEED Platinum, it can be seen that nearly every credit may have to be attempted to accomplish 80 points, particularly if all the available points for the credits having a range of points are not achieved. In the Pre-Design HOQ, this matrix makes it simple to identify if a particular OPR is being adequately addressed by the design team. With the LEED HOQ this is simply providing insight into the difficulty of achieving certification and assisting the owner in determining a realistic LEED goal and credits to attempt.

One of the most valuable components of any HOQ is the roof as it represents the affects, either negative or positive, one design criteria has on another. It offers a quick visual for a CxA and owner to understand the impacts one design discipline’s decision will have on another design discipline’s work. This also provides a quick reference for any designer to understand that communication with another designer or team will be necessary if a +, -, or +/- is found in the cell. Figure 4.2 represents an abbreviated roof of the LEED HOQ.

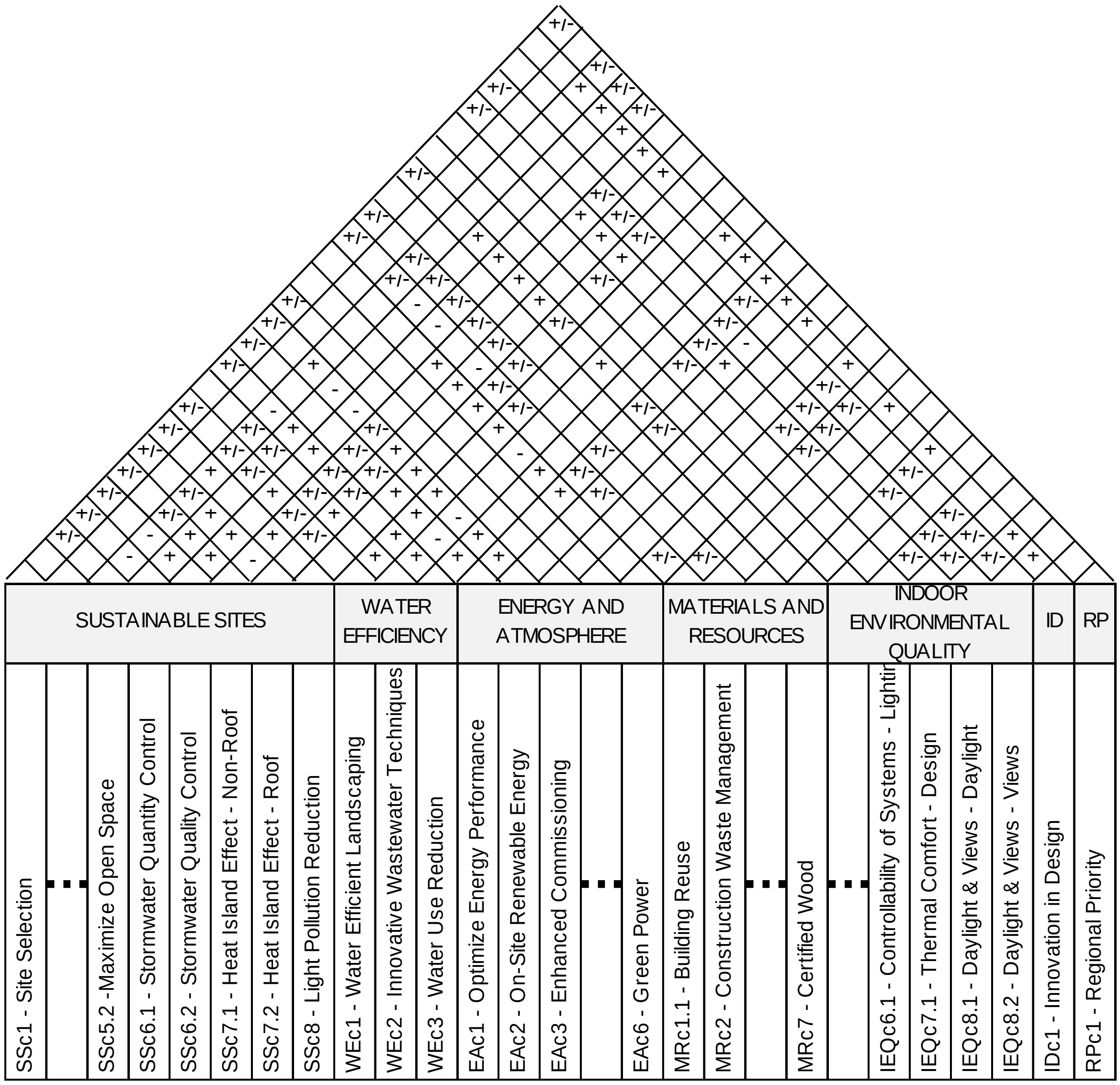


Figure 4.2. LEED HOQ Roof

To illustrate the need for optimal design team communication and as a supplement to the roof a responsibility matrix was developed to include each of the possible design disciplines and the LEED Credits. The matrix was populated using the author's knowledge of the design and construction process. Figure 4.3 represents an abbreviated responsibility matrix. Notice that some of the credits do not have a design discipline with primary responsibility for achieving that credit. This means that multiple disciplines will be involved, each designing for partial points, and each may be presenting designs that conflict with others.

	SSc1 Site Selection	SSc2 Development Density and Communit Connectivity	SSc3 Brownfield Redevelopment	SSc4.1 Public Transportation Access	SSc4.2 Bicycle Storage and Changing Rooms	SSc4.3 Low-Emitting and Fuel-Efficient Vehicles	SSc4.4 Parking Capacity	SSc5.1 Site Development-Protect or Restore Habitat	SSc5.2 Site Development-Maximize Open Space	SSc6.1 Stormwater Design-Quantity Control	SSc6.2 Stormwater Design-Quality Control	SSc7.1 Heat Island Effect-Nonroof	SSc7.2 Heat Island Effect-Roof	SSc8 Light Pollution Reduction	WEc1 Water Efficient Landscaping	WEc2 Innovative Wastewater Technologi	WEc3 Water Use Reduction	EAc1 Optimize Energy Performance	EAc2 On-site Renewable Energy	EAc3 Enhanced Commissioning	EAc4 Enhanced Refrigerant Management	EAc5 Measurement and Verification	EAc6 Green Power
Owner	❶	❶	❶	❶	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	❶
Architect	②	②	②	②	②		Δ		❶					②			②	②	②	②			Δ
Civil	②	②	②	②		②	❶	❶		❶	❶	❶		②		②		②	②	②			
Structural													②					②	②	Δ			
Mechanical\Plumbing					②										②	②	❶	②	②	②	❶		Δ
Electrical							②							②				②	②	②		❶	②
Landscaping			②		②	②	②	②	②	②	②	②		②	❶		②	②	②				
Interior Design														②			②	②					
Energy Consultant							②						②	②			②	②	②	②			Δ
LEED AP	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ
CxA	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	❶	Δ	Δ	Δ

❶ Primary responsibility for selection, design, or specifications

② Shared responsibility, or their design is affected by the primary design

Δ Requires consultation

Figure 4.3. LEED Responsibility Matrix

Some design decisions may affect or impact more than one design area or credit. In this situation a chain reaction of impacts occurs. An example might be: Sustainable Sites, Credit 7.2, Heat Island Effect – Roof, exposes a number of relationships that should be considered. There are many design strategies that may achieve this credit but let's look at the vegetative or "green" roof option. First, the cost to install a "green" roof would need to be compared to a more conventional roof which would also accomplish the credit (budget impact). Second, the "green" roof will likely have greater mass and may require an increased structural system in the building (budget impact and possibly a reduction of the interior volume, which reduces the available space for the building systems and occupants). Any roof that qualifies for SS Credit 7.2 will reduce the heating and cooling loads on the building and, therefore, reduce the amount of energy required to maintain thermal comfort (life-cycle cost). Another advantage with reduced heating and cooling loads is that the equipment required to heat and cool the building can be reduced (first cost reduction).

Since the HVAC system is smaller, so too will be the electrical system necessary to supply the equipment (smaller electrical gear and lower first-cost). This is a vegetative roof so it will require irrigation to keep the plants alive (higher water usage and utility bill). This will negatively affect the water efficiency of the building (WE Prerequisite 1). With this there is an opportunity to plant indigenous vegetation and attempt Water Efficiency (WE) Credit 1, Water-Efficient Landscaping or SS Credit 5.1, Site Development – Protect and Restore Habitat.

Adding a skylight(s) to this roof will reduce the area of the vegetation, the heat island effect will still be reduced, the required irrigation will be reduced, but now the additional sun introduced through the skylight will contribute to achieving Indoor Environmental Quality, Credit 8.1, Daylight and Views – Daylight. However, the insulating factor of the vegetative roof is now reduced and solar heat gain is introduced, which will increase the heating and cooling load, HVAC system requirements, and electrical system requirements.

The HOQ roof as designed for product development cannot take into account all of these impacts at one glance, but does still have the ability to expose the possible path of the affects and provides a method to navigate the possibilities. Knowing that one technical response will have an effect on another can still lead to the understanding that a third and fourth response is affected.

LEED certification will likely be only a small part of the OPR, but much of the design directed towards meeting the other OPR can contribute to meeting the LEED certification. Based on other OPR some of the LEED credits can or will be eliminated. For example, the owner may have decided that in no circumstance shall the new building be located on a property that is considered a brownfield site. This would eliminate LEED opportunity Sustainable Sites, Credit 3, Brownfield Redevelopment. This is a simple and obvious example, but as some credits are eliminated it reduces possible impacts that might be imposed on other credits.

Additionally, some credits may be eliminated because given certain circumstances they are impossible to obtain. Reviewing the LEED HOQ roof it can quickly be seen that nearly all of the Sustainable Sites credits will have positive or negative impacts on each other. The site selection is critical to many other credits and may be outside the control of the design team. Often an owner will have purchased a piece of property long before contacting an architect, design team, LEED AP, or CxA. The location and size of the property will immediately either eliminate the possibility of achieving or promote achievement of other credits. For example, if a site is selected in a rural setting, outside city limits perhaps, it is likely that it will eliminate the possibility of SSc2, Development Density and Community Connectivity and SSc4.1, Public Transportation Access. What begins to happen is that the list of possible credits shortens and the need to maximize points of other credits heightens. Looking at the relationships area of the LEED HOQ it can be seen that these numbers will have to increase as fewer possibilities are available. Now many if not all of the relationships will be rated as a 9. It may also be seen that it is impossible to achieve LEED-Platinum or even Gold.

When this process is complete and the LEED certification level and credits to be attempted have been determined, the credits should be added to the OPR as a sub-requirement to the LEED level. Now the BoD presented to the owner by the design team will be directed towards meeting those specific LEED credits as well as the other OPR. It is recommended that the full LEED HOQ (all of the credits are listed) be kept intact for future review of impacts caused by late design change proposals. The CxA and owner can quickly go back to the roof and determine if a proposed change will negatively impact the original credits, thus providing a greater opportunity to determine if the change has value to the owner.

5. PROPOSED FOUR-PHASE MODEL

5.1. INTRODUCTION

If the owner's project requriements are not met in the finished product it is unlikely the owner will feel they have received the expected or anticipated value.

Design/bid/build construction projects have distinct phases: pre-design, design, construction, and operations and maintenance. Each phase has specific deliverables which are passed to the following, finally ending with the deliverables in the O&M phase. The responsible parties of each phase are a customer of the previous. The phases, responsible party, and the deliverables are illustrated in Table 5.1. Each deliverable in Table 5.1 must be handed off to the next responsible party and each previous deliverable must be sufficient for the next party to complete their deliverable(s). Each party is independently contracted by the owner and though each has a requirement to provide the owner what is expected they also have a responsibility to themselves and may have a tendency to act in their own interests.

Table 5.1 Responsibilities and Deliverables

Phase	**Responsible Party**	**Deliverable**
Pre-Design	Owner	Owner's Project Requirements
Design	Architect and Engineers (A/E)	Drawings and Specifications
Construction	General Contractor and Subcontractors	Submittals, O&M training, test systems, documentation, finished building
O&M	O&M Staff (owner employed or contracted)	Operate building in an efficient and sustainable manner (as designed and built)

Though building commissioning is not a new concept and is the focus of much work by Cx organizations and practitioners, there are still weaknesses in the process that can be addressed. This research focuses on developing a methodology for applying quality function deployment (QFD) to the entire Cx process. This will provide a means for creating the necessary links between phases, a means for ensuring each deliverable is sufficient for the next customer and that each meets the OPR, a means for the owner and all team members to quickly see the status of the project and Cx process, and a means to track and build the document library.

Clausing's four-phase QFD model [1994] will be used in the proposed Cx methodology and modified to capture the differences between product development and manufacturing process and the design and construction process. Cohen [1995] presented Clausing's four-phase model with different, possibly more intuitive, titles. The proposed methodology based on the four Cx phases aligns with these models. The similarities among the three can be seen in Table 5.2.

Table 5.2. QFD Four-Phase Model Titles

Clausing's Model	House of Quality	Part Deployment	Process Planning	Operations Planning
Cohen's Titles	Product Planning	Design Development	Manufacturing Planning	Production Planning
Cx Process	Pre-Design	Design	Construction	Operations and Maintenance

The Cx four-phase process is shown in Figure 5.1. In the figure, the Cx phase is bolded with the corresponding step from Cohen's model and Clausing's model provided below for reference. A distinct difference in the model, from that of Cohen's and Clausing's is the addition of a roof on the owner's project requirements for use in identifying conflicting owner's wants and needs. The components of each matrix and expected benefits to the CxA, owner, and project team for making use of the matrix are explained in the following subsection. The development of each phase will be discussed later. These phases include Pre-Design, Design, Construction, and Operations and Maintenance.

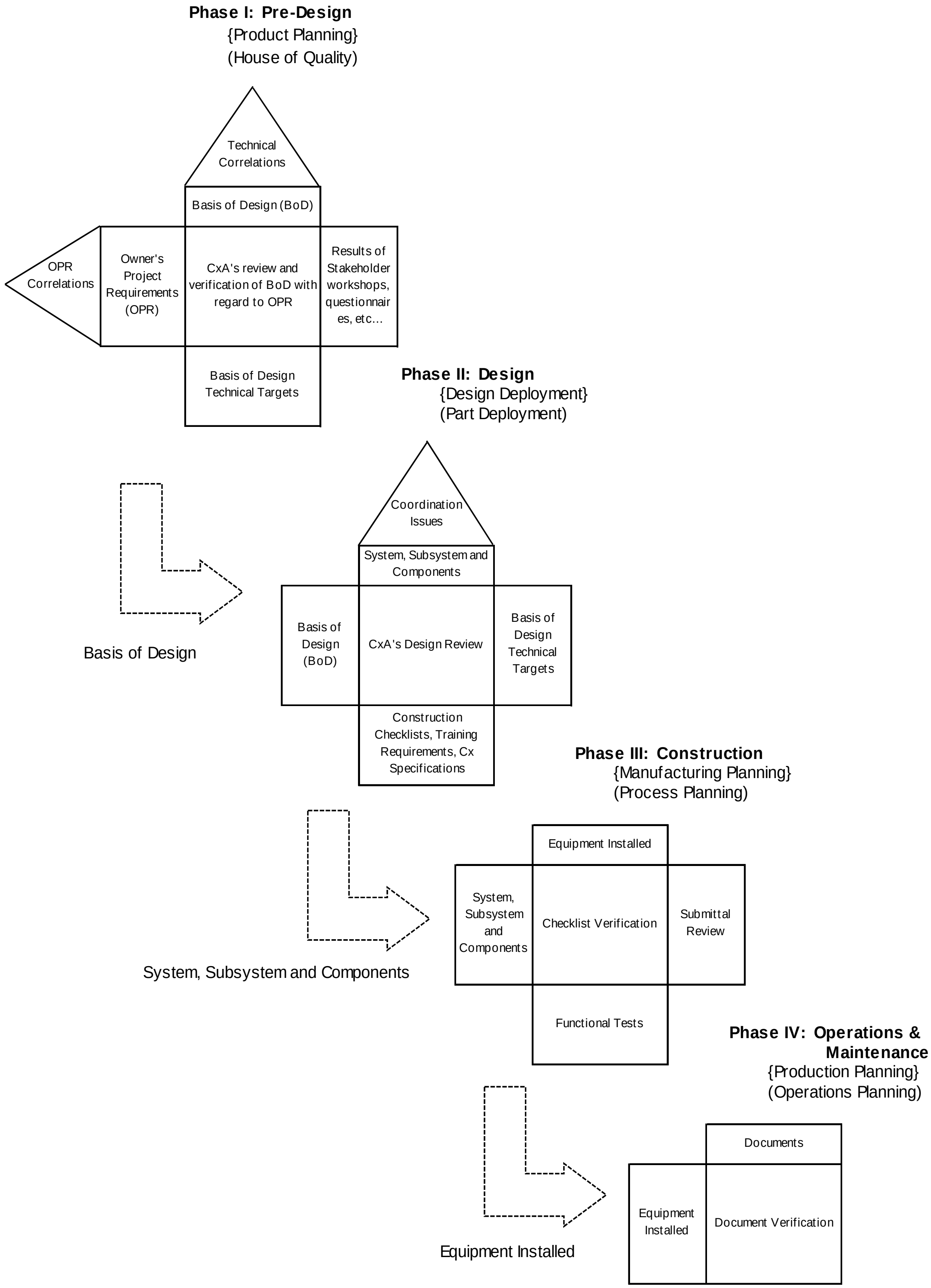


Figure 5.1. QFD Four-Phase Model for Cx

5.2. BUILDING THE FOUR-PHASE MODEL

5.2.1. Phase I: Pre-Design. Though this initial matrix is known as the House of Quality (HOQ) it serves as the foundation for the remaining phases. It will provide a link between the owner and the designers. The components and development steps of the pre-design matrix are:

1A. Developing the owner's project requirements (whats)

1B. Prioritize the OPR based on the development process information

1C. Identify the basis of design (hows)

1D. Establish the relationships between the whats and hows

1E. Establish the BoD correlations matrix

1F. Establish the OPR correlations matrix

1G. Analyze the Pre-Design matrix

The basis of design is transferred to the next phase and becomes the whats.

Key benefits of Phase I: The owner will provide the OPR to the designers and can be assured the designers will have what is necessary to begin schematic design. The designers can be assured they are beginning design with an approved OPR which has been developed by the owner with the assistance of technical experts from the CxA team. After the analysis of the matrix is complete the designers can move forward knowing that their basis of design has been approved as satisfactorily meeting the OPR and will likely reduce late changes. The OPR and BoD roofs will provide a quick method for analyzing the effects of proposed design changes in later phases of the project.

5.2.2. Phase II: Design. This phase will serve to verify the final design meets the basis of design and to provide a link from the designers to the general contractor. From this matrix forward the focus will be reduced to the systems to be commissioned. Typically, these are the energy consuming systems that include mechanical, electrical, plumbing, life safety, and building envelope. The development steps and components of the design matrix are:

2A. The BoD become the whats

2B. Determine the building systems, subsystems, and components, separated by division

2C. Establish the relationships among the BoD and the building systems

2D. Develop construction checklists

2E. Cx specifications verification

2F. Develop training requirements

2G. Establish correlations of the building systems which will identify possible construction coordination issues with the different trades

The building systems, subsystems, and components will be transferred to the next phase and become the whats.

Key benefits of Phase II**:** The owners will now know they have the most accurate construction documents for bidding purposes. The designers will have a verified and approved design. The contractors can find Cx requirements in the technical specifications of the documents, understand the training requirements they need to provide to the O&M staff, review and comment on the construction checklists prior to start of construction, reduce coordination issues, and understand how the remainder of the project will be commissioned. Any change that is proposed can be analyzed and evaluated with regard to how it affects the OPR.

5.2.3. Phase III: Construction. This phase will establish a link from the general contractor back to the designers and forward to the O&M staff. The development steps and components of the construction matrix are:

3A. The building systems, subsystems, and components become the whats

3B. Determine the required equipment installations, separated by construction trade (hows)

3C. Verify the relationships among the whats and hows using the construction checklists

3D. Identify which checklists have been completed and verified for accuracy

3E. Verify submittals for materials and equipment against the building systems and components

3F. Functional tests for each system will be developed and tracked for completion

Key benefits of Phase III: The owner will know the building has been built as designed and specified in the OPR. The general contractor can be confident that all of the equipment installations meet the design and OPR and rework should be reduced. O&M staff will know that the systems will be functioning as expected and training has been conducted. Again, any change that is proposed can be analyzed and evaluated with regard to how it affects the OPR.

5.2.4. Phase IV: O&M. This phase is primarily used as a checklist to verify all documentation, which includes O&M manual, systems manual, and training documents, are complete and accurate. This also provides a link back to the owner by confirming the completed building is now able to be operated and maintained as specified in the OPR.

6. CASE STUDY: DETAILED FOUR-PHASE MODEL

6.1. INTRODUCTION

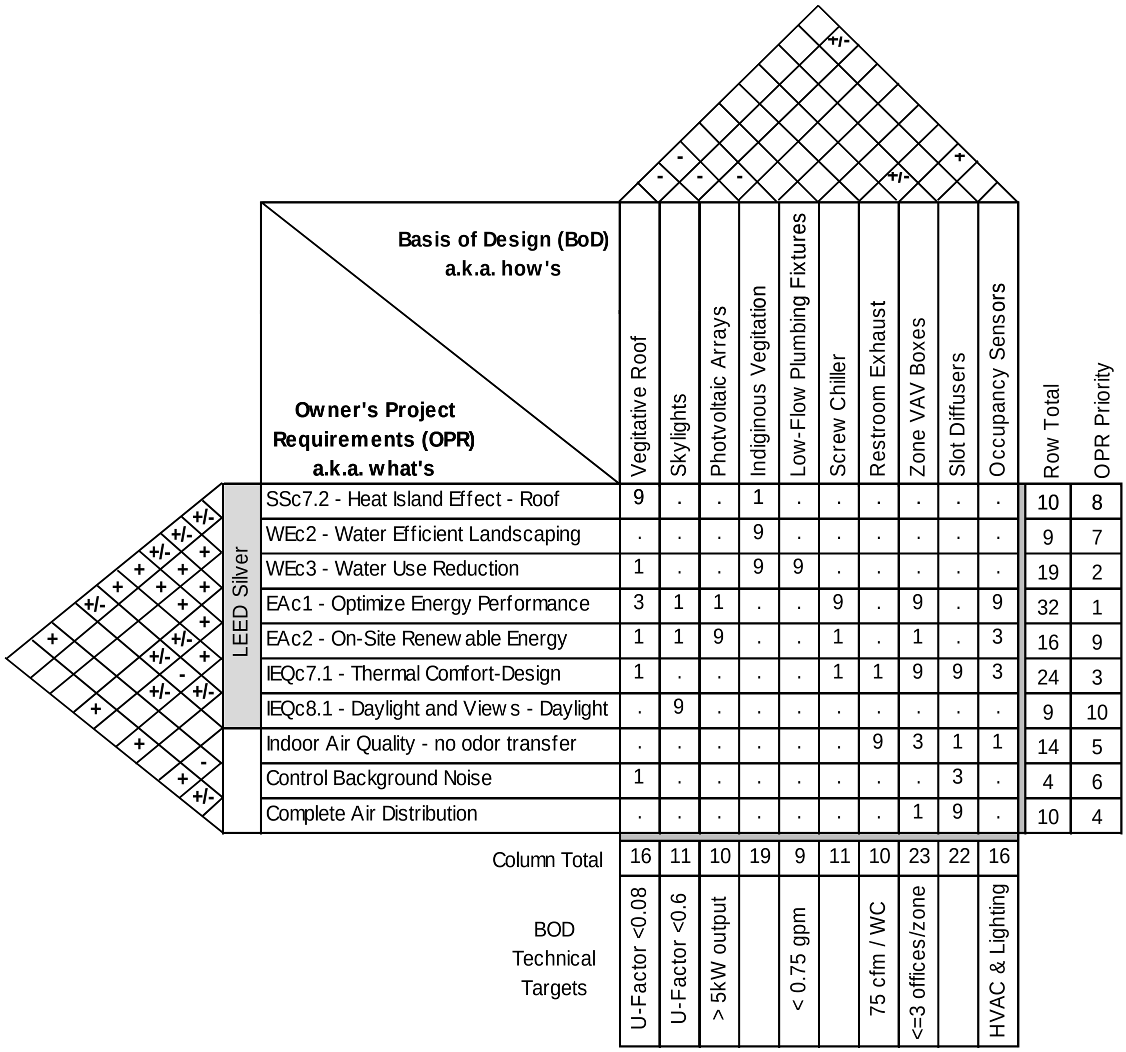
As each phase begins the CxA should meet with any new teams coming into the project to explain how QFD and the four-phase model will manage the overall quality of the project. The goal is transparency and an understanding that each activity links back to the OPR. Any proposed changes, such as some type of value engineering initiative, can be easily traced back through design, BoD, and OPR to determine the impact on the entire project. The CxA should also express to the team the benefits that can be achieved for each while using this methodology. The entire four-phase model should be used at each Cx meeting to illustrate to the Cx team how the project is progressing.

The OPR and the BoD are living documents and are subject to change. The model provides a method to track and evaluate any changes back to the OPR. This can be a valuable tool at design review meetings with the owner and the A/E team.

To illustrate the methodology a hypothetical case is presented. With this case, the OPR is significantly reduced from that which would be found with a typical new-construction building project.

6.2. DETAILED FOUR-PHASE MODEL

6.2.1. Phase I: Pre-Design. (see Figure 6.1)



OPR	Vegitative Roof	Skylights	Photvoltaic Arrays	Indiginous Vegitation	Low-Flow Plumbing Fixtures	Screw Chiller	Restroom Exhaust	Zone VAV Boxes	Slot Diffusers	Occupancy Sensors	Row Total	OPR Priority
SSc7.2 - Heat Island Effect - Roof	9	.	.	1	.	.	.	.	.	.	10	8
WEc2 - Water Efficient Landscaping	.	.	.	9	.	.	.	.	.	.	9	7
WEc3 - Water Use Reduction	1	.	.	9	9	.	.	.	.	.	19	2
EAc1 - Optimize Energy Performance	3	1	1	.	.	9	.	9	.	9	32	1
EAc2 - On-Site Renewable Energy	1	1	9	.	.	1	.	1	.	3	16	9
IEQc7.1 - Thermal Comfort-Design	1	.	.	.	.	1	1	9	9	3	24	3
IEQc8.1 - Daylight and Views - Daylight	.	9	.	.	.	.	.	.	.	.	9	10
Indoor Air Quality - no odor transfer	.	.	.	.	.	.	9	3	1	1	14	5
Control Background Noise	1	.	.	.	.	.	.	.	3	.	4	6
Complete Air Distribution	.	.	.	.	.	.	.	1	9	.	10	4
Column Total	16	11	10	19	9	11	10	23	22	16		
BOD Technical Targets	U-Factor <0.08	U-Factor <0.6	> 5kW output		< 0.75 gpm		75 cfm / WC	<=3 offices/zone		HVAC & Lighting		

Figure 6.1. QFD Model: Pre-Design Phase (HOQ)

6.2.1.1. Step 1A: Developing the OPR (whats). The OPR is critical to the success of the project. There are many methods for assisting the owner in developing the OPR, some of which include workshops with key stakeholders, questionnaires, group meetings, or nominal group technique. For example, two-day courses are offered on developing Owner's Project Requirements, which is based on the use of the nominal group technique. For the focus of this research these methods will not be discussed here.

It has been determined that the project will seek LEED certification with a goal of achieving a level of Silver. Several credits the owner has decided should be attempted are Heat Island Effect – Roof, Daylight and Views - Daylighting, Optimize Energy Efficiency, Water Efficient Landscaping, and Thermal Comfort – Design, feeling these will contribute to the LEED goal and align well with other OPR. These are added to the matrix along with other OPR determined during the development process.

6.2.1.2. Step 1B: Prioritize the OPR based on the development process information. The prioritization of the OPR will be addressed during the development process, which is not discussed in this work. The level of prioritization is added at the far right of the matrix. The prioritized OPR will be presented to the A/E team to use as a compliment to their programming effort. The prioritization will help the A/E understand what the level of importance each OPR criteria is to the owner. If the budget is tight, as most are, the team can pull certain OPR that have low weight factors and use them as alternates during the bidding process. An example could be an outdoor patio area to be used for employee breaks. It is on the wish list but may exceed the budget. Essentially this is low priority, but still desired. For this example LEED credit EAc1 – Optimize Energy Performance has been identified as having the highest priority, while LEED credit IEQc8.1 – Daylight and Views-Daylight has the lowest priority. This would indicate to the design team that having daylight in the building is least important.

6.2.1.3. Step 1C: Identify the basis of design (hows). The A/E team is provided with the complete and prioritized OPR to use for development purposes. The A/E team will develop the BoD during schematic design and present the document to the owner and CxA. All design criteria are expected to address the OPR. The BoD that was proposed by the A/E team included a vegetative roof, skylights in the roof, solar arrays on grade on the south side of the building, and indigenous vegetation on grade and the roof to name a few. The BoD are added to the matrix as the hows. The technical target data provided with any BoD requiring such are added at the bottom of the matrix.

6.2.1.4. Step 1D: Establish relationships between the whats and hows. The relationships between the OPR and the BoD are now determined. The body of the matrix will be used by the CxA during the review of the BoD to verify it meets or addresses each of the OPR. A numbering scheme of 9 (strong relationship), 3 (medium), and 1 (weak) is used in each cell to specify how well each BoD meets a particular OPR. A "**.**" is used to populate a cell in which no relationship is identified. This is meant to reduce the duplication of work which may occur if the cell is left blank. It is important to understand that these entries are the professional opinion of the CxA and are not intended to be a critique of the design per se, rather to identify points of discussion between the owner and design team if it appears some OPR are not well represented. One example is the use of a vegetative roof for meeting the OPR Heat Island Effect-Roof. A "9" is entered in the cell to identify that this approach strongly addresses the OPR.

6.2.1.5. Step 1E: Establish the BoD correlations matrix. The correlations matrix identifies the impact one BoD has on another BoD. For example, the impacts are identified using a "-" for a negative impact, a "+" for a positive impact, and a "+/-" if it could be either positive or negative. This roadmap of impacts can also be used to analyze the impact of proposed changes in later stages of the design and construction.

6.2.1.6. Step 1F: Establish the OPR correlations matrix. The same process as the BoD correlations matrix discussed in Step 1E is used to populate the OPR correlations matrix. It can be seen that most of the LEED credits can have both positive and negative impacts on the other credits.

6.2.1.7. Step 1G: Analyze the pre-design matrix. Summing each OPR row identifies how well the entire BoD addresses one particular OPR. The same procedure is conducted for the BoD. The CxA can now discuss with the owner how well the OPR are addressed. With this information the owner may discuss with the design team the options of placing more or less design emphasis on certain OPR. If a BoD has little or no total value in the column this may indicate that the BoD does not need to be taken to the final design. There may be an opportunity to save project funds or shift funds toward different OPR. This analysis may also identify an OPR that needs to be modified or eliminated. The owner making these decisions at this phase can save significant time, money, and effort. Any OPR or BoD that are changed must be updated within the matrix. The owner and A/E team now know their ideas and efforts are synchronized and can agree to proceed to the next phase of design.

6.2.2. Phase II: Design (see Figure 6.2)

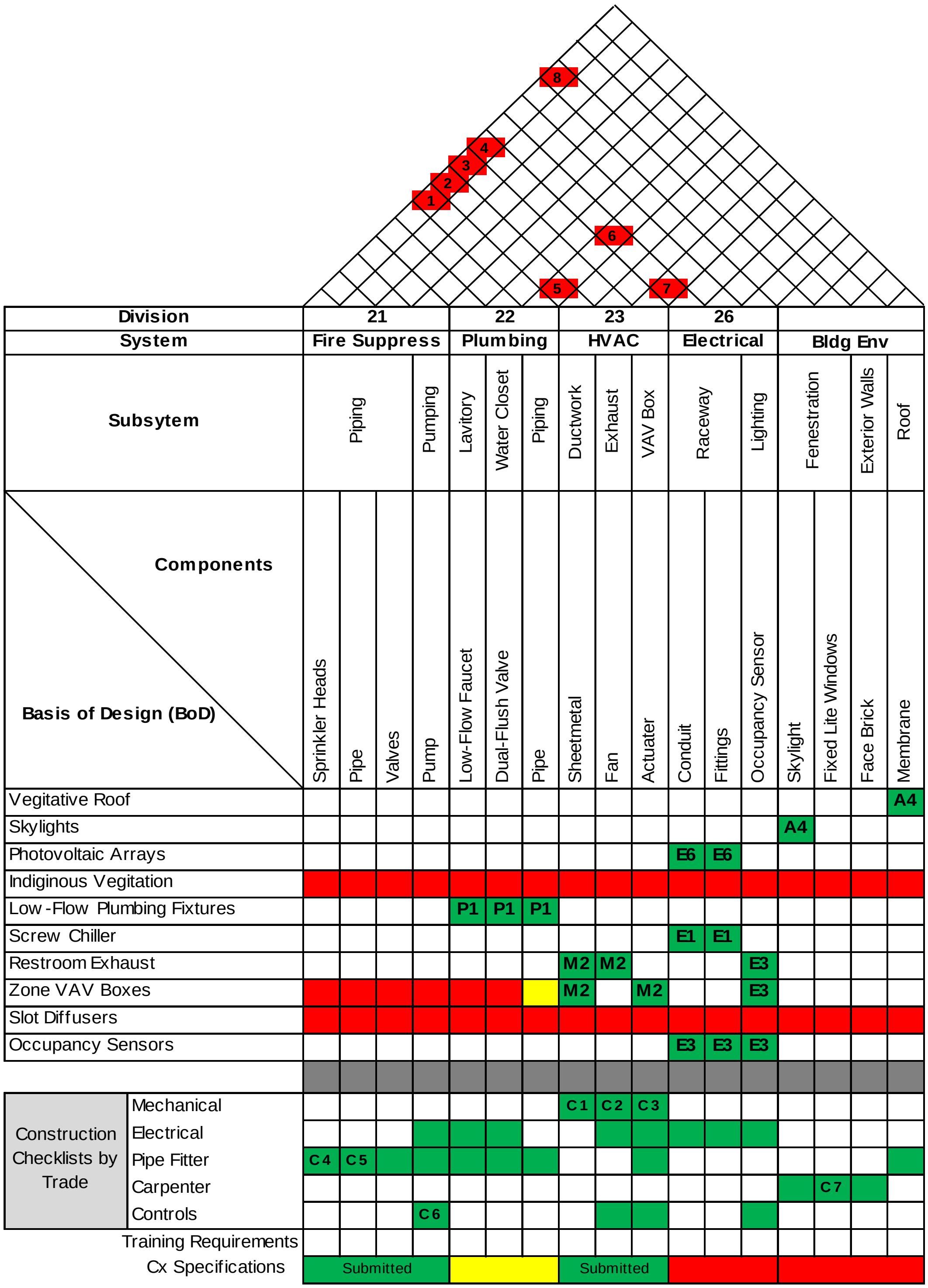


Figure 6.2. QFD Model: Design Phase

The typical Cx process requires a minimum of three design reviews during the design development and construction document phases of the process. The body of the matrix is used at each review to verify the design meets the BoD.

6.2.2.1. Step 2A: BoD become the whats. The BoD are now transferred from the pre-design matrix to the whats section. This provides the connection between the Pre-Design and Design phases.

6.2.2.2. Step 2B: Determine the building systems, subsystems, and components, separated by division. Beyond the OPR and BoD, the Cx process is typically concerned with the energy consuming systems within the building and generally verifies the design and installation of those systems and components. The commissioned systems would have been identified in the contract with the owner. Future analysis focuses on those systems. Typical systems include mechanical, electrical, plumbing, life safety, and building envelope. These systems are entered as hows in the technical response section. The goal is to enter these by division and break them down to system, subsystem, and component levels. The division is added to identify the requirements for Cx specifications in the A/E team's technical specifications. Sub-systems and components are important because they are used to generate the construction checklists.

The hows section is entered as a tree diagram is constructed, first by the division number, followed by the system, subsystems, and finally the components. The purpose is to provide easy identification of how the system is broken down and which trade is constructing the system. Many of the trades will overlap on the systems and now a checklist can be developed for each trade that has responsibility for the subsystem components. This ensures that each trade involved in the installation will be assigned a checklist. An example is a variable air volume (VAV) box. The sheet metal crew installs the box, which may include a reheat coil, the plumbers attach the piping and control valves to the coil, the controls crew installs the control devices and may run the necessary control wire, but the control wire installation could be left for the electricians. This small sub-system component may have as many as four different trades involved in the installation. Each trade should be provided a checklist to understand what is expected of them for their part of the installation.

6.2.2.3. Step 2C: Establish the relationships among the BoD and the designed systems. The body of the matrix should be used to verify the design meets the BoD. To truly verify the design meets the BoD it is not sufficient to simply add some type of symbol, such as a check mark, to claim the verification was completed. The recommendation is to fill the cell with the drawing number where it is confirmed the design addresses the BoD. If the models are built in an Excel worksheet there are other features that can be used to improve the documentation. For example, the comments feature can be used to provide information regarding the drawing number and a grid location on the drawing. Different cell colors, such as green (verified), yellow (in process), red (not addressed), can be used to identify progress. In the example, the slot diffusers and indigenous vegetation are not addressed by the design. Drawing numbers have been added to cells to identify where the BoD was found to be addressed.

6.2.2.4. Step 2D: Develop construction checklists. Construction checklists are developed based on the system, subsystem, or components identified. For the focus of this research these methods will not be discussed here. Templates are available from several sources, two of which are Building Commissioning Association (BCA) (www.bcxa.org) and The Building Commissioning Handbook [Heinz and Casault, 2004]. These templates can be modified to suit specific project parameters. The goal is to make certain each need for a checklist is addressed. Each checklist developed should have a unique identifier which will be added to the cell to provide a quick reference back to the checklist. If no checklist is required an "**X**" should be placed in the cell so it is clear that nothing was overlooked.

6.2.2.5. Step 2E: Cx specifications verification. The cells used for the Cx specifications need to be checked off twice, once when the Cx specifications are created and again when the Cx specifications have been verified that they have been added to the technical specifications. Again color coding is used, green (complete), yellow (in process), and red (not started) to identify progress. After the Cx specifications have been submitted to the A/E team the word "submitted" is also added to the cell. Cx specifications require expertise in the development of specifications. BCA (www.bcxa.org) also offers Cx specification templates which can be used as a starting point. For the focus of this research the methods to refine these templates will not be discussed here.

6.2.2.6. Step 2F: Develop training requirements. If the O&M staff is known and available at this phase of the project, the staff should be interviewed and the proposed systems discussed. Any necessary training for the O&M staff will be identified by comment in the cell below the proper system or subsystem. An example might be "one week on-site training provided by the boiler vendor" entered below the boiler subsystem. No systems requiring training have been added to the example matrix. If the O&M staff is not known during this phase a conversation with the owner and the A/E team can help identify possible needs. The training requirements are then added to the technical specification for bidding purposes.

6.2.2.7. Step 2G: Establish correlations of the building systems. The roof in this phase is again used to identify correlations among the hows, but since this is a review of the complete design, the consideration will be on potential construction coordination issues. Once these are identified the owner can discuss these issues with the A/E so they can determine if there truly is an issue that requires design modifications. If no design changes are required, the owner should discuss the locations of possible coordination issues with the contractors once they are hired. These locations should be reviewed during site visits. The roof in Figure 6.2 identifies a few possible coordination issues. Consecutive numbers are used in the cells along with the fill color of red to make identification easier. A separate numbered list, corresponding to those numbers in the roof, is created to provide a narrative describing in detail the possible issues.

6.2.3. Phase III: Construction (see Figure 6.3)

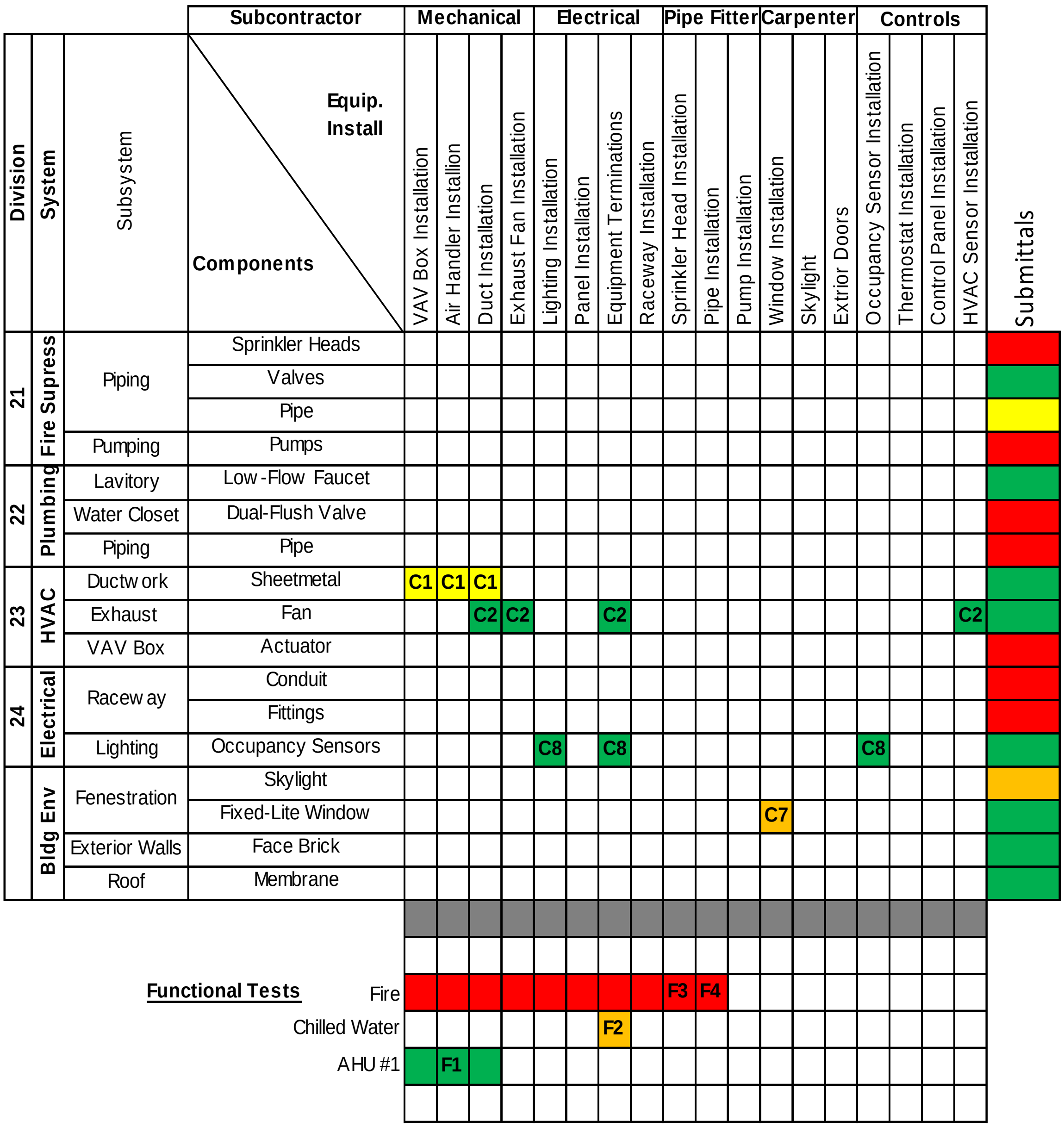


Figure 6.3. QFD Model: Construction Phase

6.2.3.1. Step 3A: The building systems, subsystems, and components become the whats. Transfer the building systems, subsystems, and components from the design matrix to the whats. Include the divisions as in Step 2B above.

6.2.3.2. Step 3B: Determine the required equipment installations (hows). The equipment installations are broken down by construction trade. Enter each trade which will be required to install the systems within the design.

6.2.3.3. Step 3C: verify the relationships among the whats and hows using the construction checklists. The construction checklists developed in the design matrix can be transferred to the body of the matrix to match the whats with the hows. This process identifies that each trade required for a subsystem installation has a checklist assigned. If any were overlooked in the previous matrix one should be developed now.

6.2.3.4. Step 3D: Identify which checklists have been completed and verified for accuracy. The contractors have their own internal methods and quality control and the CxA has no authority to request that they change their process; therefore, the relationships matrix focuses on what is needed to verify that the contractors' methods are sufficient to meet the expectations of the owner. This is accomplished by developing construction checklists which will be filled out by each subcontractor during the installation process. The required checklists were identified and developed in the previous phase. The construction matrix is a means for tracking the verification process. Each subcontractor will be given their respective checklists prior to the beginning the construction process. Their input and approval will be necessary to ensure buy-in and completion. As the checklists are completed, this should be documented and the completed checklists should be randomly sampled for accuracy by verifying during site visits that each item on the checklist has been completed properly. The suggestion is to mark the matrix to indicate which checklists have not been started, which are in process, and which are complete. Different symbols can be used or a cell color, such as green (complete and without issue), yellow (in process), red (not started), and orange (complete but with unresolved issues). It can be seen in Figure 6.3 that checklist C7 is colored orange indicating there was a problem identified during the verification process. Checklists C2 and C8 are complete and verified to be accurate. C1 is in the verification process.

6.2.3.5. Step 3E: Verify submittals against the building systems and components. As submittals are presented by the general contractor to the A/E and CxA the submittals must be confirmed to meet the OPR and final design before being checked off as verified. A suggestion is to house the submittals in electronic folders by division and provide a link to the folder and file for each submittal. This will provide for quick reference later. This can also be the basis of an electronic O&M manual and systems manual. The cells are color coded green (verified and approved), yellow (in process), and red (not started).

6.2.3.6. Step 3F: Develop functional tests. The area below the body matrix will be used to identify those equipment installations and systems which require functional tests and later for verification that the tests are complete and without issue. As the submittals come in from the contractors, and the equipment is approved, the functional tests can be developed. A unique identification for each functional test should be developed and entered into the appropriate cell at the bottom of the matrix. The sources mentioned previously can provide templates for the functional tests. For the focus of this research the methods to refine these templates will not be discussed. Again, links can be provided to electronically stored functional tests for quick reference and for use later in the systems manual. Color coding is again used to identify the status of the tests.

6.2.4. Phase IV: O&M (see Figure 6.4)

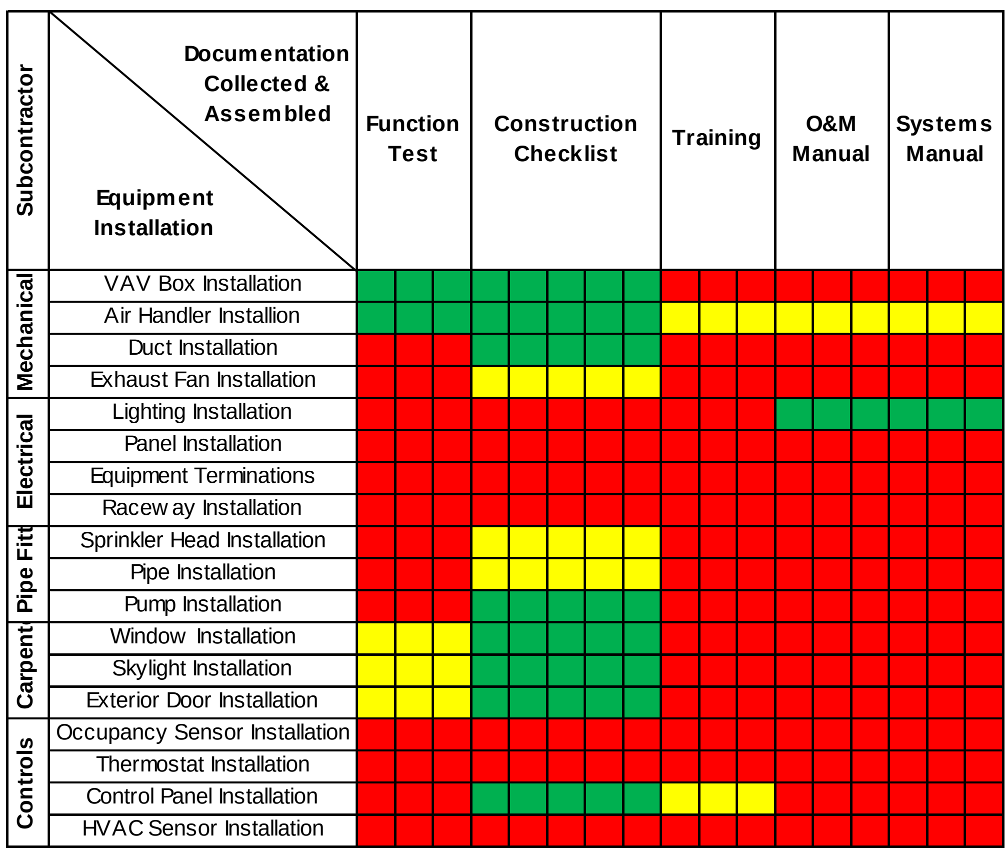


Figure 6.4. QFD Model: O&M Phase

The equipment installation entries are then transferred to the whats in this matrix. The hows are the documents that need to be collected and provided to the O&M staff at building occupancy. Documents to be tracked are functional tests, construction checklists, O&M manual, systems manual, and training documents. Color coding the relationships area is used to identify the status of the documents as they are provided by the contractor. The entire matrix is red at the beginning. Yellow represents those documents that are under review and green represents the approved documents that are in the CxA's possession.

7. VALIDATION/RESULTS

7.1. INTRODUCTION

The demand for commissioning services for new-building construction projects is experiencing rapid growth. Commissioning is touted as being a quality-focused process for ensuring the owner's project requirements are met by the design, final construction, and operations of the building. To an owner this is just what is needed to receive a perfect building at occupancy. However, as many owners have realized, the Cx process does not guarantee the completed building will be what was expected. It should be pointed out that this is typically not caused by the Cx process; but the Cx process should or could have identified, in the early phases of the project, many of the issues that made it through to the completed building. There are a number of reasons why the Cx services received may not be optimal. Often it is poor communication and the transfer of knowledge between project teams. Cx should and can facilitate both communication and the transfer of knowledge from phase to phase. The adaptation of the QFD four-phase model can accomplish this by filling the gaps among the major Cx activities and provide a standard approach to the process. The four-phase model effectively links each of the Cx activities to each other and back to the OPR providing a method for improved communication and knowledge transfer. Potential reasons for inconsistent Cx services are presented, an investigation into the literature regarding Cx issues, and an argument for the need of a Cx standard is made.

Many potential new building owners do not know what Cx is, more so for those that have not constructed a new building. They may be introduced to the concept for the first time by the architect they have selected to design their building. They will certainly be exposed to Cx if they have decided to pursue LEED certification. But actually, many owners that have contracted Cx services for their own buildings and have experienced the process might still not fully know what Cx is or at least what Cx should have been. Doty explains that Cx should protect the owner's interest at each stage and fill gaps left from cost pressures in the design and construction methods. The core concepts of Cx are (1) identify the intent of the work and how the goals will be met; (2) provide early detection and intervention of issues; (3) train operations staff; (4) prepare maintenance activities for sustainability; and (5) quantify the Cx benefits. The goal is to detect issues early using sampling techniques with a primary purpose of correcting systemic problems which would become long-term and costly.

Doty also expresses that owner support of the process is essential for success. For those owners who have experienced Cx and still do not know what the Cx process should have provided, it is possible the necessary owner support was missing from the project. It is also possible they had no idea they should have been involved in the Cx process. What Cx is or should be is up for debate. There are differing philosophies about the process and how it should be administered. Many Cx organizations and professionals are working toward improving the process and ultimately that the process should be directed toward ensuring the owner will be delivered the highest quality building their budget, timeline, and other requirements allow. Obviously each project will have different parameters but a satisfied owner at project end is the goal of the Cx process.

One difficulty faced by owners, especially those who have not contracted Cx services, is who and what should be asked for and expected. There is currently no standard for the Cx process, therefore services can and will vary. A quick look at the available guidelines and certification options will shed light on the issue.

7.2. COMMISSIONING GUIDELINES

The Cx industry and organizations generally align with ASHRAE's definition of Cx. With that though there are many different approaches to the practice. The following is a list of organizations that have published either guidelines or best practices for defining what Cx is and how to go about providing the service. These are all well respected organizations which have contributed to the improvement of the Cx practice but nonetheless have not come to an agreement on one standard method for delivering Cx services.

- American Society of Heating, Refrigerating and Air-Conditioning Engineers: *ASHRAE Guideline 0-2005, The Commissioning Process*
- Building Commissioning Association (BCA): *New Construction Building Commissioning Best Practice*
- California Commissioning Collaboration (CCC): *California Commissioning Guide: New Buildings*
- General Services Administration (GSA): *The Building Commissioning Guide*
- AABC Commissioning Group (ACG): *ACG Commissioning Guideline*
- National Institute for Building Sciences (NIBS): Provides a number of technical commissioning guidelines for specific building systems.

Each of these guidelines has variations based on the organization's business focus. Other technical commissioning guidelines, focusing on Cx of specific systems, have also been developed by ASHRAE and NIBS with Guideline 0 as a platform for the others (see Figure 7.1).

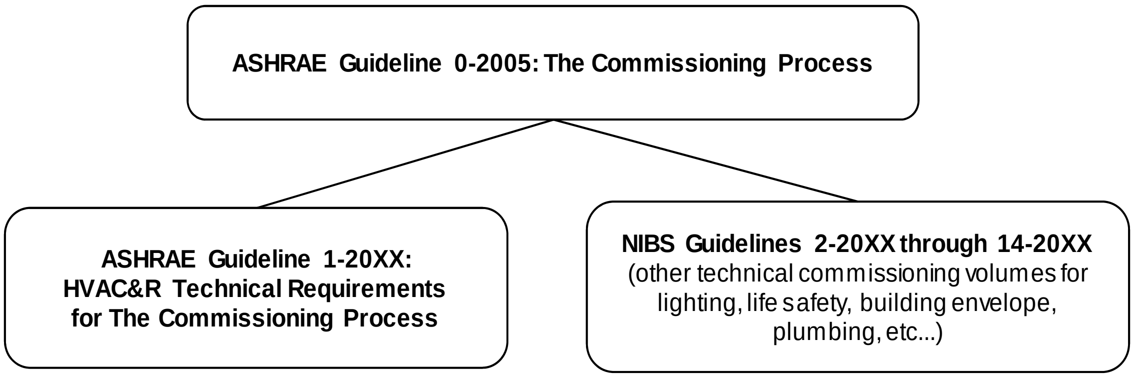


Figure 7.1. Commissioning Guidelines: ASHRAE and NIBS

The USGBC's LEED 2009 for New Construction guideline requires an abbreviated version of Cx. Two levels can be achieved; first the prerequisite (required by every project) in its Energy and Atmosphere credit category; EA Prerequisite 1, Fundamental Commissioning of Building Energy Systems; and for an opportunity for two additional points the project may attempt to meet EA Credit 3, Enhanced Commissioning [USGBC, 2009]. Enhanced Cx requires that additional Cx activities are conducted and the Cx process more closely meets the recommendations of ASHRAE Guideline 0-2005, but is still far from a full Cx process. The Newsham et al. [2009] research questioned whether the Cx process had been conducted properly, it's possible the question should have been whether the process was conducted completely. Again the question of what should be required arises.

The major activities are critical, but only part of what the process needs to be. Serious consideration must be put into whom to contract to conduct the process. The current growth of Cx is increasing the demand for qualified providers but what constitutes qualified is still in question.

7.3. DEMAND GROWTH FOR COMMISSIONING SERVICES

Mills et al. [2004] reported in a comprehensive study of the cost-effectiveness of building Cx that initiatives by utility companies, inclusion of Cx in some building codes, government requirements, and professional organizations are contributing to growth, but the biggest driver at the time was the LEED certification process and the fact that LEED had a Cx requirement. LEED is continuing to drive growth. In 2006, 552 buildings had been certified under the LEED system [Turner and Frankel, 2008]. In November 2010, the USGBC reported that LEED certification had recently surpassed the one billion square feet mark worldwide with an additional six billion square feet currently registered for certification [USGBC, 2010]. Other contributions to the growth have been created by states adding Cx to codes. California, Washington, and Massachusetts have Cx requirements in there building codes. Idaho public schools require Cx. Oregon schools require Cx for certain building systems [PECI, 2009]. With the rapidly growing industry the need for qualified practitioners is in demand and supply is not keeping up with the demand [Tseng, 2005].

7.4. COMMISSIONING PROFESSIONAL CERTIFICATION

A professional certification typically indicates that an individual holds a certain level of competence in a given discipline. There are currently no laws which require a Cx certification for an individual to enter into a Cx services contract and many, with a wide range of abilities, background, and experience, are offering to provide Cx services. Some have or claim to have professional certification for providing such services. Ultimately, it is left to the discretion of the owner as to whether the potential commissioning provider is qualified. Table 7.1 presents a breakdown of the organizations who are certifying Cx professionals, the designation, what is required for the certification, Cx training requirements, and certification renewal.

Table 7.1. Cx Professional Certifications

Certification	Organization	Cx Experience Required	Training Required	Exam Format	Renewal
Commissioning Process Management Professional (CPMP)	ASHRAE	3 projects	no	115 questions 2.5 hours	3-year, 45 PDHs
Certified Commissioning Authority (CxA)	ACG	3 projects	no	100 questions 3 hours	Annual, Fee only
Certified Commissioning Professional (CCP)	BCA	3 projects 150,000 SF $30,000,000 const. cost	optional	125 questions 2 hours	3-year, Proof of continued Cx work
Associate Commissioning Professional (ACP)	BCA	none	optional	125 questions 2 hours	none
Commissioning Process Authority Provider (CxAP)	UW-Madison	2-4 projects SF and cost minimums	40 hours	4-part 2.5 hours	5-year, Fee only
Qualified Commissioning Process Provider (QCxP)	UW-Madison	none	40 hours	4-part 2.5 hours	Valid for 5 years

These are common certifications attained by Cx providers, but other certifications are available. Two organizations providing certifications not listed here are the National Environmental Balancing Bureau (NEBB) and Testing Adjusting and Balancing Bureau (TABB). The following are examples of the range of experience required for certification:

Table 7.2 contains the range of professional experience required to qualify to take the respective exams. This is not an aoo-inclusive list of the requirements for ASHRAE and BCA, rather the extremes for each.

Table 7.2. Range of Professional Experience Required

ASHRAE's CPMP range of professional requirements	Government-issued license as a professional engineer or architect with at least 3 years' facilities operations/ management, construction, design, or consulting experience
	High school diploma or equivalent or construction-related trades training or building operations training from a nationally or internationally recognized trade association with at least 10 years' facilities operations/management, construction, design, or consulting experience
BCA's CCP range of professional requirements	Four-year undergraduate degree or higher in a building science field (such as mechanical or electrical engineering, construction science, and construction) and a minimum of 3 continuous years as commissioning provider in a lead role within the past 5 years
	Two-year undergraduate degree in a non-building sciences field or high school diploma or general educational development (GED) and minimum of 3 continuous years as a commissioning provider in lead role within the past 5 years and minimum of 12 years of building-related experience

It can be seen that there is a wide range of requirements to qualify for the respective exams, different levels of education and or training combinations, different exam formats, Cx project experience, and different renewal requirements. It is unknown which certification will provide the owner with the best Cx service provider. It is likely that as more individuals are certified the requirements for certification will be tightened and become more difficult to meet. Opportunities for service providers to improve their skill set are available and required by at least one of the certifying organizations. UW-Madison, BCA, ASHRAE, and others provide formal Cx training in one form or another. With these varying abilities of professionals, a standard method of the Cx process would provide a means for the owner to have a better understanding of what service they should expect.

7.5 DISCUSSION

The focus of the Cx literature appears to be at the front and back ends of the project. The common thread across all phases of the project is poor communication. Given the varying guidelines, capabilities of the potential Cx providers, the current and expected growth and demand for Cx services, a standard methodology for connecting each of the Cx activities within the process back to the OPR is needed.

The OPR and BoD are considered living documents and are subject to change. In Figure 1.1, two activities, 'verify BoD meets the OPR' and 'verify construction checklist completeness', are typical points in a project when the OPR and BoD are frequently required to change. Late in pre-design or early in the design phase the design team provides the BoD to the owner for review. If the BoD and OPR do not align well then it must be determined which document or both must change. To make an informed decision as to whether to allow the change it must be analyzed for how it will affect the OPR. The same holds for proposed changes during construction. The change must be traced back to the BoD and OPR to analyze how the change will impact other design criteria and OPR. Quick analysis is extremely important at this phase of the project. Hurried decisions are often made to keep the project on schedule without a complete understanding of how the decision will impact the project as a whole. A standard methodology utilizing an adapted quality function deployment (QFD) four-phase model can provide a means for tracing the proposed design changes back to the OPR. Figure 7.2 illustrates the proposed four-phase model.

7.6. VERIFICATION OF THE FOUR-PHASE MODEL

7.6.1. Phase I: Pre-Design. The OPR is the start of the process. An accurate document will provide the design team with enough functional information about the building to develop their BoD for how they will meet all of the expectations. The first phase of the QFD model will compare these documents. Any deficiencies will be entered into the issues log and the owner will be notified. This begins the discussion or negotiation between the owner and design team. Either or both documents may be updated depending on the discussion. This will likely require multiple iterations to come to agreement, but agreement is the goal. At the end of this phase the OPR and BoD should align and the design team can take both documents into the design phase.

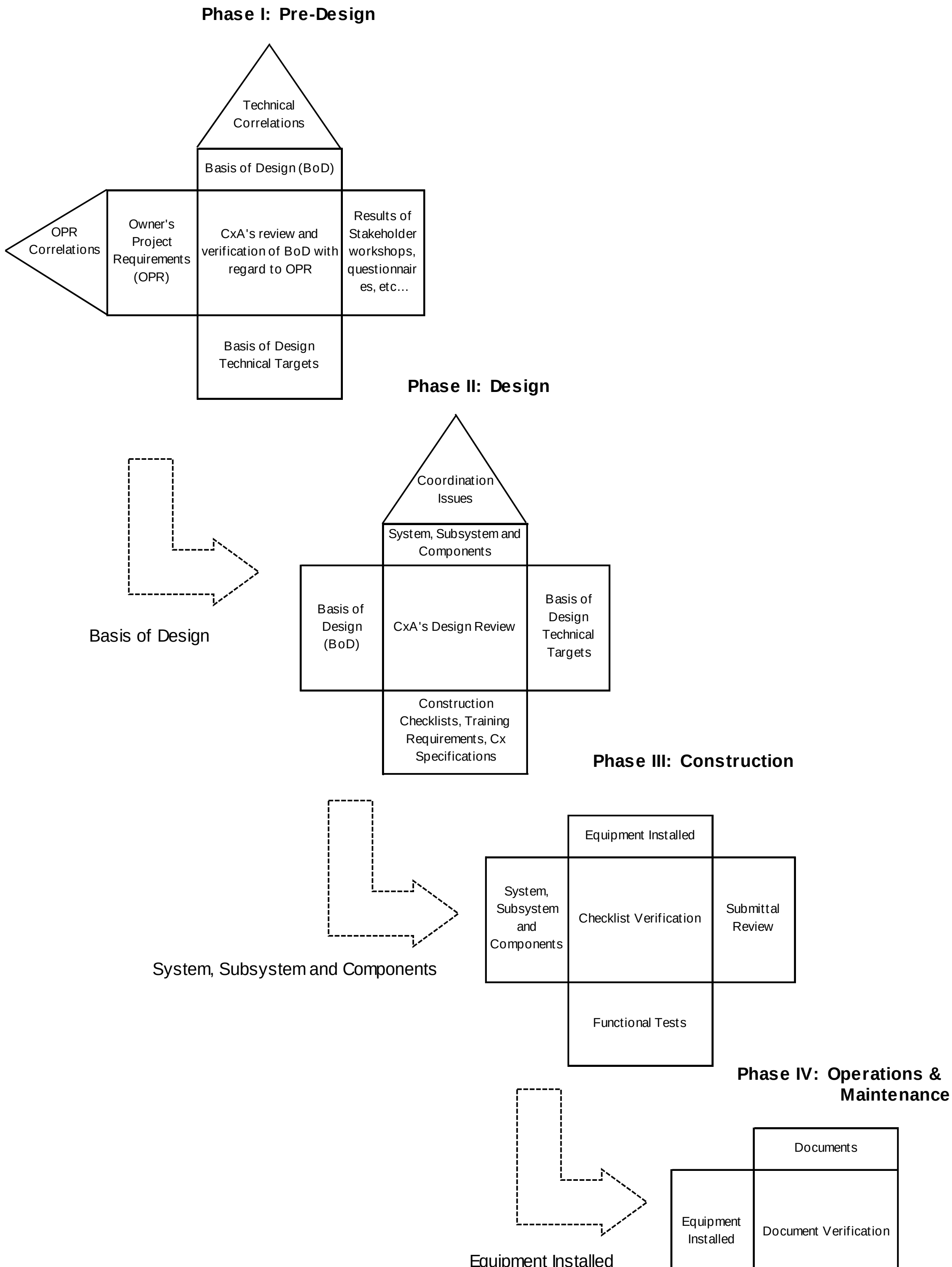


Figure 7.2. QFD Four-Phase Model for Cx

Each item that was logged as an issue will be analyzed for its root cause. The analysis should uncover one of several causes. First, the necessary information was not provided in the OPR. This may be because the information was never considered or it was somehow left out when the final document was prepared. If the information was provided the problem may be that the information was vague or inaccurately presented (one might argue that this is the same as not having the information at all). The design team may have misinterpreted the information and based their decisions on what they thought the correct information was. The design team may have made assumptions based on their experience or they did not address the requirement at all. Whatever the cause, the knowledge of why there was a problem will assist in improving the process by finding ways to improve the communication. Since this phase may require multiple iterations there may be an opportunity for immediate improvement.

7.6.2. Phase II: Design. The next phase looks at the design review(s). Now the design will be verified against the BoD. Typically the CxA will conduct one review of the design development documents and two reviews of the construction documents. The number of reviews and at what percentage of document completion would have been determined by the contract with the owner. Again any deficiencies or issues will be logged and reported to the owner. The issues will be traced back for root cause. The linked QFD model will allow a quick trace back to the BoD and OPR if necessary. This may uncover a cause within the design document, the BoD, or the OPR. Any or all of the three documents may need to be revised. With this phase having multiple reviews there will be an opportunity to improve communication for each later review. Other activities occur during this phase and will be captured in the QFD model, including the Cx specification development, construction checklist development, and construction coordination review (the roof of the model). The goal is to provide the most accurate and complete construction documents for the bidding process. This phase not only reviews the current work against the work of the previous phase but also begins preparing for the downstream customers, the contractors and the O&M staff.

7.6.3. Phase III: Construction. The third phase is primarily about construction. The construction, by trades, will now be verified against the design. This will be accomplished using the construction checklists developed in the previous phase. The subcontractors will use the checklists during installation as a quality assurance measure. This does not eliminate the need for the subcontractor's internal quality assurance/quality control processes. It is a measure to ensure certain aspects of the installation meet the OPR, mainly that there is easy access for any type of maintenance that will be required. The CxA will sample the completed checklists and verify accuracy during site visits. Again deficiencies or issues will be logged and investigated. A possible cause might be the coordination of the trades. The plumbers may have run their pipe in front of a variable air volume (VAV) access panel that is now blocked from removal. Now the issue analysis will have to determine why this happened and provide feedback for continuous improvement. Once again the linked QFD phases will allow the issue to be quickly traced back and any of the previous documents may require updating.

Other activities during this phase will include submittal review, functional test development, and training. Submittal review will determine if the materials and equipment proposed by the contractor align with all of the previous documents. If not, why. The functional tests will be used at the end of construction to verify the systems are functioning as expected. This phase again looks back at the previous phases for verification but also looks downstream and begins to prepare for the O&M phase. An accurately built and functioning building, OPR, BoD, construction documents, functional tests, O&M manuals, systems manual, and training documents all come out of this phase and are the deliverables to the O&M staff. Everything there is to know about this new building should be available for the O&M staff to review in order to provide complete transparency of what, when, why, and how.

7.6.4. Phase IV: O&M. The O&M phase of the model is simply a checklist for gathering all of the necessary documentation for the O&M staff at turnover. Having the complete documentation allows the staff to maintain and operate the building at optimal performance. The information contained within this documentation provides a method for continued communication among the O&M staff and occupants. One example of an opportunity to make use of the OPR and BoD documentation at building turnover is to develop a training session for the building occupants. Most times the occupants are not aware of the efficiency requirements that have been incorporated into the design and construction. Field experience has shown that the efficiency standard that is most often noticed by occupants and the cause of many calls to maintenance is the control of the HVAC system. Most have experienced a cold or warm period in their work space and have attempted to adjust the thermostat to improve the conditions. If it is cold in the office the thermostat is adjusted to a higher temperature and the expectation is that the space will become warmer. This is not an unreasonable expectation, but one that is often not realized. This may be caused by the HVAC control strategy. For example, ASHRAE Standard 55.1-2010, Thermal Environment for Human Comfort informs the designer that most occupants will not be uncomfortable if the temperature is approximately 70-76 degrees Fahrenheit. In the HVAC controls the set points for the temperature control are then locked to these temperatures. Meaning if the temperature is already 76 degrees and the thermostat is increased to a value above 76 the system will not respond by making the space warmer. This frustrates occupants that are feeling cold and frequently generates a call to maintenance with the complaint that the heat is not working. Other occupants in the area might appreciate the fact that the space is not getting any warmer. This scenario is also true for the opposite state when more cooling is desired.

If the OPR and BoD are clear and provide information as to why this control strategy was pursued, the occupants can be informed of this when they move in. With a bit of understanding as to how the system is designed to operate the complaints may be reduced. The few occupants who prefer a temperature outside the set points will know to dress accordingly to personally adjust for their own comport before calling maintenance with a complaint. This is a result of simple communication that is typically not accomplished. The Cx process is about quality, but quality requires communication, particularly through documentation. Detailed and accurate knowledge and information must be transferred through the project so each team has the best opportunity to deliver what is expected of them.

In the previous example if the information regarding the HVAC set points is not available this is again a breakdown in the communication and transfer of knowledge in the documentation. As this information should be presented in the OPR and BoD the trace back through the four-phase model would lead back to those documents. The cause of the failure for those entries would be investigated. This issue of course would have been identified before the O&M phase as the set point information is required for HVAC controls programming during construction.

7.7. CASE STUDIES

7.7.1. Introduction. The purpose of Cx is to ensure the owner has been delivered a building that was designed as requested in the OPR and built and operating as designed. It comes down to how the owner feels at the end of the Cx effort and whether there is satisfaction. Much of this is subjective. Issues are the key to determining if this has been accomplished. Obviously, if hypothetically there were no issues during the project, one would expect that the owner would be satisfied with the end product and the project would be considered a success. But, of course looking only at issues as a total count is not sufficient. When an issue occurred (project phase), what it involved, and what it cost the owner above the original budget need to be considered. For any issue that is analyzed, traced back to the root cause, and provides feedback for improving the Cx process, this may do little to benefit the owner of the current project. With that though, if the analysis of issues is deferred to project end, any improvements to the process will certainly only help to improve the project of the next client.

The methodology will be evaluated based on issues throughout the Cx process. Each issue that is discovered needs to be analyzed for root cause. With an expectation that every issue is caused by a breakdown in communication somewhere in the process, this will provide feedback to a possible weakness in the methodology and an opportunity for improvement. When considering a document as the means of communication there may be a breakdown in the information that was input, the preparation of the document, the review of the information, or the use of the information. Each of these will need to be considered when evaluating improvement options. Shakoorian [2006] presented a table which illustrated the relationship for each of the Cx documents, the team members who will provide input, prepare the document, review the document or use the information in the document, and which role they have with the document. The table was then used to identify which documents were most important. As might be expected, the OPR ranked highest. This indicates that this document should receive significant attention.

The accuracy of each document is of utmost importance to the downstream team or user. If the documents are not accurate, issues are certain to occur. Careful attention to inputs, the drafting or creation of the document, and any review(s) will improve the ability of the user to complete their work accurately. In the interest of the CxA providing continuous improvement, even if it only benefits the next client, the issues need to be analyzed as they are discovered and resolved. The primary focus of the analysis is to discover the cause of the communication breakdown and to uncover ways to improve the process, but the analysis should include other perspectives.

First is the cost, if any, to the owner, designer(s), or contractor(s) for not stopping this from becoming an issue in the first place. Nearly every issue will have some cost associated with it, be it money, time, labor, or even reputation. Typically the sooner issues are identified and resolved the lower the cost to resolve. The analysis should also consider the other direction. What is the savings associated with identifying and resolving the issue at this particular point in the project. In addition, it is important to consider the cost if the issue was not caught. Nicholson and Molenaar [2000] investigated the savings aspect of the Cx process primarily to use as a point for selling Cx services to future project owners. Cost avoidance is certainly an important motivation for eliminating or reducing issues.

The goal with continuous improvement is to eventually contain the majority of the issues to the start of the project while the teams are attempting to bring the OPR and the BoD into alignment. Resolution of these issues should not be costly.

7.7.2. Project Data. Two recent projects were selected for review of the Cx process as it relates to project issues and the opportunity to analyze the issues backwards through the phases for discovery of the root-cause. Issues were considered to be any request for information (RFI), change order (CO), warranty issue, maintenance work order (WO) submitted beyond the warranty period, and issues recorded by the CxA on the Cx issues log. Table 7.3 contains the tabulated information gathered regarding project issues.

Table 7.3. Project Issues

Building	# of RFIs	Change Orders		# of Warranty Issues	# of Work Orders	# of Cx Issues	
		Quantity	Cost ($ M)			Design Issues	Construction Issues
#1	312	173	$ 3.9	Note 1	75 Note 2	Note 3	Note 3
#2	23	34	$ 0.2	3	Note 4	263	44

1. The documentation regarding warranties was unable to be located.
2. Issued during the second and third year. The majority being HVAC and lighting related. Both systems have been a problem from building completion primarily due to the lighting controls and HVAC design and controls.
3. Documentation for Cx issues was not located.
4. The building is just out of the warranty period and no work orders have been submitted.

Building #1: This was a four-year, multi-phase project to expand and renovate an existing building. The site consisted of two buildings, one to be razed and one to remain for the renovation and expansion. The remaining building was a two-story, approximately 67,000 sq. ft. and used for classrooms, offices, and experimental and teaching laboratories. An attached three-story addition was added in the location of the razed building. The addition was approximately 90,000 sq. ft. and primarily lab space with a few offices. Once the addition was completed the offices and labs were relocated from the existing building to the new section and a complete renovation of the old side was then conducted. Construction cost was $26 Million.

Building #2: This was a major renovation project with complete demolition down to the shell. Most of the masonry interior partitions remained as the building programming did not change. The building is three-stories with a full basement, 30,000 sq. ft. of primarily research laboratories with a few offices on each of the upper three floors. Construction cost was $4.6 Million.

The same project manager, construction project manager, and director and assistant directors of operations were involved with both buildings from start to finish. During conversations with these owner representatives regarding Cx of Building #1 many negative recollections were expressed. Generally this project was not considered a success at completion. Consider the information provided in Table 7.3. Much of the information that should have been documented and provided by the Cx provider was not located. It is unknown to the researcher if the information was originally provided and not properly filed or if the information was not provided at all. While reviewing the project files no information regarding any Cx services was located including the original proposal for the Cx services, which would have identified what was actually expected of the Cx provider. It was pointed out by the construction manager that when issues were discovered they were quickly remedied and did not likely end up on the issues log of the Cx provider. This was not the case for Building #2.

During the Building #2 project it was explained to the Cx team, which included the construction manager and general contractor, that documenting the issues was not an attempt to point fingers or to point out substandard work but rather to document what occurred, how it was resolved, and to ultimately use the list to improve the process on the next project(s). This explanation was well received and most issues were added to the Cx issues log. The documented issues available for both projects was evaluated and traced back through the phases to determine if the issue could or should have been identified in an earlier phase of the project.

7.7.3. Building #1 Issues Review. There were 312 total documented RFIs. The first nine RFIs were regarding details of the expansion joints between the new addition and the existing building. Three additional RFIs for expansion joints were submitted, with the last being 14 months after the first, again requesting details. The lack of these details should have been identified during one of the three or four Cx design reviews in the design phase of the project. At a minimum the first nine requests should have prompted a full review of the expansion joint drawings and details. Ten RFIs were regarding lighting, mainly schedule deficiencies and electrical/control connection questions, were identified. The schedule deficiencies would have been identified during design reviews. It is unclear whether the electrical connection issues would have been discovered prior to construction. Sixty-three, or 20% of the total, RFIs identified were regarding the HVAC system. These span a full range of issues from coordination problems (ducts will not fit in space, interferences, penetration locations, etc.) and diffuser types to the hydronic piping for an air handler completely missing. The hydronic piping issue resulted in a $44K change order during construction. Again, most of these would have been identified during a Cx design review while utilizing the roof of the design phase model to identify coordination issues and development of the construction checklists below the body of the matrix. Seven related to doors, with one for lack of a door schedule in the drawings. Another was questioning electronic access which resulted in a CO of ≈ $245 K. This is an OPR that should have been captured prior to the architect's programming and definitely should have been identified as to whether the BoD addressed this OPR during the pre-design phase.

The number of change orders was high at 175 for a cost of ≈ $3.9 Million. Just over $1M was caused by a project delay that would not have been impacted by the Cx process. Along with the two COs mentioned previously in the RFI discussion a couple of standouts were identified. First are changes to the electrical one-line drawings to correct discrepancies at a cost of ≈ $70K. Second is to move the generator and associated wiring at project phase change for a cost of ≈ $99K. Both of these would have been identified in the Cx design review.

As identified in Table 7.3 the warranty issues and issues logs from the Cx provider, for both the design and construction phases, either do not exist, were never received by the owner, or have been misplaced. Either way, these important documents are not available and indicate a serious breakdown in the process.

The work orders during the two year period after warranty identify multiple issues which should have been captured during the Cx process. First note that there were 75 WOs submitted, most of which involved the HVAC and lighting systems, and door locks. The various controls and control components appear to be at fault for the majority of the issues. As mentioned previously the owner's representatives identified the HVAC and lighting systems as problematic from turnover to date. Though the documents are unavailable, the owner's representatives have identified that these systems had significant warranty calls and service. The root cause issues were never identified and resolved and the maintenance calls continue. Potential problems that the Cx process should have identified: the complexity of the control systems raising concerns of maintainability, review of the proposed equipment, submittal reviews, O&M staff training, functional testing, and the systems manual to explain how all of this works. A summary of the issues is provided in Table 7.4.

Table 7.4. Building #1 Summary of Issues

Issue Type	Qty or Cost	Description of Issue	Identified by Methodology at	Savings
Request for Information	12	Expansion joint details missing	Design review	Associated change orders and project delays
	10	Lighting schedule deficiencies	Design review	
	63	HVAC	OPR / design review	
Change Orders	$44,000	Hydronic piping not on drawing	Design review	$44,000
	$245,000	Electronic door access	OPR development	$245,000
	$75,000	Electrical one-line drawing deficiencies	Design review	$75,000
	$99,000	Move generator and associated wiring	Design review	$99,000
Work Orders	75	HVAC, Lighting and door locks	Various phases	Hundreds of maintenance man hours with associated cost as well as lost opportunity
Documentation		Missing documentation: warranty items, all Cx documents, systems manual, functional performance tests.	Various phases	Improved response time, troubleshooting efficiency, preventive maintenance, and reduced system downtime.

7.7.4. Building #2 Issues Review. RFIs accounted for 23 of the issues. These included requests for details for installation of certain electrical, duct insulation, concrete walk elevations, and chilled water risers. These are relatively minor requests but these missing details should have been identified during the drawing reviews in the design phase.

There were 34 COs at a cost of ≈ $ 0.2M. The most significant included a $65K CO to add data and VOIP capability to each space. This should have been picked up during pre-design as an OPR and then ensuring it was addressed in the BoD. Another was a $38K CO to add five additional new fume hoods to the labs. Again, this should have been picked up in the pre-design phase.

The design issues were recorded as comments for each drawing during the review. These comments totaled to 263. Many of the comments were made by the O&M staff which was included in the Cx review of the drawings. Most of the comments requiring changes to the design were able to be corrected without cost. The reviews with the O&M staff were conducted after the start of construction. These changes should have been included in the OPR early in the pre-design phase. Again a breakdown in communication, but the results were not costly.

The Cx provider recorded 44 issues during construction, most of which were during the functional testing. Many of the issues involved the HVAC control and were presented to the owner as possible points of improvement. Some included lack of alarms to notify O&M of failures. These are simple control programming changes as each of the required sensors was available. Several involved the ballasts on specified emergency lights that were not functioning to turn on the lights during power outage simulations.

Several other items were identified to not match the original design and were found to have been approved and changed by design and the owner, had been documented in the as-built documents, but the Cx had not been notified. One change identified was the addition of a bypass pump for freeze prevention on the outside air coil. This change was made but never made the as-built drawings and was not brought to the attention of the O&M staff. This became a failure point on the system during the first hard cold. It took some time to discover the issue through troubleshooting efforts. This was a failure of communication during the construction phase and leading into the O&M phase. The Cx identified the issue and the designer was to update the as-builts but the information was never passed to the O&M staff. A summary of the issues is presented in Table 7.5.

Table 7.5. Building #2 Summary of Issues

Issue Type	Qty or Cost	Description of Issue	Identified by Methodology at	Savings
Request for Information	23	Minor requests for details of electrical, ducts, concrete walks, and chilled water risers.	Design review	Associated change orders and project delays
Change Order	$65,000	Add data and VOIP to each space	OPR development	$65,000
	$38,000	Add five additional fume hoods	OPR development	$38,000
Cx (Design)	263	Small issues with various building systems will little or no cost to resolve	OPR development	Associated change orders and project delays
Cx (construction)	44	Primarily during functional testing: lack of system alarms, sequence programming,	Design/construction review of control logic	Associated change orders and project delays

After the experience of Building #1 this project was considered to be a success at completion. The Cx experience was considered to be much improved but there was still a desire to have a standard method to provide to potential Cx providers on future projects as a way to specify this is how it is expected to be done.

7.8. TRACING BACK DESIGN CHANGES AND ISSUES

The following is an example of a proposed design change traced back to the OPR to identify the cause of the issue and potential design impacts of the proposed change. In this example assume a change was proposed in construction and involved the installation of a section of HVAC duct. This is a coordination problem in which electrical conduit, HVAC duct, and fire sprinkler lines are competing for the minimal space between the suspended ceiling and the structure above. The conduit and sprinkler lines have been installed and the proposed change is to reduce the size (the cross-sectional area of the duct would be reduced from the original design) of the duct as it passes through this area.

The installation of the duct can be traced back through the construction checklist, to the System, Subsystem and Components, then back to the design phase. At the design phase the trace can be followed through the CxA's Design Review matrix to any associated BoD (there may be more than one). As a side analysis the trace also looks up into the roof (Coordination Issues) for potential coordination issues. As it turns out this coordination issue was identified in the design phase and the owner was notified by the CxA. Having used building information modeling (BIM) during design, the design team felt there was sufficient room for all components. Somehow this 3-D modeling information did not get transferred to the general contractor and subs for use in construction. Though the model proved that all of the equipment would fit into this space as modeled, it didn't account for the fact that three different trades needed to communicate and coordinate their individual installations. This is an opportunity for improvement and a solution for dealing with this knowledge transfer needs to be investigated.

Continuing the trace back to the pre-design phase it is found that a change of this BoD criteria will impact other BoD (identified in the roof, Technical Correlations) and those impacts will need to be analyzed. Now following the trace to the OPR it is identified that this BoD is connected to and may impact an OPR for low HVAC noise and another for efficiency. This is a LEED project and it is also found that a change in these OPR may affect other LEED credits that are being attempted. Once all of the impacts are understood the owner has some decisions to make, but can now make the decisions from an informed position regarding how any decision will impact the project as a whole, rather than from the perspective of simply keeping the project on schedule.

7.9. CONCLUSIONS OF THE METHODOLOGY VALIDATION

There are many different approaches to the Cx process and levels of ability among the Cx providers. A standard for the process is required. Utilizing this methodology to adapt the four-phase model provides forward verification of the required information and documents to each phase of the project. This will provide any CxA, regardless of their certification, Cx training, experience, and preferred guideline, a means to offer a consistent approach to all owners. Regardless of the project size and complexity, by virtue of constructing the model and tracking the required information, the project will have reduced issues by improving communication and knowledge transfer and providing proper documentation to the O&M staff at project end.

The first step to accomplishing this is the addition of the correlation matrix to the OPR in the Pre-Design phase model. This allows the owner and design team to align the OPR and BoD while be able to understand the impact(s) each change will have on either the OPR or BOD. The addition of the correlation matrix to the system components in the Design Phase model allows the CxA to investigate potential coordination issues that might occur during the construction phase. This matrix will improve the efficiency of the construction phase.

As previously mentioned the successful Cx of a new building is only the beginning. Much is required for Cx to be considered successful but one key is the documentation to the O&M staff. If the O&M staff is prepared to operate and maintain in a sustainable manner they will have greater opportunity to run at peak efficiency for the life-cycle of the building. Improving the knowledge transfer from the owner to the design team, design team to the general contractor and subs, and from the GC to the O&M staff, provides a baseline for ongoing Cx and benefits back to the owner, coming full-circle of ensuring the OPR is met. The model also provides a means to trace issues back through the entire process to identify the root-cause and allowing discovery of communication breakdowns and opportunities for continuous improvement, along with the ability to understand the impact(s) of proposed design changes on the project whole.

The proposed methodology does provide a standard for conducting the Cx process and provides a platform for future academic research relating to improved project communication and documentation, continuous improvement of the major and minor Cx activities, and deeper analysis of cost avoidance and the cost of quality. Until a standard methodology is implemented it will be difficult, if not impossible, to conduct this type of research.

8. CONTRIBUTIONS TO THE BODY OF KNOWLEDGE

The methodology proposed in this research provides the first utilization of the QFD in the Cx industry. The proposed methodology provides a systematic and integrative approach to the design/build/bid process in new building construction utilizing QFD. This will allow Cx providers to effectively connect each of the Cx activities back to the OPR, therefore, carrying the OPR through the design and construction phases to ensure the OPR is achieved with the final building. This methodology can provide a standard method for applying the Cx process and in turn provide a platform for future research in the Cx industry.

This methodology also modifies the four-phase model for application of the Cx process. Key modifications are (1) the addition of a roof on the OPR to serve as a second correlation matrix for identifying conflicts within the OPR, (2) the addition of a roof on the design phase HOQ to identify potential coordination problems that may occur among the different equipment installations during construction, and (3) the development of a stand-alone HOQ for use in LEED projects to provide both, a method to quickly examine the certification options and associated points, and an understanding of the design impacts among the credits.

9. SUMMARY

A new methodology is presented which integrates QFD into the Cx process. Current Cx guidelines and best practices provide little direction regarding how to improve communication and knowledge transfer through the phases of the project. They provide no guidance regarding how to assist the owner when design changes are proposed. The CxA is entrusted with managing the quality of the project as the owner's representative and to ensure the OPR is met at the end of the project. The OPR is a living document and, therefore, is subject to change, but any change late in design or in construction needs to be carefully evaluated as to how it will affect the project as a whole. Information for how to accomplish this is unavailable.

Well established Cx consulting firms were asked in a formal RFQ, (1) how they would verify the BoD with regard to the OPR and (2) how they will verify the final design with regard to the BoD. These are just two critical steps in the Cx process and the quality of those two activities may determine the ultimate success of the project. None of the responses to the RFQ received provide a method for accomplishing those tasks. Either the firms had no method or did not want to disclose what they do use. For an owner there is no way then to assess whether the potential CxA will be able to provide quality for those tasks. This situation provided motivation for this research.

QFD was investigated as a solution to closing the gaps among the critical Cx processes. Though QFD was created for use in product development and manufacturing it is well suited for the similar development activities of building design and construction. QFD is used to carry the voice of the customer to product design/development and through to manufacturing. This capability of QFD can provide the CxA with the same opportunity to carry the OPR through design and construction when used in the Cx process. The RFQ questions that were not answered by the Cx consulting firms can now be answered using QFD. The methodology does bridge the gaps in the Cx process.

The traditional QFD four-phase model used in product development was modified to intergrate with the Cx process. Emphasis was placed on improving communication and transferring knowledge among the different project teams and the project phases. Early detection of potential issues in the pre-design or design phases is critical to reducing costs associated late issues; therefore, two key modifications were made to the model in the early phases. The addition of a roof to the OPR, used to identify potential conflicts among the different OPR, is essential for bringing the BoD into alignment with the OPR. The traditional HOQ already places a roof on the BoD to identify potential conflicts among the design criteria, so if an item in the BoD must change to accomplish OPR alignment it can quickly be seen if that BoD change will impact other design criteria. This ability to investigate potential conflicts must also be available if it is decided that an OPR must change to accomplish alignment. With this additional roof a change in OPR can be investigated for how it will impact other OPR.

A roof was also added to the Phase II: Design so coordination issues that may occur during construction can be identified well before construction. This will allow for either a design change during the design phase to reduce the risk or for the development of a plan to help the general contractor and subcontractors understand the potential issues early in construction. Having the knowledge that there is a potential issue and being able to communicate that to the next team will provide a greater opportunity to avoid the issue.

The methodology has obstacles that can be overcome. The work in the pre-design phase will take a significant amount of effort to accomplish. Of course this means more time and money which will translate back to the owner in higher fees, which might keep owners and CxA's from wanting to use the process without some proof of a payback and ROI. Shakoorian [2006] determined that the best method for applying the Cx process was for the owner to conduct the process themselves. Some large university systems have realized the advantage of Cx, particularly for re-commissioning, and have developed their own in-house Cx team. There is an opportunity for this type of owner, who has dedicated Cx employees, to implement this methodology at little extra cost. With more buildings being commissioned using the methodology there is a greater opportunity to conduct additional research with regard to the methodology.

10. FUTURE RESEARCH

The methodology to adapt the four-phase model in this research can be used to standardize the Cx process in turn providing opportunities to more deeply study methods for continuous improvement, improved communication and knowledge transfer through the project phases, and the costs and or savings associated with issues identified during the Cx process.

A software package should be created to improve the efficiency and speed the development of the four-phase model. This would likely help overcome some of the potential obstacles associated with the extra time and cost this methodology may require. A feature of the software would interact with BIM programs, Revit for example, to extract the required information for automatic population of the system, subsystem, and components area in Phase II of the methodology.

This methodology was developed for the design-bid-build construction delivery process. The design-build delivery method has similarities to the concurrent engineering methods used in product development and manufacturing. Further research to adapt this methodology to the design-build project delivery method should be conducted.

The roof of the LEED HOQ used to understand design impacts among the LEED credits needs to be enhanced to better track the chain reactions certain design decisions create among the credits.

The goal is to find ways to continuously improve the opportunity for providing the owner of a new building with, at minimum, the value they were expecting at the start of the project.

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