Title

Managing Project Structural Complexity by Integrating Facility Management in Planning, Designing, and Execution of High-End Facility Upgrades

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Publication Date
2017

Peer reviewed|Thesis/dissertation

Managing Project Structural Complexity by Integrating Facility Management in Planning, Designing, and Execution of High-End Facility Upgrades

by

Audrey Marie Bascoul

A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy

in

Engineering – Civil and Environmental Engineering
in the
Graduate Division
of the
University of California, Berkeley

Dissertation Committee in Charge:

Professor Iris D. Tommelein, Chair
Professor C. William Ibbs
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Fall 2017

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ABSTRACT

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Ensuring that a building consistently supports occupants in producing value is a global challenge. To tackle this challenge, the discipline of Facility Management (FM) emerged in the 1970s. FM became responsible for steering the building toward a constantly changing desired future state. Since then, buildings have become increasingly more complex. Despite the existence of FM, buildings still fail in terms of value delivery. Failure to meet customer requirements is waste. This motivated this research.

Through review and analysis of the literature, the researcher classifies FM failures in five aspects: (1) building systems, (2) people, (3) tools and data, (4) processes, and (5) changes. To prevent those failures, researchers and practitioners have developed solutions. However, these solutions have not been able to reduce waste in facility delivery for at least three reasons. First, they fail to capitalize on FM knowledge, and thus miss the opportunity of learning from other completed facilities. Second, they do not address the Transformation-Flow-Value (TFV) views of FM. As a result, they focus on ensuring that building components function and omit value delivery to customers. Third, they do not acknowledge the complex nature of FM, which manifests itself at the organizational and at the project level. This leads to FM not being able to steer the building so that it meets customer expectations.

This dissertation advocates that the late involvement of FM in project delivery contributes to waste and is manifested in a lack of awareness of structural complexity. Structural complexity is the condition of a system whose behavior emerges from the interactions of its parts. The burden of managing that complexity falls on FM during operations and maintenance of the completed facility. By not engaging FM strategically in project delivery, such complexity is not managed easily and the facility may fail to deliver the expected customer value. The use of the Design Structure Matrix (DSM) methodology, a matrix-based method to model structural complexity, and Hoshin Kanri, a Lean planning process used to deploy strategies in organizations, will help generate value to owners and occupants by enabling FM involvement in the planning, designing, and execution of facility upgrades and construction projects in general.

To substantiate this argument, this research investigates the manifestation of structural complexity and its implications for FM at two levels. First, at the project level, it documents and analyzes two examples of high-end facilities that failed to deliver value to occupants. Both examples explore how the lack of management of structural complexity contributed to FM

failure. The researcher uses DSM to gain insight into FM failure and uses the Lean Project Delivery System (LPDS)-Multi-Domain Matrix (MDM) framework, to make the interdependences between project elements and thus some aspects of complexity visual. Second, at the organizational level, this research documents how two large public organizations have integrated FM in project delivery. Furthermore, this research presents a novel model based on Hoshin Kanri, named Hoshin-for-Facilities, to support and enable FM integration. This model builds upon Lean Construction principles and methods, while acknowledging the complex nature of FM.

By analyzing the case studies, the researcher identifies five aspects of structural complexity in projects involving high-end facilities: (1) customer complexity, (2) organizational complexity, (3) product complexity, (4) process complexity, and (5) market complexity. Poor FM integration in project delivery has a compounding effect with product and process complexity. At the project level, DSM is fit for modeling structural complexity. Its early use on projects could help avoid negative design iteration (process complexity) and increase transparency in design decision making (product complexity). The LPDS-MDM framework offers a holistic approach to manage project structural complexity. At the organizational level, Hoshin-for-Facilities seems promising for engaging FM in project delivery.

This research contributes to knowledge by augmenting the literature on FM at its intersection with D&C, revealing by using DSM how structural complexity manifests itself in projects, formulating the implications thereof for facility delivery, and proposing Hoshin-For-Facilities to enable strategic FM integration in project delivery.

This dissertation shows how project structural complexity can be managed by integrating FM in project delivery. This research helps ensure that facilities support organizations' business objectives. It is targeted to business owners of high-end facilities, i.e., facilities that house sophisticated systems and/or equipment, whose performance is critical for the organization to meet its business objectives. Future research can deepen understanding of how the language used during project delivery contributes to complexity and then explore how project teams can leverage those findings (if any) to manage complexity.

DEDICATION

I dedicate this dissertation to my late grandparents, Louisa Bascoul and Manuel Delgado.

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ACKNOWLEDGMENTS

I am most grateful to my research advisor, Professor Tommelein, for guiding me in this academic endeavor, sharing her enthusiasm for Lean Construction, and demonstrating that excellence in both teaching and research is possible. Her academic achievements are exemplary and I feel immensely privileged to have worked under her supervision. I hope to keep collaborating with her in the future and I am very much looking forward to it. At a personal level, I thank her for always being approachable and helping me gain self-confidence.

I would like to thank Professor Ibbs, without whom I would not be here today. I owe him my first experience at UC Berkeley during Summer 2012, the start of my interest in research, and the completion of this PhD. His continued support has been invaluable at times I self-doubted my ability to complete this endeavor. I also thank him for reminding me that patience and pragmatism are a virtue. I am also most grateful for his guidance in this research and his career advice.

I would like to thank Professor Radke for his suggestions and comments on my research and for recommending me to: “just lay outside in the grass, close (my) eyes, and think.” His high-spirited personality is contagious. I also thank Professor Ryokai for serving on the qualifying exam committee.

I want to thank the academic staff Shelley Okimoto and Julia Konopasek at UC Berkeley, for their exceptional support. They have helped me overcome homesickness many times.

In the industry, many people have made this academic pursuit possible and enriched it in many ways.

I have an immense gratitude for Danielle Douthett, with whom I have worked on the Facebook West Campus construction project during a year-long internship at Level 10 Construction. I very much admire her for her outstanding career, her determination, and the respect she has gained in the industry. She has taken me under her wing and I could not have dreamed of a better mentor. She has a special place in my heart.

At the Lawrence Berkeley National Laboratory (LBNL), I want to thank Dr. Stan Tuholski and Ellen Ford, for their invaluable support in research. I also want to thank George Thomas for his tremendous encouragement and his insights on the first case study; Ben Bolles for his curiosity about Lean, Jim Haslam for his insights on the second case study, John Braithwaite for his precious input, and Laura Chen for her delicious baking creations. I also want to thank Rick Chapman from the Department of Energy (DOE) for reviewing a portion of this work.

At the University of California San Francisco (UCSF), I want to thank Michael Bade, Scott Muxen, and Dr. Patricia Tillmann for their contribution to this research, and Beth Piatnitza for her friendship.

At DPR Construction, I want to thank Dr. Atul Kanzhode, Dr. Andrew Arnold, and Dr. Arundhati Ghosh for their encouragement to stick with the PhD and for initiating my interest in Facility Management.

At Level 10 Construction, I want to thank my dear friend Jonathan Peterson for teaching me how to be a good project engineer, the superintendents Russell Burt and Duane Kissinger for sharing their knowledge accumulated in the field, and Michelle Smith and Jessica White for their kindness.

My friends in 407 McLaughlin have also been an invaluable source of encouragement and intellectual stimulation: Nigel Blampied, Sevilay Demirkesen, Markus Kohl, and Ergo Pikas, and former PhD students: Paz Arroyo, Adam Frandson, Eder Martinez, and Mike Taptich.

I cannot thank enough my friends from here for their patience when the PhD was taking precedence over social life (I'm sorry!): Karina Cucchi, Soazig Kaam, Laure Leynaud Kieffer (cheers to all the tears you've wiped away, what would I do without you?), Thibault Martin, Alma Osseiran, Peter Razavi, Jean-Baptiste Sibille, Robert Uomini, and the friends who visited: Hugues Piazza and Rémi Raffin. I am also thankful to my friends from France. They have showed continuous support through messages, Skype calls, postcards, letters, and translation from Japanese to English: Othmane Benchekroun, François Debaillon, Cyrille Debray, Constance Frénois, Anne-Hélène Kotoujansky, Amélie Lengaigne, Claude Lormeau, Marion Olekhnovitch, Matthieu Pluntz, Marie Rouquette, Marion Sathicq, Sara Whomsley, and Marine Peyregne.

None of this would have been possible without the infinite and unconditional love from my family. To my mother, Dominique Bascoul, you are my rock and words cannot describe the magnitude of your emotional support, see… we did it! To my father, Joël Bascoul, the tears of joy and pride you poured for even the smallest of my achievements gave me the strength to work even harder and the boldness to dream bigger, and to my sister and best friend, Emmanuelle Bascoul, thank you for always being supportive of my choices even if it meant living an ocean away from one another.

This work was funded in part by industry contributions made in support of the Project Production Systems Laboratory at U.C. Berkeley. All support is gratefully appreciated. Any opinions, findings, conclusions, or recommendations expressed here are those of the author and do not necessarily reflect those of contributors to P2SL.

DEFINITIONS

Words can have different definitions depending on their context. In order to develop a shared understanding of the proposed research question and findings, this section lists the definitions adopted for this research.

Term	**Definition**
Building performance	Building performance describes the response of a building to a satisfaction problem in which the conditions to satisfy depend on building occupants and the organization's business drivers. Examples of such conditions include: occupant satisfaction, savings in energy performance, alignment with the organization's long-term objectives, etc. Expected performance is the desired response of the building to the satisfaction problem, whereas actual performance is the response of the building experienced by building occupants.
Building system	"A building system is a group by which building elements are group according to a common function within the building." (buildingSMART 2017).
Choosing-By-Advantages	A decision-making system that supports sound decision-making using specific comparisons of importance of advantages of alternatives (Suhr 1999).
Commissioning	"A quality-focused process for enhancing the delivery of a project. The process focuses on 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 2013a).
Constraints	Limitation or restriction applying on the Means. Examples can be: location, cost, and time.
Design concepts	Ideas presented as solutions to the alignment between Ends, Means, and Constraints.
Design Structure Matrix (methodology)	Methodology used "to perform both the analysis and the management of complex systems. It enables the user to model, visualize, and analyze the dependences among the entities of any system and derive suggestions for the improvement or synthesis of a system." (Lindemann 2016).

Term	Definition
	Synonyms: Design Structure System (Steward 1981), Dependency Structure Matrix, Problem Solving Matrix (PSM), Design Precedence Matrix, etc.
Detailed engineering	The identification of the uses of design (i.e., permitting, bidding, purchasing, providing submittals, specifying facility systems, producing fabrication and installation instructions, commissioning, operating, maintaining, altering and decommissioning) and the joint production of needed information for each use (after Ballard 2008).
Domain Mapping Matrix	Matrix resulting from the enhancement of the DSM methodology to inter-domain matrices. (Maurer 2007).
Facility upgrade	Act of improving the condition of a facility/building so that it meets customer requirements. Synonym: building upgrade.
Hoshin Kanri	Lean planning process coming from Japan that links strategic objectives with tactical and operational objectives and that is based on a Plan-Do-Check-Act (PDCA) cycle.
High-end facility	Facility housing sophisticated systems and/or equipment, which performance is critical to allow the organization to meet its business objectives (e.g., hospital, laboratory, power plant, etc.) Synonym: high-end building
Installation	Putting in place materials or assemblies according to the design and production plans.
Iteration	"Repetition of a process that already has been performed once." (P2SL 2017a).
Last responsible moment	"While considering alternatives, the last responsible moment for one alternative is the time at which, if that alternative is not selected and pursued, that alternative is no longer viable." (P2SL 2017a).
Lean Assembly	"Lean Assembly begins with the first delivery of tools, labor, materials or components to the site and ends when the keys are turned over to the client." (Ballard 2000a).

Term	Definition
Lean Construction	"Application of lean thinking to the designing and making (delivery) of capital projects (or projects in general)." (P2SL 2017a). Synonym: new production philosophy.
Lean Design	"The Lean Design phase develops the conceptual design from Project Definition into Product and Process Design, consistent with the design criteria produced in Project Definition." (Ballard 2000a).
Lean Supply	"The Lean Supply phase consists of detailed engineering of the product design produced in Lean Design, then fabrication or purchasing of components and materials, and the logistics management of deliveries and inventories." (Ballard 2000a).
Multiple Domain Matrices	Matrix composed of at least two Design Structure Matrices and two Domain Mapping Matrices. Synonym: Multi-Domain Matrix
Negative iteration	Iteration without value being added. (P2SL 2017a).
Positive iteration	Iteration that adds value (e.g., learning taking place). (P2SL 2017a).
Process design	Determining the sequence of operations, and steps involved in the delivery of a product.
Product design	The conceptualization and expression of customer value into the representation of a product. (Tuholski 2008).
Production control	The monitoring of work flow and production unit by managing the cause of production reliability instead of identifying variations between plan and actual (after Ballard 2000).
Production-system team (also project team)	"All participants of the AEC production system engaging in a specific project. This includes the owner, designers, engineers, contractors, subcontractors, suppliers, and inspectors." (Tuholski 2008).
Project Definition	"Process of aligning Ends, Means, and Constraints" (Ballard 2008).

Term	Definition
	"Project definition starts with business planning, proceeds to business plan validation if the initial plan appears to be feasible, and ends with a decision by the client to fund or not fund a project." (Ballard 2008).
Project stakeholders	"Members of the production system who are impacted directly by efforts to reconfigure project activities or processes. By definition, the owner is a project stakeholder. Production-system members are stakeholders to the extent that they are impacted based on individual value perceptions." (Tuholski 2008)
Purposes	What the customer wants to accomplish with the artefact (after Ballard 2008).
Structural complexity	Characteristic of a system that has a "large number of parts that interact in a non-simple way. In such systems, the whole is more than the sum of the parts […] in the […] sense that, given the properties of the parts and the laws of their interaction, it is not trivial to infer the properties of the whole." (Simon 1962).
Value	"Something is "of value" to someone when it is appreciated by them. This may be expressed by saying "Thank You," willingness to pay for it, offering something non-monetary in return, etc." (P2SL 2017a). Value is subjective: what is of value to someone may be of no value to someone else. Value is changing: what someone values on a given day may be different from what the person valued in the past, and from what the person will value in the future. Value can also be defined as "fitness for purpose" as value is the translation of the company's purposes (Ballard 2008).
Waste	"Anything with a cost of any kind, the elimination of which does not reduce value delivered." (P2SL 2017a).
Work structuring	"The development of operation and process design in alignment with product design, the structure of supply chains, the allocation of resources, and design-for-assembly efforts" with the goal of making "work flow more reliable and quick while delivering value to the customer." (Ballard 2000).

ACRONYMS

Acronym	**Stands for…**
AEC	Architecture Engineering Construction
ALS	Advanced Light Source (also B6)
ARCOM	Association of Researchers in Construction Management
ASCE	American Society of Civil Engineers
B1	Building 1
BAS	Building Automation System
BEMS	Building Energy Management System
BIM	Building Information Modeling
CAD	Computer Aided Drawing/Design
CAFM	Computer-Aided Facility Management
CBA	Choosing-By-Advantages
CMMS	Computerized maintenance management system (CMMS) is also known as computerized maintenance management information system (CMMIS).
COBie	Construction Operations Building Information Exchange
CRTF	Computational Research and Theory Facility
D&C	Design and Construction
DCiE	Data Center infrastructure Efficiency
DMM	Domain Mapping Matrices
DOE	Department of Energy
DPM	Design Precedence Matrix (synonyms: DSM, PSM)

Acronym	Stands for…
DSM	Design Structure Matrix or Dependence Structure Matrix (synonyms: PSM, DPM)
EMS	Energy Management Systems
FDD	Fault Detection and Diagnostics/Diagnosis
FM	Facility Manager or Facility Management
GC	General Contractor
GIS	Geographic Information System
HPC	High-Performance Computing
IFC	Industry Foundation Classes
IGLC	International Group for Lean Construction
IPD	Integrated Project Delivery
LBNL	Lawrence Berkeley National Laboratory
LCI	Lean Construction Institute
LCW	Low Conductivity Water
LLNL	Lawrence Livermore National Laboratory
LPDS	Lean Project Delivery System
MDM	Multi-Domain Matrix
NEPA	National Environment Policy Act
NERSC	National Energy Research Scientific Computing Center
O&M	Operations and Maintenance
P2SL	Project Production Systems Laboratory
PCO	Projects and Construction Office (at LBNL)

Acronym	**Stands for…**
PDCA	Plan-Do-Check-Act
PM	Project Management, Project Manager
POE	Post-Occupancy Evaluation
PSM	Problem Solving Matrix (synonyms: DSM, DPM)
QFD	Quality Function Deployment
SME	Subject Matter Expert
TCO	Total Cost of Ownership
TFV	Transformation Flow Value
TPS	Toyota Production System
TQM	Total Quality Management
TVD	Target Value Design/Delivery
TW	Treated Water
UC	University of California
UCSF	University of California, San Francisco
US	United States
VE	Value Engineering
2D	Two Dimensions
3D	Three Dimensions

1. INTRODUCTION

The goal of this chapter is to introduce the research interest. The chapter is organized as follows. Section 1.1 describes the research background and formulates the problem statement. Section 1.2 describes the motivation underlying this research. Section 1.3 captures the relevance of the research for the Architecture/Engineering/Construction (AEC) industry, owners and decision makers, and academia. Section 1.4 describes the research framework. Section 1.5 formulates the thesis of this research. Section 1.6 lists the research questions that result from the thesis. Section 1.7 expresses the objectives of this research. Section 1.8 defines the scope boundaries. Section 1.9 outlines the research methodology. Last, section 1.10 captures the dissertation structure.

1.1 Research Background and Problem Statement

In an era where technological breakthroughs might make any building occupants dreams come true, numerous publications still report seemingly dissatisfied building occupants. Owners and occupants may lay the blame on architects and contractors for defective design and execution, or on Facility Managers (FM) for not being able to tune the building to accommodate their needs.

Dissatisfied occupants constitute a market in the AEC industry that benefit consultants and engineers offering Post-Occupancy Evaluations (POEs) and other building technical assessments (acoustics, thermal insulation, lighting, etc.). POEs were conducted as early as in the 1960s with as primary objective gaining understanding on how occupants experienced buildings and assessing whether buildings were meeting the requirements specified in the programming phase. More than a half century later, buildings have become increasingly more complex and POEs are not the remedy to ensure value delivery. At best, POEs provide assessments of the defects and propose solutions, but they remain punctual and do not ensure that value is delivered to occupants on a longer term.

In addition to these challenges, what building occupants value varies with time and varies from one individual to another. Over a typical 60-year lifespan, the building may house different types of businesses, each with different needs. This makes the following question arise: "How can we ensure that a building consistently meet customer requirements?" In addition, technological breakthroughs have increased occupants' expectations on building performance.

In this regard, research efforts have looked at examples of flexible building designs (Greden 2005, Maclise et al. 2013), investigated ways of adding flexibility in building designs (Keymer 2000, Slaughter 2001, Fernandez 2002, Greden 2005), and made the business case for flexibility in building design (Slaughter 2001, Greden 2005, Manewa 2012). In this respect, Manewa (2012) developed a framework to help owners make decisions on design for adaptations. Keywords other than "design for flexibility" point to this literature. Examples are "design for changes," "design for adaptability," "design for reuse," and "future-proofing buildings," among others. Despite the existence of strategies for increasing building flexibility in design, the entire spectrum of future needs cannot be reasonably taken into account at the time the building is designed (Ellingham and Fawcett 2006). This exacerbates the need for FM.

In this research, we see a building as an artefact that houses occupants and delivers value by supporting its occupant business. A building crystallizes what the owner valued at the time of the design process (at best), and the "value-delivery"-baton is passed from the Design and Construction (D&C) team to the FM. Following the turnover process, the FM becomes responsible for servicing and managing the building so that the building delivers value to building occupants. The importance of FMs in the value creation of the built environment has been well documented (Clayton et al. 1999, Jaunzens et al. 2001, Saxon 2005, Enoma 2005, Aune and Bye 2005, Aune et al. 2009, McAuley et al. 2016, Kalantari et al. 2017, to name a few).

Over the use phase of the building life-cycle, FM is traditionally tasked with listening to occupants, capturing their needs, prioritizing them, developing plans to act on them, and eventually acting on them. In other words, FM steers the building toward a constantly changing future state. During the 'steering', FM develops a deep understanding of how buildings behave and react to changes. FM accumulates knowledge on how occupants experience buildings, but surprisingly the integration of FM in project delivery is still not common practice.

Put simply, the problem is that FM involvement in projects from initiation through disposal is not systematic in many organizations. At best, FM is involved too late or only perfunctorily in the preconstruction and construction phases. This is manifested in a lack of awareness of structural complexity in project delivery. Structural complexity is a state of a system whose behavior emerges from the interactions of its parts. As a result, such complexity is not managed and the facility fails to deliver the expected customer value.

This research explores how FM is commonly segregated from project delivery teams. It investigates the impacts on project performance of the lack of FM involvement. The goal of this research is to propose a new FM paradigm in order to avoid waste and generate value in projects through a more strategic and early FM integration in project delivery.

1.2 Motivation

This research draws on two motivations: (1) tackle the recurrent and substantially documented problem of buildings' failure and (2) propose a new FM paradigm by using the Transformation-Flow-Value (TFV) production theory.

The first motivation results from reviewing the literature pertaining to buildings value delivery to occupants. It was rich in publications documenting the lack of performance of facilities (section 1.2.1) and describing the limitations of computer models to accurately simulate some buildings' attributes (section 1.2.2). The second motivation draws on the received traditions of our industry (section 1.2.3), the segregation of D&C and FM research (section 1.2.4), and our industry's over-reliance on the improvement of data flows (through Building Information Modeling (BIM)) to improve FM (section 1.2.5).

1.2.1 Underperforming Facilities

The term "performance" is used across various domains in the AEC literature. The term has been used in work attempting to qualify and/or quantify some buildings attributes pertaining to: thermal comfort, indoor air quality, acoustics, lighting, energy performance (Bordass et al. 2001, Usable Buildings Trust 2001, Bordass et al. 2004, Demanuele et al. 2010, Ahn et al. 2016), life-cycle impact assessment, ergonomics, etc. Thus, buildings "underperform" when the measured attributes (energy usage, acoustical insulation, etc.) are worse than what was planned and/or calculated. Research also looked at the correlation (or not) of occupants' productivity with either one or more of those attributes as variables.

Performance is seldom assessed in terms of value delivery and at the level of granularity of the building occupants. The researcher can think of a few reasons that could account for this literature gap. First, the subjective and changing nature of "value" makes developing consistent research methodologies around it difficult (the research methodology section enables other researchers to reproduce the research if they want to). Second, the subjective and changing nature of "value" requires comprehensive data collection for the building under study.

In order to be comprehensive, this research will use the word "failure" instead of "lack of performance" to refer to all the cases when buildings fail at delivering value to building occupants. Unlike "underperformance," the expression "building failure" is not limited to the difference between what was planned in the design and the actual behavior of the building. Thus, failure is when buildings do not live up to customer expectations and this constitutes waste.

1.2.2 Faulty Performance Predictions and Limitations of Simulation Tools

Research on underperforming buildings has compared planned against actual performance. Gaps between the two have motivated researchers to investigate the reasons for these discrepancies. They can be classified in two groups: (1) faulty predicted performance, and (2) differences between predicted and actual performance (Menezes et al. 2012). Faulty predictions are mainly caused by: (1.1) incorrect design assumptions and/or (1.2) limitations of the building energy performance simulation tools are the main drivers for inaccuracies in predicted performance. The next paragraph expands on (1.2).

Simulation tools represent a simple model of reality: wisdom is knowing what to ignore. Maile et al. (2010) give the example of two interconnected hot and chilled water loops. Because the building energy performance simulation tool did not have an object to represent the connection, the model was simplified. As a consequence, the simulation showed a lower water flow rate in the main water loop of the model than in the reality.

Extending Menezes et al.'s (2012) analysis, the researcher sees two additional reasons for faulty predicted performance. First, the data that serves as input to the model may not be available. Second, the simulation tool's results depend on the assumptions made by the user.

1.2.3 Received Traditions of Architecture/Engineering/Construction (AEC) Industry

The AEC industry has a long tradition of adversarial relationships abetted by the misalignment of the commercial terms, the organization, and the operating system. When construction projects fail, a common reaction from the owner, the architect, the engineer, the GC, and the subcontractors is finger pointing. Although Lean Construction has paved the way for a mindset shift in this culture of blaming, the industry has still a long way to go. This received tradition has significantly impacted the orientation of research efforts. Finger pointing goes hand in hand with the culture of seeking local fixes. Building failures are thus analyzed from a specific trade-, engineered system-, or domain- perspective rather than from a holistic one, which leads to the next point: "segregation of D&C and FM research."

1.2.4 Segregation of Design and Construction (D&C) and Facility Management (FM) Research

Although significant research exists on the designing, construction and management of buildings, D&C and FM research remains mostly segregated. A reason for that is viewing FM as a "postconstruction service" (Edum-Fotwe et al. 2003) rather than as a fundamental contributor to whole building life-cycle service. The fact that research in FM is mainly conducted separately from the research in D&C constrains the potential impact of innovation in FM. For example, although FM emerged in the 1980s, advocating for the early involvement of FM is more recent (early 2000s).

In addition, the segregation of D&C and FM research certainly worsens the lag in adopting innovative technologies in FM.

1.2.5 Reliance on Data to Improve FM

Research on BIM has gained momentum over the years taking advantage of the multiple technological breakthroughs (faster computing times, better computer graphics cards, etc.) on which BIM relies. One of the questions that BIM enthusiasts have tried to answer is: "How can the D&C data embedded in BIM be transferred to FM?" A paper that has been particularly popular in the ASCE library is: East et al.'s (2013) "FM handover view" which specifies open-standard information exchange format to hand over D&C information to FM. The AEC industry's enthusiasm for BIM results from a focus on one of the three models of production, namely flow, disregarding the two others: transformation and value. The three models of production are described in section 1.4.

1.3 Relevance

This research is relevant at three levels: (1) the AEC industry, (2) owners and decision makers, and (3) academia.

1.3.1 AEC Industry

Overall, the US new construction market has recovered well from the financial crisis of 2008 but threats to its long-term growth are looming at the horizon. The four threats are: (1) the shortage in skilled labor compounded by (2) an increase in complexity of products installed (i.e. controls) and materials used (i.e. modern concrete mixes), (3) limited constructable space in big cities, and (4) increasingly more stringent environmental regulations and financial incentives. Those threats may encourage owners to increase facilities life expectancy through FM as opposed to constructing new facilities.

1.3.1.1 Labor Shortage

The construction industry has been severely impacted by a shortage in labor (ENR 2014, ENR 2016) over the last years. Hiring field workers on construction projects has become difficult especially on large ones. Bids reflect the labor shortage: subcontractors are forced to inflate their prices to preserve profit margins. They must raise labor wages to attract workers and increase their contingency to absorb the risk of longer project durations due to a lack of labor.

Construction-oriented magazines have also reported a shortage in skilled labor due to the high turnover in craft workers. The shortage amplifies the negative impact on project performance (money, time, and quality) of the increase in complexity.

1.3.1.2 Increasing Complexity

Engineering fields have been experiencing an increase in complexity. The automobile industry is a case in point. In the early days, car manufacturers used to produce cars that would last for a long time (Edgerton 2006). Then car manufacturers started to deliberately use components with inferior shorter lifetimes: predictable failure allowed them to continue to make profits during the entire life-cycle of the car. Car buyers were able to buy the components off the shelf and make the repairs themselves for some components of the cars (e.g., side mirrors, windshield wipers, headlights). Then, car manufacturers started to include an increasing number of electronics, which made the self-repairing of cars by laymen almost impossible because of the interdependences of electronic components. The high interconnectivity of components makes diagnosing a problem difficult, which now requires domain-specific knowledge and specific testing equipment (i.e., car engine fault code readers).

Similar to the automobile manufacturing industry, the construction industry has become more complex. Referring to the trend of increasing maintenance costs, Chew et al. (2004) write: “This trend is due to the growing complexity of buildings, the increasing proportion of systems in them, higher levels of service (…).”

1.3.1.3 Limited New Constructible Space in Big Cities

The amount of constructible space is limited in already densely occupied areas which makes the upgrades of existing facilities a more affordable option. Because cities impose maximum building height and building occupant population density, owners have sometimes no other options than retrofitting an existing facility to accommodate changes in business needs.

1.3.1.4 Stringent Environmental Regulations and Financial Incentives

Environmental regulations are becoming increasingly more stringent. Regulations that pertain to waste management may discourage demolitions and new constructions, and by default encourage facility upgrades and longer use phases in buildings’ life-cycles. In addition, states and federal agencies encourage retrofits by offering financial incentives.

1.3.2 Owners and Decision Makers

The findings of this research have the potential to influence the decisions of managers and policy makers from a variety of groups and organizations:

- The Lawrence Berkeley National Laboratory (LBNL) as illustrated in Chapter 5.
- The University of California, San Francisco (UCSF) as explored in Chapter 5.
- Any other organization owning and managing facilities housing sophisticated systems and/or equipment, which performance is critical to allow the organization to meet its business objectives, that is, high-end facilities; to name a few:
    - The healthcare industry: hospitals, laboratories.
    - The biomedical, pharmaceutical industries: laboratories, research facilities.
    - The oil and gas industry: refineries, chemical plants, offshore platforms.
    - The aerospace industry: laboratories, manufacturing plants.
    - Universities and research campuses.

1.3.3 Academia

This research is relevant to researchers interested in design, in construction, or in FM. The tools and research methodology used will also be of interest to researchers looking for analyses of project structural complexity on real case studies.

1.4 Research Framework

The Lean Construction philosophy and underlying principles frame this research. They build upon Lean production, which was developed by Toyota starting in the 1950s.

At the time, the well-known Japanese car-manufacturer was led by Engineer Taiichi Ohno (Howell 1999). Unlike Ford, its American competitor, who benefited from almost unlimited demand and resources, the Japanese firm confronted an economy barely recovering from World War II. Seeing an opportunity in the American market, Toyota decided to offer car mass customization to compete with Ford, which could only propose a black car model. However, due to limited resources, Toyota had to build cars to customer order (as opposed to made to stock) so as to limit the immobilization of capital. This led to the redesign of the existing Toyota Production System (TPS) with the following objectives: produce a car to the requirements of a specific customer, deliver it instantly, and maintain no inventories or intermediate stores.

Today, the TPS is based on a philosophy, principles, and methods. The philosophy is to "maximize value while minimizing waste and meet the customer requirements." Section 1.4.1 lists the TPS's 14 principles.

1.4.1 Toyota's 14 Principles

The Toyota Way Fieldbook from Liker and Meier (2006) lists the 14 principles serving as foundation to the TPS. They are:

1. Base your management decisions on a long-term philosophy, even at the expense of short-term financial goals.
2. Create a continuous process flow to bring problems to the surface.
3. Use "pull" systems to avoid overproduction.
4. Level out the workload (work like the tortoise, not the hare).
5. Build a culture of stopping to fix problems, to get quality right the first time.
6. Standardized tasks and processes are the foundation for continuous improvement and employee empowerment.
7. Use visual control so no problems are hidden.
8. Use only reliable, thoroughly tested technology that serves your people and process.
9. Grow leaders who thoroughly understand the work, live the philosophy, and teach it to others.
10. Develop exceptional people and teams who follow your company's philosophy.
11. Respect your extended network of partners and suppliers by challenging them and helping them improve.
12. Go and see for yourself to thoroughly understand the situation.
13. Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly.
14. Become a learning organization through relentless reflection and continuous improvement.

The TPS is at the core of Lean Construction, which sees construction projects as temporary production systems (Koskela 1992, Ballard and Howell 1998, Howell 1999, Koskela 2000). However, this paradigm shift required the adoption of a new production theory, which was formalized by Koskela in 2000 and coined the "TFV production theory." Unlike former production theories that considered these three views (aka., Transformation, Flow, and Value) independently, the TFV production theory acknowledges that the three views are complementary and must be assimilated together to improve production systems. These views are described next.

1.4.2 New Production Philosophy

1.4.2.1 Transformation View of Production

The Transformation view of production views production as the mere conversion of input into output. Under this view, the transformation of raw materials into a finished good can be decomposed into multiple transformations, which can themselves be further decomposed into smaller transformations (or sub-transformations), named tasks. Those tasks are considered to be independent on one another. The main optimization principle is to produce efficiently. As a result, efforts focus on reducing the duration of each task and executing them as efficiently as possible, and thus disregard their interdependences.

1.4.2.2 Flow View of Production

In the Flow view of production, the transformation of raw materials into a finished good no longer equates to the discrete sum of sub-transformations: the work in progress may wait, be inspected, or be moved/transported. These additional activities are wasteful, that is, what the customer is not happy to pay for, and must therefore be eliminated. In the Flow-view, principles to improve production include: compress lead time, reduce variability, simplify, and increase transparency.

1.4.2.3 Value View of Production

The Value view of production focuses on the customer. Where the Flow view of production aims at eliminating waste and reducing cycle time, the Value view aims at delivering the best value to the customer, that is, delivering a product that meets the customer requirements. This third view of production had been long overlooked: companies were striving to eliminate waste and drive down the cost of production, but were forgetting an essential part of production, the ultimate goal, which is meeting customer requirements. Without a customer, a production system has no reason for being.

1.4.2.4 TFV Production Theory

In the three presented views of production, the Transformation view is the most acknowledged by traditional construction project management (e.g., the Project Management Body of Knowledge (PMBOK) by the Project Management Institute). The paradigm shift in production theory that Koskela proposed in 2000 relies on the realization that the three views of production are complementary and must thus be assimilated together.

Recently, research in FM has become increasingly more focused on the flow of information from the D&C team to FM, which is one view out of three in the TFV production theory. The TFV production theory therefore constitutes a new approach to the problem under study.

1.5 Thesis

The late involvement of FM in project delivery contributes to waste and is manifested in a lack of awareness of structural complexity. Structural complexity is the condition of a system whose behavior emerges from the interactions of its parts. The burden of managing that complexity falls on FM during operations and maintenance of the completed facility. By not engaging FM strategically in project delivery, such complexity is not managed easily and the facility may fail to deliver the expected customer value. The use of the Design Structure Matrix (DSM) methodology, a matrix-based method to model structural complexity, and Hoshin Kanri, a Lean planning process used to deploy strategies in organizations, could help generate value to owners and occupants by enabling FM involvement in the planning, designing, and execution of high-end facility upgrades and construction projects in general.

1.6 Research Questions

The thesis (section 1.5) entails the exploration of the next corollary questions:

1. What is the case for FM integration in project delivery?
2. How does FM fail?
3. May the late (or lack of) FM involvement in project delivery impact (or not) project performance? If so, how?
4. How does integrating FM in project delivery transform organizations into learning organizations?
5. In what aspects is FM complex? How does structural complexity manifest itself in facility upgrades?
6. Is there a unique ('a right') classification of complexity aspects for construction projects?
7. Can aspects of project structural complexity be addressed separately?
8. Can the Design Structure Matrix (DSM) methodology be applied to facility upgrades work?
9. Can DSM help reduce waste in facility upgrades?
10. How might Hoshin Kanri be applied to FM?
11. What best practices can we recommend to engage FM in project delivery in order to avoid waste and generate value to owners and occupants?

1.7 Objectives

The objectives of this research are to:

- Identify, categorize, and illustrate how FM fails at delivering value to occupants
- Characterize aspects of structural complexity in FM
- Raise awareness about the importance of FM in project delivery and value generation
- Gain greater insights into waste caused by the late involvement of FM in projects

- Extend the body of knowledge on DSM, and specifically AEC applications of DSM
- Explore Hoshin Kanri as a process to enable FM integration in project delivery
- Recommend best practices to enable the integration of FM in project delivery

1.8 Scope

This research focuses on high-end facilities (section 1.8.1), and specifically two case studies of major facility upgrades (section 1.8.2). The researcher analyzed the case studies using the structural complexity framework (section 1.8.3) and compared them against one another. Furthermore, this research compares two large public organizations owning multiple and various high-end facilities, LBNL and UCSF (section 1.8.4). The comparison contrasts how these large organizations involve FM in project deliveries. It identifies opportunities for improvement and propose best practices accordingly.

1.8.1 High-End Facilities

This research focuses on high-end facilities because they make the problem identified in this research more obvious. First, they exacerbate the structural complexity found on projects. Second, FM failures have larger consequences in high-end facilities, which often require continuous operations. Examples of high-end facilities include: dry and wet laboratories, facility plants, hospitals, etc.

However, the findings of this research are extendable to other types of facilities (aka. not necessarily high-end), where complexity may manifest itself at a smaller magnitude and hence constitute a smaller challenge.

1.8.2 Major Facility Upgrades

FM involves many activities ranging from space planning, through real estate, data tracking, inspection, testing, predictive maintenance, to corrective maintenance, among others. This dissertation focuses on major facility upgrades, which are differentiated from routine work (Figure 1-1). The reason for focusing on facility upgrades lies in their structural complexity: they involve coordinating different trades, designing, planning and scheduling, etc.

1.8.3 Structural Complexity

Multiple theories and definitions of complexity exist. A few of them are explored in Chapter 2. This research focuses on structural complexity. Different aspects of structural complexity exist. A categorization is proposed in Chapter 2. In this respect, high-end facilities are characterized by customer complexity, market complexity, and product complexity.

Figure 1-1 illustrates the scope of this research.

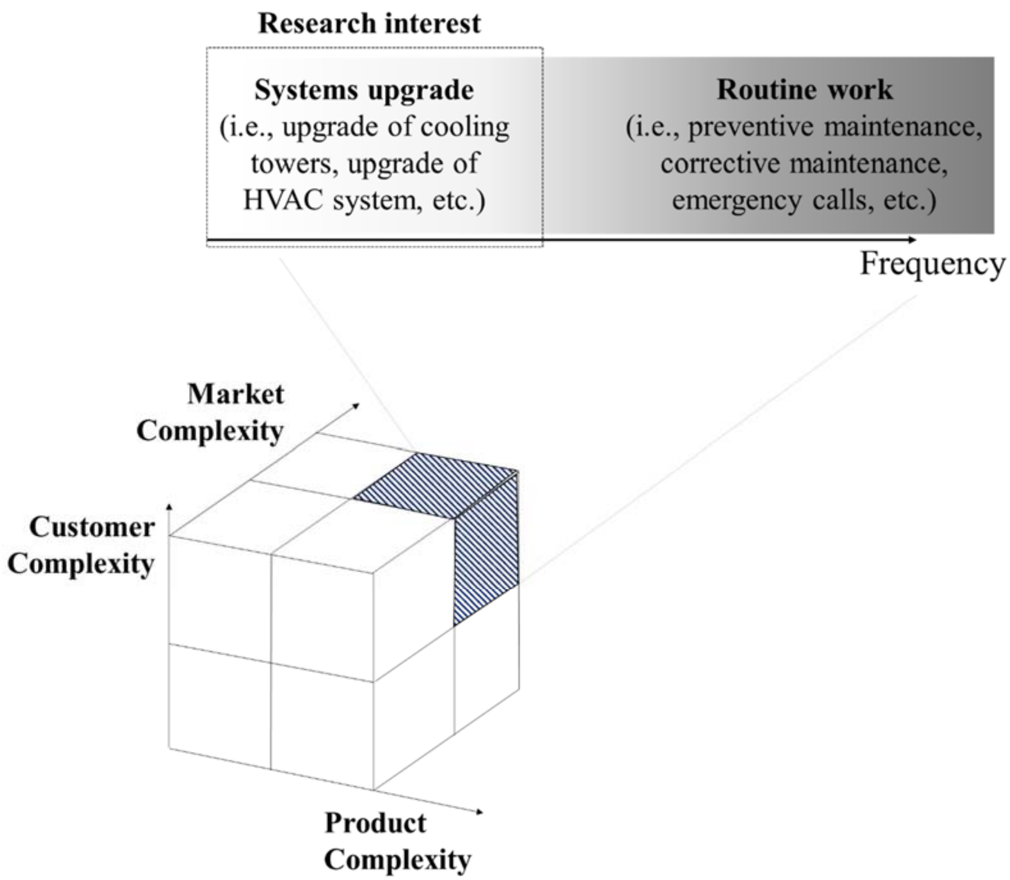


Figure 1-1: Research Scope

1.8.4 Large Public Organizations

UCSF and LBNL are two large public organizations. UCSF is spread across 17 sites in San Francisco, CA. UCSF is part of the UC system, which encompasses 10 campuses across the state. LBNL is a national laboratory supervised by the US Department of Energy (DOE) and is operated by UC under a contract with DOE. LBNL is part of a network of 17 laboratories across the country.

This research focuses on these organizations because they have very different approaches to FM despite obvious similarities (i.e., public organizations operating high-end facilities).

1.9 Methodology

Figure 1-2 and Figure 1-3 illustrate the research methodology.

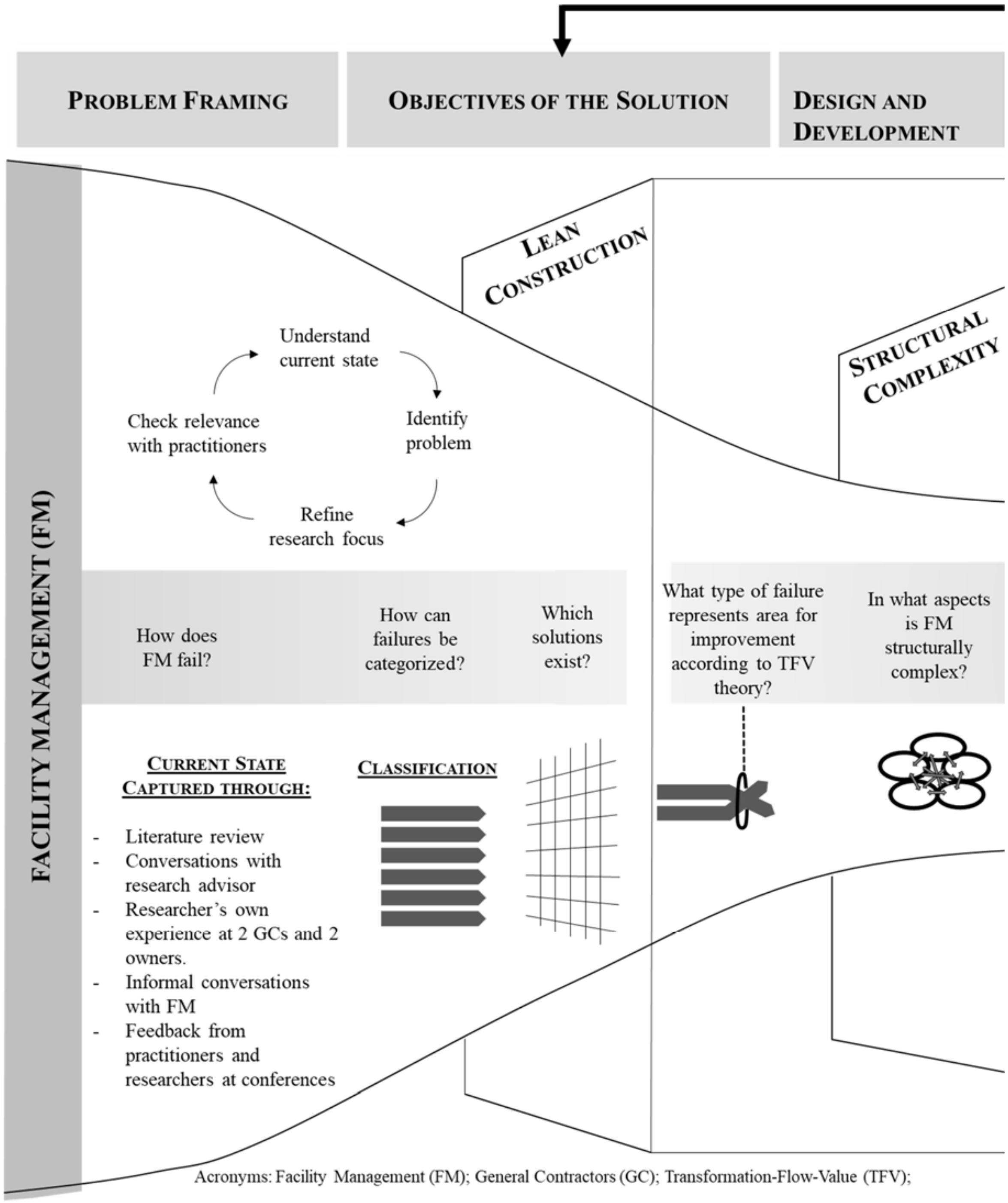


Figure 1-2: Research Methodology (1/2)

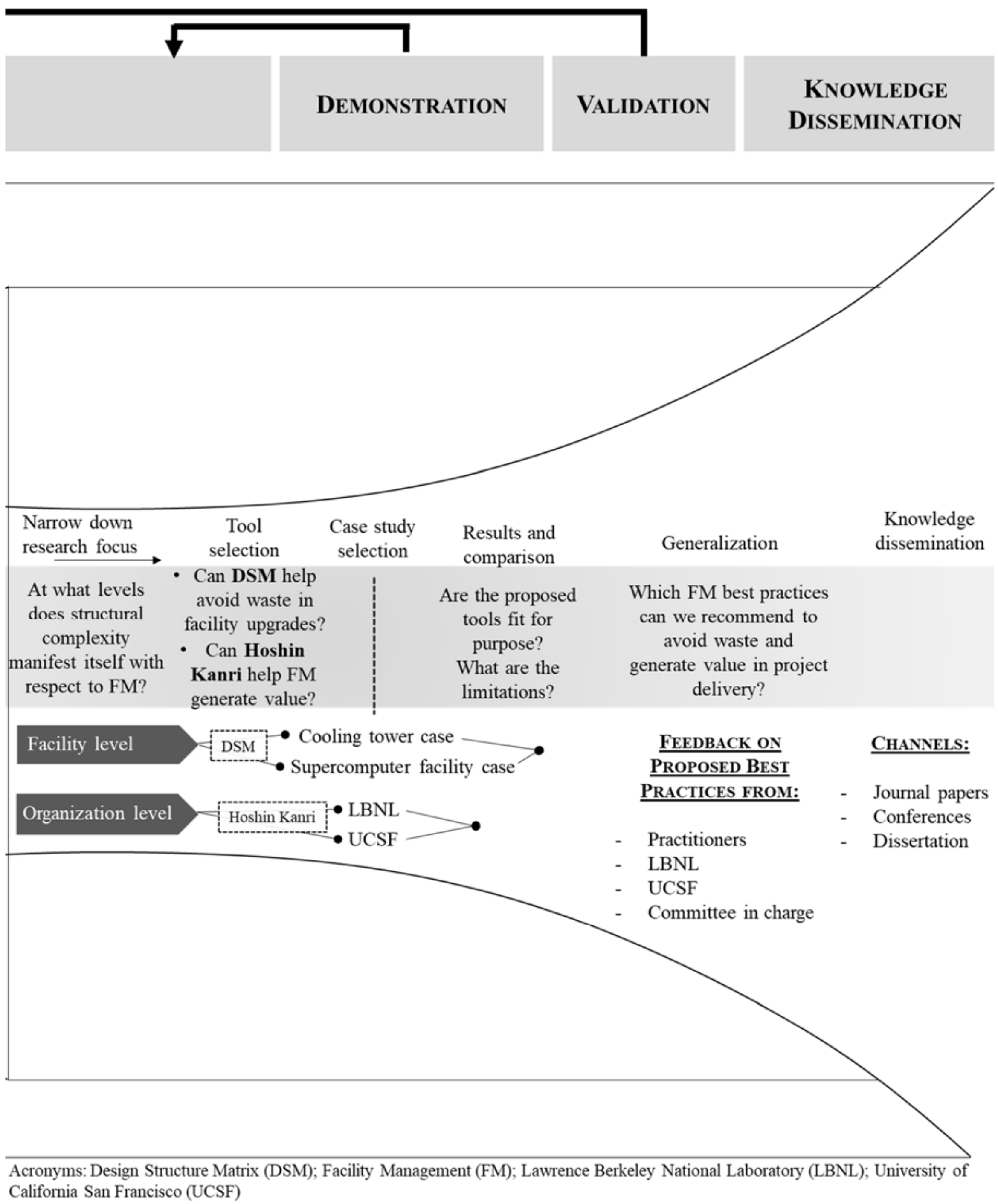


Figure 1-3: Research Methodology (2/2)

1.9.1 Design Science

Design science "has its roots in engineering and the sciences of the artificial" (Hevner et al. 2004). The well-known *The Sciences of the Artificial* by Simon (1969) lays the foundations of design science.

Design science is a research methodology that aims at creating artifacts to solve a problem and evaluate the performance of these artifacts (Hevner 2004). Design science is fit for looking at "wicked" problems (Rittel and Webber 1973).

1.9.1.1 Characteristics of Wicked Problems

Characteristics of wicked problems are (Rittel and Webber 1973):

- "There is no definitive formulation of a wicked problem
- Wicked problems have no stopping rule
- Solutions to wicked problems are not true-or-false but bad-or-good
- There is no immediate and no ultimate test of a solution to a wicked problem
- Every solution to a wicked problem is a one-shot operation
- Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions
- Every wicked problem is essentially unique
- Every wicked problem can be considered to be a symptom of another problem
- The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution."

In this dissertation, the problem under investigation concerns the lack of integration of FM in project delivery; a problem that translates into a lack of awareness of structural complexity, which in turn, results in waste and lost opportunities in value generation. This problem appears to qualify as a wicked problem in the light of Rittel and Webber's characterization.

1.9.1.2 Steps in Design Science Research

Hevner (2004) provides the following design-science research steps: "(1) design as an artifact, (2) problem relevance, (3) design evaluation, (4) research contributions, (5) research rigor, (6) design as a research process, (7) communication of research," which are followed in this research. Different models of design-research processes exist; Peffers et al.'s (2006) was chosen for its comprehensiveness and clarity. Figure 1-2 and Figure 1-3 build upon the steps defined by Peffers et al.'s (2006). The figures summarize the steps undertaken in this research following the design science research methodology. The left side of the funnel reflects when and how we narrowed down the scope of the research as we refined the understanding of the problem. The right side of the funnel reflects when and how we generalized the knowledge acquired from the demonstration step.

1.9.2 Literature Review

The review of the literature informed the first two steps of the design science research process captured in Figure 1-2, namely "Problem Framing" and "Objectives of the Solution." Moreover, the purpose of the literature review is threefold: (1) show where the proposed research question stands within the existing body of knowledge, (2) show how answering the proposed research question may expand the existing body of knowledge, and (3) provide a starting theory that the research will either validate and build upon, or debunk and re-create.

1.9.3 Case-Study Research

The "demonstration" step of the design science research methodology (Figure 1-3Figure 1-2) is split between two streams of case studies.

One stream looks at structural complexity at the facility level. For this stream, the case studies chosen are: the cooling tower case and the supercomputer facility case. The reasons why these specific case studies were chosen are:

1. Case studies fall within the research scope.
2. The project documentation is available and rich.
3. The resources (people working on the project) are available.
4. The comparison across the case studies is relevant: the two cases were directed by the same owner which enables to look at variations in how the lack of FM integration impacts project performance within a same organization.

The research methodology followed to analyze complexity in these case studies is detailed in Chapters 3 and 4.

The other stream looks at structural complexity at the organization level for two organizations: UCSF and LBNL. The reasons why the researcher chose these specific organizations are:

1. Organizations fall within the research scope (operating high-end facilities).
2. We, P2SL, have experience in collaborating with the two organizations, which facilitates access to data and resources.
3. The comparison across the two organizations is relevant: the organizations have both expressed the need of improving FM integration in project delivery. However, one organization started its Lean journey 10 years before the other.

1.9.4 Cross-Case Analysis

Cross-case analysis comes here as the second level of analysis following the case study approach (Mathison 2005). This research method consists in comparing case studies to identify differences and shared features (Kahn and VanWynsberghe 2008). The comparison allows to:

"Delineate the combination of factors that may have contributed to the outcomes of the case, seek or construct an explanation as to why one case is different or the same as others, make sense of puzzling or unique findings, or further articulate the concepts, hypotheses, or theories discovered or constructed from the original case." (Kahn and VanWynsberghe 2008).

1.10 Dissertation Structure

Figure 1-3 illustrates the dissertation structure. The chapters are organized as follows:

- **Chapter 1: Introduction** introduces the research background and motivations. It describes the Lean Construction philosophy and the underlying 14 principles in TPS that frame this research. It lists the research questions formulated in order to meet these research objectives. Finally, it depicts the methodology designed to meet the research objectives.
- **Chapter 2: Literature Review on Facility Management (FM) and Value Generation** provides the requisite background on: FM, Lean Construction, and structural complexity and their overlap (if any) in the reviewed literature. It proposes a categorization of how FM fails at delivering value to occupants. It reviews (commercially available and prototyped) solutions addressed to FM, which are compared against how FM fails. The comparison reveals a general lack of understanding of the nature of FM. This translates into a lack of awareness and hence consideration of structural complexity at the project and organizational levels. Finally, it introduces the DSM methodology and Hoshin Kanri, which are used in subsequent chapters to model and manage structural complexity.
- **Chapter 3: Cooling Tower Case** documents a case study, that is, the cooling tower project at LBNL and analyzes how it failed to deliver value to occupants. It describes how the lack of management of structural complexity contributed to FM failure through analyses of the planning process and the cooling tower selection.
- **Chapter 4: Supercomputer Facility Case** documents a second case study, that is, the Computational Research and Theory Facility (CRTF) named here the "supercomputer facility case" at LBNL. The chapter describes how the facility failed to deliver value to occupants. The analysis of the Value Engineering (VE) process shows how the poor management of dependences contributes to FM failure.
- **Chapter 5: Cross-Case Analysis** presents the cross-case analysis of the cooling tower case and the supercomputer facility case using the LPDS-MDM framework. It attempts to generalize the findings from Chapters 3 and 4 by highlighting how Lean Construction can help manage structural complexity and enable FM engagement.
- **Chapter 6: Hoshin-For-Facilities to Engage Facility Management (FM) in Project Delivery** proposes a model, Hoshin-for-Facilities, to support and enable FM integration with project delivery teams. The model builds upon Lean Construction principles and methods and acknowledges the complex nature of FM. The chapter gives recommendations for best practice after validation with practitioners and researchers at UCSF and LBNL.
- **Chapter 7: Conclusions** summarizes the findings of this research. It answers the proposed research questions underlying the research objective. It presents recommendations for best practice to integrate FM in project delivery. It identifies contributions to knowledge and discusses possible limitations. Last, it suggests directions for future research in D&C and FM.

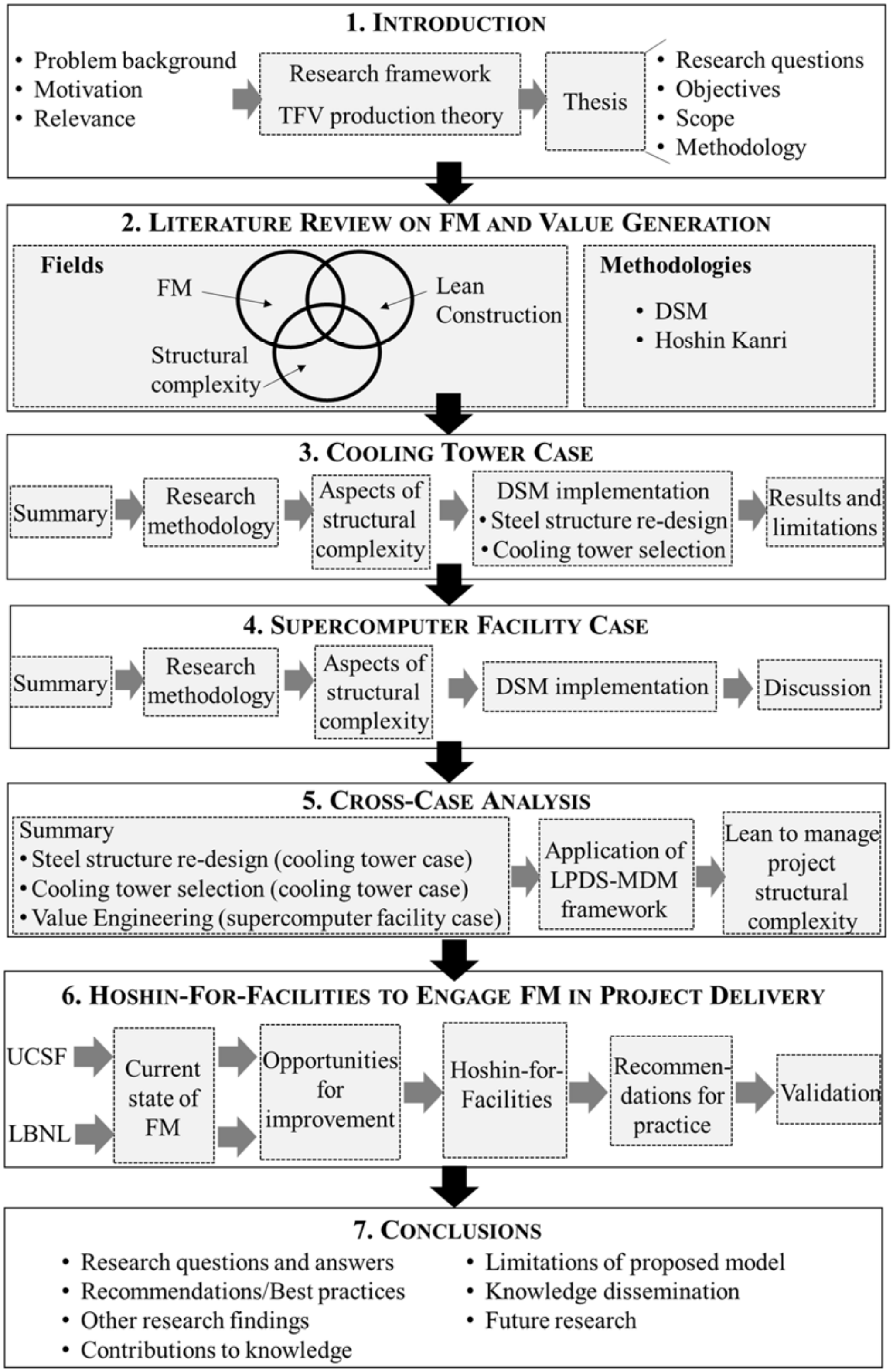


Figure 1-4: Dissertation Structure

2. LITERATURE REVIEW ON FACILITY MANAGEMENT (FM) AND VALUE GENERATION

The goal of this literature review is to present the requisite background on Facility Management (FM), structural complexity, Lean Construction, and their overlap (if any). This will provide the backdrop for understanding the thesis defined in Chapter 1 and gather evidence of a gap in the literature. It also gives a shared language for comprehending the ideas distilled in this research.

The chapter is organized as follows. Section 2.1 illustrates the evolution of FM's role within the London Underground (LU) Supply Chain (SC), and within LBNL's project delivery SC. Section 2.2 summarizes the literature on FM. Section 2.3 makes the business case for FM integration in project delivery. Section 2.4 proposes a classification of FM failures at ensuring that facilities consistently meet customer expectations. Section 2.5 presents the solutions aiming at addressing these failures and their limitations. Section 2.6 uses the Cynefin framework to qualify the environment in which FM operates as complex. Sections 2.7 and 2.8 summarize the literature on project complexity. Section 2.9 provides the classification of complexity aspects used to analyze the two case studies, the cooling tower case and the supercomputer facility case. Last, sections 2.10 and 2.11 describe the tools used in the following chapter to model structural complexity and visualize how it impacts project delivery.

2.1 Supply Chain and FM

2.1.1 London Underground (LU) Example

Through the historical example of the London Underground (LU) Ltd, the next paragraphs illustrate how the role of FM within an organization's Supply Chain (SC) has evolved over the years and gained importance in response to the failure of different SC configurations. The following paragraphs focus on the various SC configurations that the LU adopted over the years from 1987 to 1997.

Historically, the LU is the world's first underground railway. Prior to the King's Cross fire in 1987, railway engineering was at the heart of the LU SC (Figure 2-1). Railway engineering is at the intersection of many fields of engineering, including: mechanical engineering, command, control and railway signaling, electrical engineering, civil engineering. LU engineering was divided in four departments: (1) signal, (2) electrical, (3) civil, and (4) mechanical engineering. Each of them was led by a departmental chief, and organized in a mechanistic structure, that is, a hierarchic structure in which top management makes most decisions (Burns and Stalker 1961). Other functions such as operations, purchasing, customer satisfaction, were pushed to the background, that is, the LU "was primarily a railway engineering system that incidentally carried passengers." (Bouverie-Brine and Macbeth 1997).

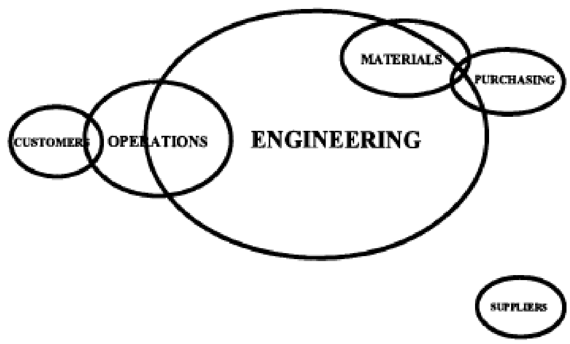


Figure 2-1: LU SC Pre 1988 (Figure 7.1 in Bouverie-Brine and Macbeth 1997)

On November 18, 1987, a fire broke out on a wooden escalator at the King's Cross station. The fire killed 31 people and injured 100. A public inquiry concluded that the fire was probably caused by a passenger throwing away a lit match that fell down in the running track of the escalator (Fennell 1988). The match ignited the grease from the tracks that was contaminated with fibrous materials. The conclusions also revealed that the intensity of the fire and fast propagation were partly caused by an unusual accumulation of paint layers on the ceiling. Indeed, the paint caused the superheated gas resulting from the fire to get trapped against the tunnel's ceiling: the paint layers absorbed the warmth. When the next train arrived to the station, it fed the fire with new oxygen, which made the superheated gases ignite and cause an explosion (Fennell 1988).

Since the occurrence of the incident, journalists, researchers, decision-makers, and others have tried to understand whether the fire could have been stopped more quickly. By investigating the series of events that preceded the intervention of the fire brigade, it was revealed that a user had informed a LU ticket collector about the smoke well before the propagation of the fire (Ross 2013). The ticket collector extinguished the flames without informing anyone else and returned to his duties. Yet, the fire was still propagating. Then, another passenger informed a different LU operator, who in turn contacted the safety inspector. The safety inspector investigated the flames, but had not been trained to use the sprinkler system. By the time a third user had contacted a policeman, who in turn had contacted the headquarters. The headquarters eventually contacted the fire brigade.

From the description of the sequence of events, some questions arise (Ross 2013). First, "Why didn't the ticket collector warn anyone else?" This responsibility did not fall under his scope of duties. The mechanistic structure of the organization discouraged employees from overstepping their scope of work (Burns and Stalker 1961). Second, "Why didn't the LU operator call the fire brigade directly instead of reaching out to the safety inspector?" Investigation shows that employees had been instructed to contact the fire brigade only in case of absolute necessity out of fear of panicking users for no reason. Third, "Why didn't operators or the safety inspectors turn on the fire sprinkler system?" The answer is that the fire sprinkler system was falling under the authority of another department and the mechanistic structure of the organization deterred employees from going beyond their scope of work and responsibilities.

As a result of this event, smoking was banned on the LU. Furthermore, the big impact of the fire drew attention to the relationships between engineering, operations and customers in the SC (Figure 2-2). The last two had been overlooked and the fire was considered to some extent to be a symptom of the negligence: "This resulted in a paradigm shift in the company's purpose: to be a provider of public transport by utilizing a railway system." (Bouverie-Brine and Macbeth 1997). Suppliers were kept at a distance from engineering and operations.

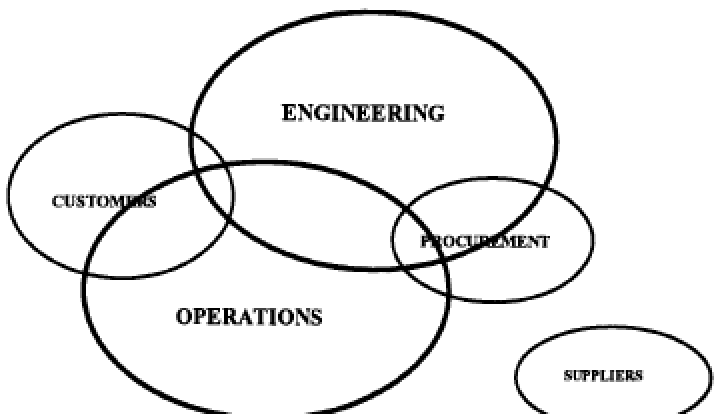


Figure 2-2: LU SC Post King's Cross Fire 1988 (Figure 7.2 in Bouverie-Brine and Macbeth 1997)

Additional factors called for a later rearrangement of LU SC. First, the annual funding mechanism did not foster consideration of whole life costing. Second, a published report established that the LU was lacking financial investments, which forced decision-makers to move money from the maintenance budget to the capital investment budget. The lack of money encouraged LU to push decentralization further and reduce staff. Assets also became part of operations (Figure 2-3).

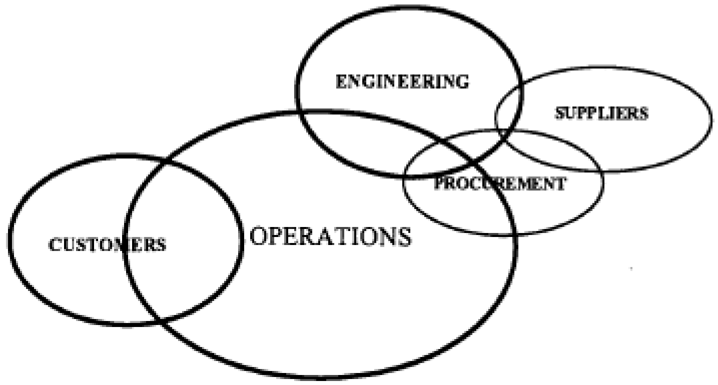


Figure 2-3: LU SC Post Company Plan 1991 (Figure 7.3 in Bouverie-Brine and Macbeth 1997)

At this time, LU started to change its professional standards. They also realized that supplier relationships had to improve. They called therefore an external consultant who helped them create a supplier management model. At the same time, they developed a vision called the Decently Modern Metro (DMM). The decrease in government funding forced LU to look for ideas that could lead to savings. They found 3: (1) optimization of current operations, (2) strategic supplier management, and (3) innovative engineering. This required a better integration of suppliers (Figure 2-4).

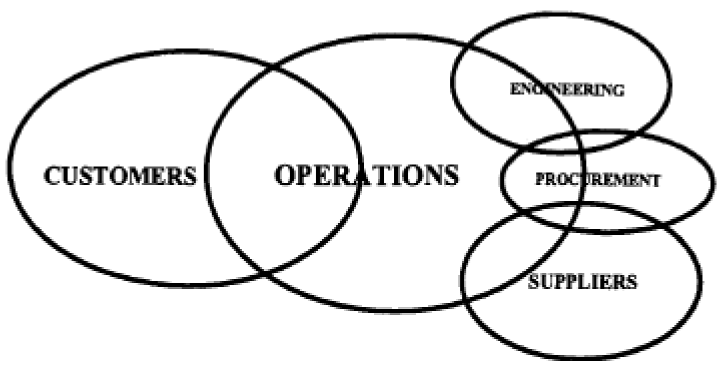


Figure 2-4: LU SC Post Introduction of Supplier Managers (Figure 7.5 in Bouverie-Brine and Macbeth 1997)

Although the integration of suppliers was assessed as critical, LU still needed to find a way to make it happen. They tried to move from adversarial to collaborative relationships. Nonetheless, the large number of suppliers made it a daunting task (i.e., “Where to start?”). Bouverie-Brine and Macbeth (1997) represented the future state (at the time) of LU SC as shown in Figure 2-5.

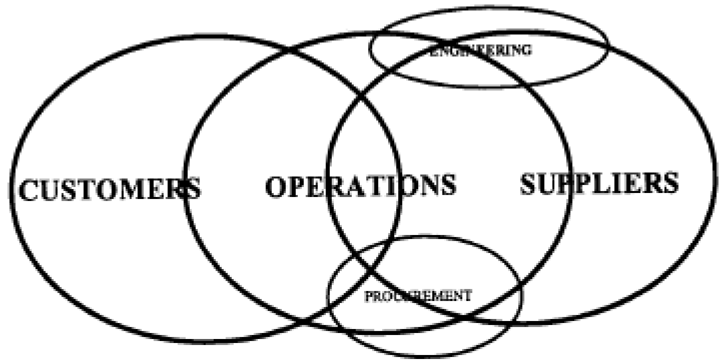


Figure 2-5: LU SC of the Future (Figure 7.8 in Bouverie-Brine and Macbeth 1997)

The LU example shows the influence of the SC configuration departments on the service delivered to passengers. A tragic example, indeed a simple match had a butterfly effect. The butterfly effect was caused by the poor management of interdependences between departments and the lack of integration thereof.

The next section describes LBNL's project SC and illustrates it by drawing on Bouverie-Brine and Macbeth's (1997) representation.

2.1.2 Lawrence Berkeley National Laboratory (LBNL) Example

The researcher identified eight groups of SC participants (project management, engineering, FM, codes and regulations, users, procurement, 1st tier suppliers, and 2nd tier suppliers) for the delivery of projects (new construction and retrofits/upgrades) at LBNL. Figure 2-6 captures the current state of SC relationships. The researcher validated it with an LBNL employee.

When a project starts, the Engineering group writes the project specifications. Recommended manufacturers, products, and materials remain the same across projects unless a change is requested by FM. The group represented by the "Codes and Regulations" circle in Figure 2-6 then checks compliance of project specifications to applicable codes and regulations. The group encompasses the Fire Marshal, Environment Health and Safety (EH&S), etc.

FM may request that changes be made to the specifications if a piece of equipment or specific product has been reported to fail or have a shorter life cycle than what claimed by the manufacturer. In that case, Engineering reviews the request and incorporates the change into the specifications. FM is the group closely in touch with building users, since they do preventive maintenance and they receive work orders from those users. When Engineering finalizes project specifications, they hand the specifications over to Project Management (PM). PM prepares the contract and select suppliers with the help of Procurement. Few suppliers (1st tier would encompass General Contractors (GCs) for example) bid on LBNL's projects at a time for multiple reasons, to name a few: stringent regulations, training requirements, project complexity. These reasons increase the risk for miscalculations in bid estimates and project durations, when contractors are unfamiliar with and/or do not know how to manage this complexity.

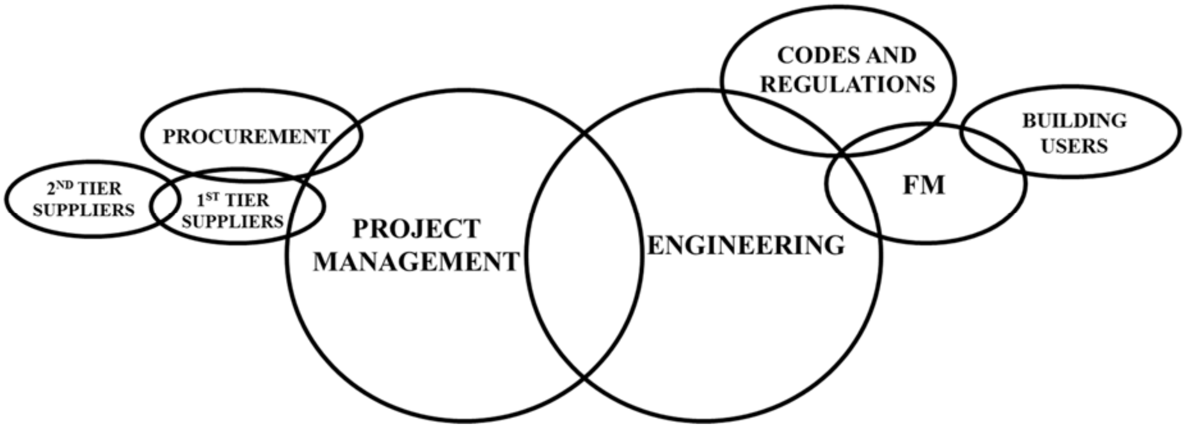


Figure 2-6: LBNL Project Delivery SC

The description of LBNL's current project delivery SC configuration gives rise to the following question: "What is the impact of the current configuration, and specifically FM integration with other departments on customer value?" "Can the current configuration be improved?" and "If so, how?"

While Chapters 3, 4 and 5 concern LBNL, Chapter 6 concerns both LBNL and UCSF and describes how UCSF integrates FM in project delivery.

Different delivery models exist for FM services. They can be grouped under 'in-house' or 'outsourced' FM. Large organizations (i.e., UCSF and LBNL) that rely on high-end facilities (e.g., laboratories, research facilities, plants) tend to have in-house FM (as opposed to outsourced FM) to guarantee the reliability of their facilities and to be responsive in case of emergencies. In addition, research-oriented organizations can be concerned about maintaining the research conducted confidential, and in-house FM presents a lesser threat than outsourced FM. Since the organizations used as case studies in this dissertation are LBNL and UCSF, the remainder of the dissertation will refer to in-house FM.

2.2 Overview of FM

2.2.1 Definitions of FM

Various literature reviews on FM exist, to name a few: Tay and Ooi (2001), Shohet and Lavy (2004), Noor and Pitt (2009), Waheed and Fernie (2009). The following list captures common definitions encountered in the literature, and there are many.

1. "The practice of coordinating the physical workplace with the people and work of the organization; it integrates the principles of business administration, architecture, and the behavioral and engineering sciences." (US Library of Congress 1982, cited in Chanter and Swallow 1996).
2. "FM is responsible for coordinating all efforts related to planning, designing and managing buildings and their systems, equipment and furniture to enhance the organization's ability to compete successfully in a rapidly changing world." (Becker 1990, cited in Noor and Pitt 2009).

3. “The integral planning, realization and management of buildings and accommodation, services and resources which contribute towards the effective, efficient and flexible attainment of organizational goals in a changing environment.” (Regterschot 1990).
4. “An integrated approach to maintaining, improving and adapting the buildings of an organization in order to create an environment that strongly supports the primary objectives of that organization.” (Barrett 1995, 2000).
5. “The application of the total quality techniques to improve quality, add value and reduce the risks involved in occupying buildings, and delivering reliable support services.” (Alexander 1996).
6. “Facilities management comprises numerous integral measures that are necessary to ensure effective use of property for owners and tenants. (…) The economic execution of the organizational, financial, and operational processes as well as the continuous fulfilment of the quality, security and environmental requirements, constitute the principal elements of facilities management.” (Clements-Croome 1997).
7. “The term “facilities management was coined to identify managers of change, and is concerned with preventing building obsolescence brought about by functional and technological obsolescence.” (Clements-Croome 1997).
8. “The practice of FM is concerned with the delivery of the enabling workplace environment, the optimum functional space that supports the business processes and human resources.” (Then 1999, cited in Noor and Pitt 2009).
9. “A focus on the management and delivery of business “outputs” of both these entities (the real estate and construction industry); namely the productive use of building assets as workplaces.” (Varcoe 2000, cited in Noor and Pitt 2009).
10. “The management of non-core company assets to support and increase the efficiency of the main business of the organization.” (Nelson and Alexander 2002).
11. “An integrated approach to operating, maintaining, improving and adapting the buildings and infrastructure of an organization in order to create an environment that strongly supports the primary objectives of that organization.” (Barrett and Baldry 2003).
12. “The practice of coordinating the physical workplace with the people and work of the organization.” (The International Facility Management Association (IFMA) 2003, cited in Shohet and Lavy 2004).
13. “The integration of multi-disciplinary activities within the built environment and the management of their impact upon people and the workplace.” (British Institute of Facilities Management (BIFM) 2003, cited in Shohet and Lavy 2004).
14. “The application of integrated techniques to improve the performance and cost effectiveness of facilities to support organizational development.” (Shohet and Lavy 2004).
15. “Facilities management is the integration of processes within an organization to maintain and develop the agreed services which support and improve the effectiveness of its primary activities.” (European Committee for Standardization (CEN) 2006).
16. “Creating an environment that is conducive to the organization’s primary processes and activities, taking an integrated view of its services and support infrastructure, and using

them to achieve end-user satisfaction and best value through support for, and enhancement of, the core business." (Atkin and Brooks 2015).

17. "Profession that encompasses multiple disciplines to ensure functionality of the build environment by integrating people, place, process and technology." (IFMA 2017a).

There is no denying that many variations of FM definition exist. For example, when trying to determine what FM manages, answers are multiple:

1. "Buildings, systems, equipment, furniture" (Becker 1990).
2. "Buildings" (Barrett 1995, 2000, Alexander 1996).
3. "The buildings and infrastructure" (Barrett and Baldry 2003).
4. "Buildings and accommodation, services and resources" (Regterschot 1990).
5. "Services and support infrastructure" (Atkin and Brooks 2015).
6. "Physical workplace" (US Library of Congress 1982, IFMA 2003).
7. "Building assets as workplaces" (Varcoe 2000).
8. "Workplace environment" (Then 1999).
9. "Built environment" (BIFM 2003, IFMA 2017a).
10. "Facilities" (Shohet and Lavy 2004).
11. "Property" (Clements-Croome 1997).
12. "Non-core company assets" (Nelson and Alexander 2002).

What are more recurrent in FM definitions are the notions of:

1. "Coordination" (US Library of Congress 1982, Becker 1990, IFMA 2003)
2. "Integration" (US Library of Congress 1982, Barrett 1995 and 2000, Barrett and Baldry 2003, BIFM 2003, Shohet and Lavy 2004, Atkin and Brooks 2015, IFMA 2017a, CEN 2006).

With respect to the customers FM serves, Finch (2010) writes about FM definitions:

"It (FM definition) identifies the support of 'services' as being the guiding tenet, with ambiguity remaining regarding whether it serves the interests of the 'business' or 'users'." Thus, common FM definitions suggest an equivalency between the two: if FM serves the interests of the business, it serves the interests of the users and vice versa.

Atkin and Brooks' (2015) definition of FM will guide this research:

"FM is creating an environment that is conducive to the organization's primary processes and activities, taking an integrated view of its services and support infrastructure, and using them to achieve end-user satisfaction and best value through support for, and enhancement of, the core business."

The researcher chose this definition for these reasons: (1) the importance put on FM for the success of the organization, (2) the consideration of both end-user and business (which are not the same as noted by Finch (2010)), and (3) the emphasis on best-value as opposed to cost effectiveness.

2.2.2 Historical Evolution of FM

Finch (2010) links the origin of FM to Florence Nightingale. While Nightingale is more frequently associated with nursing than FM, one cannot downplay her deep understanding of the relationship between the built environment and patients' recovery. In her *Notes on Nursing* (1857), Nightingale makes four recommendations with regards to the built environment in order to accelerate patients' recovery. Hospitals should have (1) outside air over recirculated air, (2) daylight over artificial lighting or dark rooms, (3) wall and floor finishes that are easy to clean, and (4) variety (in aesthetics) (Finch 2010). This in turn led to evidence-based design, which is "the conscientious and judicious use of current best evidence, and its critical interpretation, to make significant design decisions for each unique project. These design decisions should be based on sound hypotheses related to measurable outcomes." (Hamilton 2006).

With respect to when the term "FM" was first coined, it is unclear as whether the terms first appeared in the late 1960s (Finch 2010), late 1970s (Haynes and Price 2002), or 1978 (Keane 2011). Before the 1960s or 1970s, "buildings were maintained, serviced and cleaned: that was about it." (Atkin and Brooks 2015).

The reason why the 1960s are considered to be a U-turn in FM is due to the creation of the Herman Miller Research Corporation, under the leadership of Robert Propst. Similar to how research in cybernetics started, Propst brought researchers and scientists from different fields (anthropologists, mathematicians, psychologists, etc.) to understand how workers interacted with the office (Keane 2011). At the time, office layouts drew on Taylorism, the application of scientific methods to the management of factory assembly lines (Taylor 1911). Desks were aligned in long assembly lines, where the material being passed down was paper. Upper management had private offices. The office space was simple: desks, chairs, tables, file cabinets and paper, and no computers, no printers, no Internet. However, organizations started to value workers' knowledge and creativity. Some new technologies appeared too. These observations made the researchers of the Herman Miller Research Corporation conclude that office designs and the way people worked were misaligned in the sense that offices, as designed then, were rigid workplaces not supporting changes in organizations.

As a result, Propst and his team came up with new rules for office design (Herman Miller 2006): (1) the forgiving principle, (2) change with grace, (3) on-line planning and expression, (4) provide choice and variety, and (5) enrich the work experience. First, the increasing complexity and uncertainty of an organization's environment make it impossible for designers to predict future needs: "We must be allowed to change our minds. We must be allowed to respond to errors as they emerge. And this forgiving should not impose significant cost or delay on the user" (Propst cited in Herman Miller 2006). Second, a facility must be able to change easily. Third, the user should have more control over planning. Fourth, the office is a place where people create. Fifth, the office must support a culture of enjoyment. From these observations, Miller created the Action Office I in 1964, followed by the Action Office II, the ancestor of the "cubicle." The original idea behind the cubicle was to create a flexible space providing privacy to the worker, while allowing collaboration. At approximately the same time, the Bürolandschaft movement was expanding in Europe. The movement put emphasis on work and information flows, and processes and on the fact that the arrangement of the workplace should support them.

During those years, the workplace became more flexible to respond to the changing environment. New technologies such as the "linked computers, facsimile machines, and other IT communications media" (Kincaid 2002) offered new ways of doing office-type work: home-working became possible. Employers become more flexible with where employees should do their work that Kincaid (2002) captures in "looser ties between individuals and organizations." At the time, the role of "Facility Manager" had not been defined yet. Organizations however had a person responsible for managing facilities and the workplace. But something needed to be done to help people and organizations transition from a rather static and simple workplace to a dynamic, and uncertain workplace. To do so, in 1978, the Herman Miller Research Corp. held the conference "Facility Influence on Productivity," which later gave birth to the National Facility Management Association (NFMA) (IFMA 2017b).

In conclusion, the reason why FM emerged in the 1960s/1970s is attributed to a change in requirements for the built environment. Organizations needed help to integrate the people, the business processes, and the environment. This change was motivated by three factors: (1) the use of new technologies (Alexander 1994, Kincaid 2002), (2) a fast-changing business environment (Alexander 1994, Keane 2011), and (3) value for knowledge workers (Alexander 1994) manifested by the invention of the cubicles for example (Keane 2011).

Offices were not the only type of building use to undergo drastic changes due to technological breakthroughs. In manufacturing, increase in automation reduced the need for workers. Healthcare too was impacted by the fast-changing environment and medical advances. For example, minimally invasive surgeries gained momentum, since they decrease the need for a patient's post-surgery care. In light of these observations, Kincaid (2002) argues that trends are "to reduce and to alter the characteristics of the requirements placed on the built environment." While the researcher agrees on the "alteration" part of the statement, the "reduction" part is questioned. In fact, there is no evidence that there is a reduction of the requirements placed on the built environment. A supporting example could be the significant amount of tenant improvement work currently occurring in the Bay Area, and, that is for a large part requested by technology companies. Technology companies are continuously upgrading and changing their workplaces to foster creativity, collaboration, and innovation.

With respect to the evolution of FM focus, FM is as good as the owner is (Keane 2011): the focus of FM during the 1980s and 1990s was to increase space efficiency and reduce real estate costs. There was a shift in the 2000s, where owners started to see facilities as a means to advertise their brand and convey a corporate identity.

This section described the drivers to the emergence of FM. A driver was the realization that the built environment had an influence on occupants. This realization also gave birth to evidence-based design (a fascinating topic, which is not part of this dissertation). The next section describes when other countries started to give importance to FM through the creation of FM organizations.

2.2.3 FM Organizations

In the US, George Graves, Charles Hitch and David Armstrong founded the National Facility Management Association (NFMA) in 1980 (IFMA 2017b). When the organization expanded to Canada, it was accordingly renamed the “International Facility Management Association (IFMA) in 1982. IFMA is now present in 104 countries (IFMA 2017b). In the UK, Japan, and Europe, the FM profession started to appear from mid 1980s (Keane 2011). In 1986, the United Kingdom founded the Association of Facilities Management (AFM), known now as the British Institute of Facility Management (BIFM) (BIFM 2017). The Danish FM Association “DFM” was created in 1991. Multiple organizations were created in Norway and Sweden, EuroFM, the European network for FM was created in 1993.

In Japan, the term FM was imported in 1985 (Makoto 1990 cited in Alexander and Price 2012). The Japanese introduced FM by stressing its connection with the PDCA cycle. In 1987, the Japan Facility Management Promotion Association (JFMA) was established.

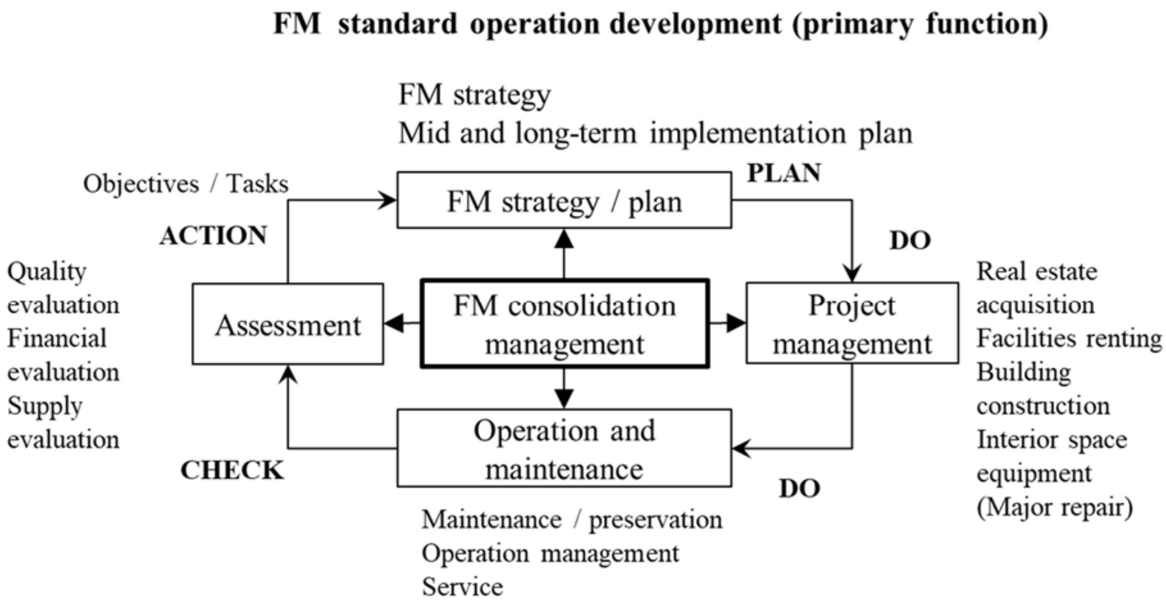


Figure 2-7: Japanese FM Association Promotes FM as a PDCA Cycle (Proposed Translation of Figure 7.2 in Alexander and Price 2012)

Although FM organizations have existed for 30 years in the US and in some European countries, the next paragraph shows the lack of agreement on the tasks encompassed in FM.

2.2.4 FM Tasks

The scope of FM is so large and varies so much from an organization to the next that it is hard to define (Chanter and Swallow 1996, Waheed and Fernie 2009). Unsurprisingly, Noor and Pitt (2009) write that “there is no universal approach to managing facilities.”

Different classifications of FM scope exist in the literature:

1. Facility planning, building operations and maintenance, real estate and building construction, and general/office services (Thomson 1990).
2. Financial management, space management, operational management, and behavioral management (Banyani and Then 2010).
3. Health and safety, fire and safety, security, maintenance systems, statistical testing and inspection, operational, and Information Technology (IT) (categories of services that FM can contribute to according to Kiviniemi and Codinhoto 2014).
4. Real estate management, financial management, human resources management, health, safety, security and environment (HSSE), change management and contract management, building maintenance, building services engineering maintenance domestic services and utility supplies (Atkin and Brooks 2015).
5. Tables 9-1 to 9-16 (in Appendix) are a summary of FM goals tasks.

FM role has received many names:

1. “Hybrid manager,” “business leader” (Alexander 1994).
2. “Teacher,” “housekeeper,” “manager,” and “juggler” (Aune et al. 2009).
3. “Jack of all trades” (Tai and Ooi 2001).
4. “Innovation leader” (Noor and Pitt 2009), “user-technician” or “super-user” (Aune et al. 2009).

Given the difficulty of defining FM scope, Finch (2010) writes: “the facility management profession could obtain greater clarity in understanding the FM mission by the identification of ‘role models’ rather than ‘task definitions’.”

Overall, the literature review suggests that FM has traditionally been considered as a support department rather than a core department, that must be cost-efficiency driven, and that is not directly contributing to meeting the business objectives (Chanter and Swallow 1996, Grimshaw 2007, Noor and Pitt 2009). In this respect, Clayton et al. (1999) write: “Maintenance, remodeling, replacement of components and daily facility operations consume a large portion of the cost of doing business.” Publications in more recent years also show that FM is ready for a paradigm shift. This paradigm shift can only happen by acknowledging the value that “FM bring(s) towards organizational effectiveness” (Noor and Pitt 2009).

2.2.5 Levels of Planning in FM

FM involves three levels of planning: (1) operational planning, (2) tactical planning, and (3) strategic planning (Chanter and Swallow 1996, Alexander 1996, Gordon and Shore 1998 cited in Vanier 2001, Kiviniemi and Codinhoto 2014).

FM was initially created to do **operational planning**. Operational planning consists of “the day-to-day support of operations that are required to keep the business functioning” (Noor and Pitt 2009), or equally “deal(ing) with day-to-day accommodation issues and the implementation of the strategic plan” (Vanier 2001).

As the importance of FM became visible to organizations, the latter started to see the value of involving FM in **tactical planning**. Indeed, FM was accumulating knowledge through their day-to-day interactions with people in the workplace and assets. They were at the forefront to understand people's needs and business processes. As a result, their scope of planning evolved from a day-to-day operations level to encompassing both the operational and tactical levels.

Organizations then understood that FM could inform decisions at a **strategic** level and plan "for service provision based on business demands" (Noor and Pitt 2009). Nonetheless, this shift in mindset is more recent. The motivation to align business needs with how facilities are planned results from the realization that facility strategic planning is a necessary step for achieving business goals.

From a complexity perspective, these planning levels show a hierarchical structure as found in complex systems according to Simon's (1962) definition.

2.2.6 Changes in Planning

In the lifetime of a facility, changes can affect the programming, design, construction and commissioning of the facility, and its use. The next two paragraphs describe first the uncertainty surrounding the preconstruction and construction of a facility and second the uncertainty surrounding the use of the facility.

Ultimately, the building crystallizes a design. The design itself results from a project definition process that can be characterized as a wicked problem (Whelton and Ballard 2003):

"The project definition process (…) occur(s) within a social system constructed of stakeholders that employ complex strategies, policies and routines. This social system is perceived to be complex in detail and dynamically complex in behavior."

A variety of stakeholders are involved in the project definition process. Usually, they include: project management, facility owner groups (users, FM, etc.), architects/designers, engineers, consultants, and regulatory agencies. Project management is responsible for the engagement and the coordination of stakeholder groups in order to achieve a common purpose, which is the design of a facility (Whelton 2004). However, stakeholders' groups and individuals within a group, may have different needs, which could (or not) be conflicting and changing (even within the timescale of the project definition process). Each stakeholder thus constitutes a source of uncertainty. Furthermore, stakeholders also "operate within their own work environments under separate organizational strategies, policies, and work routines" (Whelton 2004), which contributes to the complexity of the project definition process. Construction as well can be affected by changes in needs or out of the realization that a design detail is not constructible for example. External factors such as changes in regulations (among others) may also affect those phases.

Once the facility is built, FM plans at the operational, tactical and strategic levels. During this building life-cycle phase, changes that are internal and external to the organization still occur. For example, predicting the business needs in the long term is part of strategic planning. Unfortunately, predicting business needs with certainty can be relatively difficult for many businesses (healthcare, automotive industry, hospitality, etc.). A reason accounting for this difficulty is the fact that our world is in constant flux: people are mobile, information is shared instantly, etc. The ubiquity of digital connectivity also contributes to the flux. Changes that affect a business's environment ultimately affect requirements imposed on the facilities. Thus, changes in how the facility is used are likely to occur in the long term and in the short term. Indeed, at the timescale of a day, occupants come and go, perform different activities during the day. For example, in some tech companies in the Bay Area, employees are allowed to work from home on a given weekday. Thus, a building must be able to respond well to large variations in occupancy loads.

Figure 2-8 captures a building life cycle and incorporates FM three levels of planning occurring in the use phase. The arrow (Figure 2-8) is a feedback "learning" loop linking the use phase to the programming phase (project definition phase). The intent is to have the business's priorities as well as the lessons learned by FM from facilities already built feed facility planning for new construction projects and future upgrades.

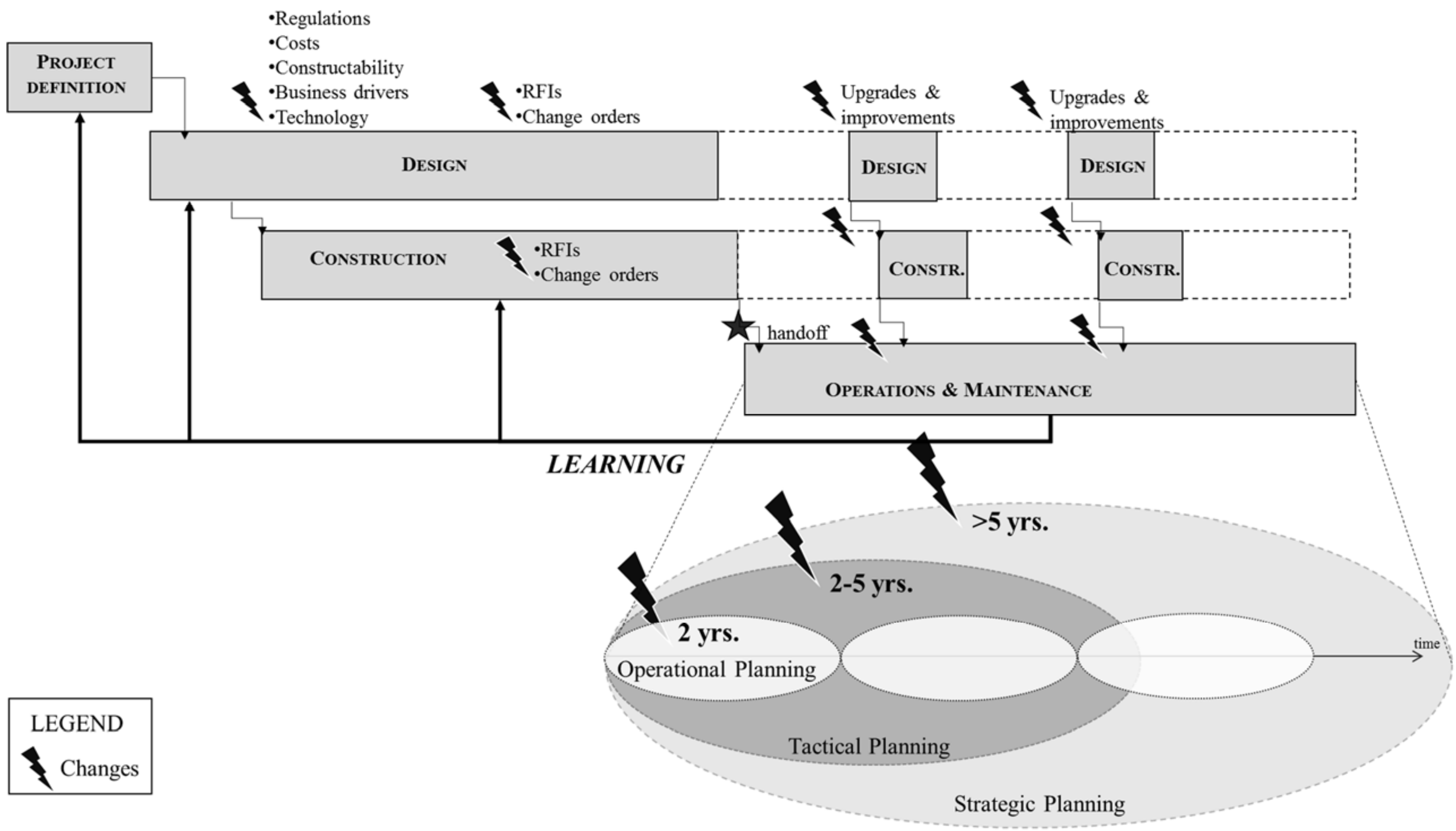


Figure 2-8: FM as Feedback Loop in Project Delivery

In conclusion, this section established the link between the increasing complexity in the workplace and the growing importance of FM in the use phase. This raises the question: "Has FM involvement been acknowledged in earlier building life-cycle phases?"

To answer this question, the following section captures arguments found in the literature on the value of integrating FM in the delivery of projects during programming, design, planning, construction, commissioning, and after the project is delivered, that is, during the use phase. The sections address the phases separately, but these phases may overlap (i.e., design and construction, construction and commissioning, etc.).

2.3 Case for FM Integration in Project Delivery

2.3.1 Programming Phase

The terms "project customers" may encompass multiple user groups within the owner's organization and FM is one of them. The early involvement of customer user groups (including FM) has been acknowledged to be critical on construction projects for multiple reasons (Jensen 2009). First, customer user groups do not always know what they want right off the bat, so the project team can help them explore their needs or refine their self-understanding of their needs (Ballard 2008, Aapaoja et al. 2013). In this respect, Aapaoja et al. (2013) write:

"Value creation is, however, more than implementing an extensive set of features. Customers do not seek products or services in themselves, they want solutions that support their processes and create value when used."

Second, customers' early involvement helps identify conflicting needs across user groups early. Third, it supports the exploration of alternatives that customers may not have considered. Fourth, customers have knowledge that can be valuable for the project team. The next paragraphs expand on the value of FM knowledge in the programming phase.

Aapaoja et al. (2013) looked at a renovation project in Finland. They used snowball sampling to identify stakeholders to interview. An intent of their study was to determine which stakeholders should be involved early and when they should be involved. In the case study, the researchers captured the "official" role of each interviewee, namely, how the person defined its own role on the project. They compared those official roles to their roles "in practice." They argue that the performance of the renovation project studied was undermined by people sticking to the scope of their "official" roles. In the stakeholder roles listed, "property management," defined by "operating the property, information management, and preparation of matters; looks for opportunities to develop the housing company" is the most similar to FM. The researchers explain for which reason(s) each stakeholder should be involved early. Thus, they write that the property manager should be involved early, because he/she "usually has the best knowledge and information about the property and what we are trying to achieve. Provides source information for designing." However, the study is not specific about the type of "information" that property management (or FM) could provide during programming.

This gives rise to the following question: what specific knowledge does FM bring once involved in the programming phase? First, FM has unique knowledge about end-users (their behaviors, their preferences), processes and activities through their interactions with them at the operational level. This is the reason why Aune et al. (2009) compare FM with "super-users" because they "see" the users. Second, FM has knowledge about how buildings have been satisfying user's needs, they have an understanding about buildings' actual performance. Thus, using the lessons learned on former projects to inform the project definition phase can help prevent architects and engineers from repeating errors (Aune et al. 2009). To this extent, Jensen (2002) lists the "transfer of experiences from existing buildings" among FM more important tasks in strategic planning.

2.3.2 Design Phase

Numerous studies have pointed out the importance of involving FM in design. Kalantari et al. (2017) list 13 of them (Arditi and Nawakorawit 1999, Dunston and Williamson 1999, Duffy 2000, Meier and Russell 2000, Jaunzens et al. 2001, Bröchner 2003, Erdener 2003, de Silva et al. 2004, Mohammed and Hassanain 2010, de Silva et al. 2012, Bu Jawdeh 2013, Meng 2013, Nkala 2016). Others could be added to this list such as: Mitropoulous and Howell (2002), Aune and Bye (2005), and McAuley et al. (2016). The next paragraphs summarize the arguments given in favor of FM involvement in the design phase.

A first argument is informing the design of maintenance considerations (Aune and Bye 2005) or "maintenance practicality" (Assaf et al. 1996) and thereby drive down building life cycle cost (Meng 2013). Accessibility of equipment, location and sizing of maintenance catwalks, selection of mechanical systems depending on their reliability, location and sizing of janitors and storage space are examples of decisions made in the design phase and that FM could inform. In this respect, Arditi and Nawakorawit (1999) conducted a survey of the 230 largest property management firms in the US. Building design inefficiencies ranked first in the maintenance-related problems experienced. Dunston and Williamson (1999) insist on the importance of FM continuous involvement during design. They argue that design and construction decisions are cost-driven and as a result, designers may disregard consequences on building maintainability. Product substitution is frequent in value engineering and is sometimes performed without a diligent investigation on the product, which could be incompatible with the existing design or not be as performant as the initially specified product. They insist that those mistakes can be unintentional: they are due to contractors' lack of understanding of FM expectations on the product performance. Meng (2013) interviewed a group of people involved in FM (74.2% of interviewees) and project delivery (design, client representatives, etc.) to inquire about UK practices in the involvement of FM in project delivery. FM involvement helps to drive down whole life cycle costs and increase building maintainability.

A second argument is increasing building efficiency. Energy efficiency can increase if FM better understands the design intent before occupancy (Aune and Bye 2005). Aune and Bye (2005) interviewed FM at college and secondary school in Norway. Overall, building operators agreed that the earlier they got involved in the design, the better, because they felt it was easier to operate the building, because they understood it better. Jensen (2009) also lists "sustainability" and "formulation of requirements for building automation system" in the reasons in favor of FM involvement in design.

A third argument is avoiding negative design iteration. Mitropoulous and Howell (2002) investigated into design iteration encountered on a renovation project of office space. Through interviews with project team members, they identified: the conditions that created design iteration, causes for design iteration, the effect of design iteration on design, and their effect on cost and time. They conclude that most of the design iteration were due to late discovery of existing conditions. Yet, existing conditions is part of FM tacit knowledge, hence the value of integrating them in the design phase would have allowed to avoid negative iterations.

A fourth argument is a better translation of user needs (Meng 2013). This converges with the arguments in favor of FM involvement in the programming phase.

The value of FM involvement in design certainly exceed the above list of arguments, because FM "hold(s) tacit and experience based knowledge" (Aune and Bye 2005). This makes FM specifically suited to reminding architects about whether or not their performance expectations are reasonable, since "designers may sometimes expect their buildings to operate in ways that are not practically feasible." (Kalantari et al. 2017).

2.3.3 Planning Phase

In high-end facility upgrades, FM involvement in planning the work is critical. They know how equipment and systems function. They possess tacit knowledge about existing conditions that may or may not have been captured in as-builts (as it often happens in successive "small" upgrades). They have also accumulated knowledge about how systems are fine-tuned, and the extent to which systems are sensitive or not to perturbations. They can inform the construction team about the feasibility and the risks associated with the construction means and methods proposed. FM may also be able to recommend strategies on how to tackle the job.

2.3.4 Construction Phase

FM involvement in the construction phase is also valuable (Enoma 2005, Aune and Bye 2005). Indeed, FM involvement in the programming and design phases is insufficient to guarantee that what they specified in programming and design has been understood by the design and construction team and will not be altered. FM is often no longer consulted in the construction phase, although changes still happen. Finishes are a case in point. FM have tacit knowledge about the maintainability of finishes and how the products used evolve and last with time. However, substitution with other products and manufacturers still happen during construction for various reasons, hence the necessity of keeping FM informed and involved.

2.3.5 Commissioning Phase

FM should be involved in commissioning (Jensen 2009). During this period, systems and equipment are tested. Commissioning allows the design and construction team to ensure that the building performs as expected. This period is followed by the turnover process during which the construction team hands over all information useful for the operation and maintenance of the building to FM. During this period, FM is also trained to operate and maintain equipment, building automation controls, etc.

2.3.6 Use Phase

During the use phase, FM adds value to the organization in many ways.

Latham (2001) cited in Enoma (2005) writes that during programming, design, and construction, FM is the eyes and ears of the clients. Enoma (2005) builds upon Latham's (2001) to depict FM role after the building has been handed over: "when handover has taken place, (…) the eyes and ears of the client then assume the role of hand and feet as well."

Additionally, FM ensures that the building performs as expected. However, Nault and Angle (2013) suggest that building performance is doomed to decrease after commissioning and tuning.

Figure 2-9 was extracted from a presentation made by Nault and Angle (2013) for the American Institute of Architects North Carolina Chapter. The graph was titled "typical building life cycle." It represents the evolution of building performance ("performance" would need to be clarified here) with time from the first day of occupancy. The curve is concave: the performance of the building increases until reaching a maximum, and then decreases till reaching "the minimum acceptable performance." The graph suggests that additional efficiency opportunity exists. It is also suggested that "automated optimization and perpetual commissioning" offer opportunities for slowing down the decrease in performance experienced after the building has been fully tuned and commissioned. The graph fails to show whether FM would contribute to offset the graph so that it reaches "additional efficiency opportunities" and whether FM involvement could slow down the decrease in performance or even change the trend of the curve.

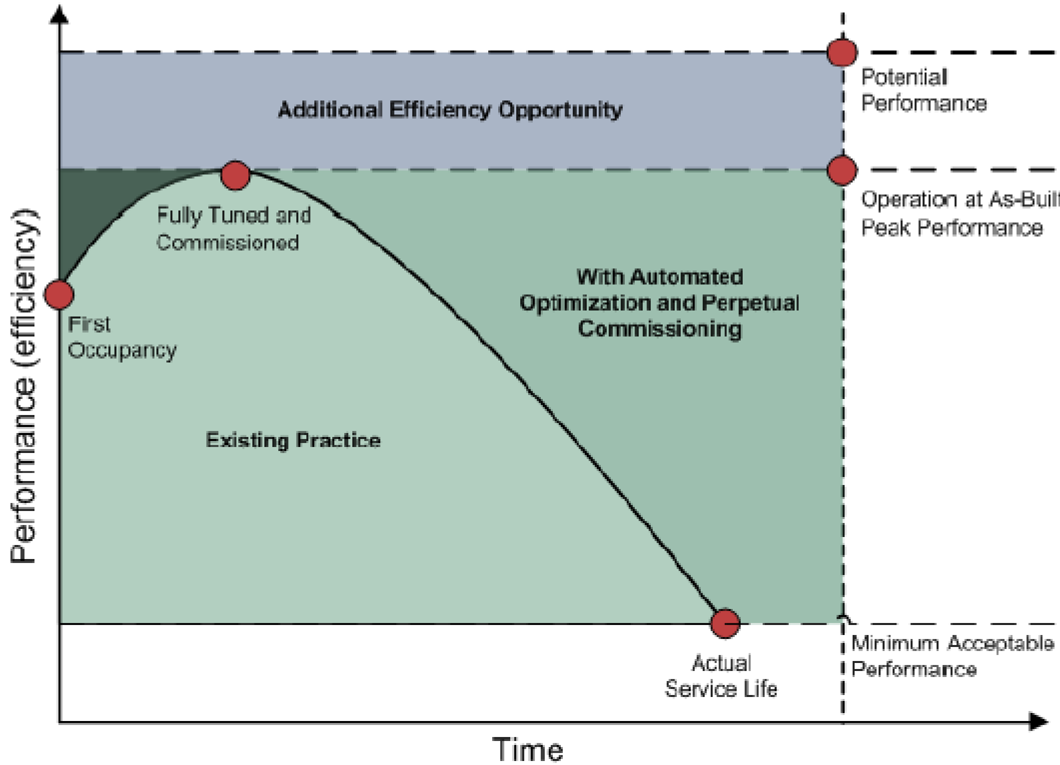


Figure 2-9: Performance in Function of Time during the Building's Operations and Maintenance Phase (No Figure Number in Nault and Angle 2013)

Although Aune and Bye (2005) refer to "energy efficiency," which is narrower than "building performance," they suggest that building operators are critical to help "fulfill the "technical" possibilities of the building (, which) is dependent on how the building is taken into use." On Nault and Angle's (2013) graph, FM value to the organization could have been represented by a vector pointing upward.

However, research validating the relationship between FM and value delivered during the use phase is lacking (May and Pinder 2008). For example, evidence-based design looks at relationship between occupants and building designs.

While the importance of involving FM in the design process has been mentioned in the literature, some barriers to collaboration between FM and designers remain (Enoma 2005, Meng 2013, Kalantari et al. 2017).

2.3.7 Barriers to FM Involvement

Enoma (2005) argues that decisions are often cost driven. As a result, it does not foster FM collaboration since the alternative with the lowest cost will be preferred over what FM recommends. Another barrier according to Enoma (2005) is the belief in construction that "the client is not the occupier," hence alleged absence of need for involving FM. In addition, business needs are often segregated from operational needs and the interdependences between the two is overlooked. This constitutes a third barrier to FM involvement.

From the researcher's experience, the fact that FM involves so many tasks and responsibilities, makes it difficult for the design and construction team to know which FM person to invite to a meeting or to consult before making a decision. Although FM may use a "representative" that will attend all meetings and serve as gateway between the FM department and designers, this person is often not knowledgeable about everything (and cannot be).

Kalantari et al. (2017) conducted 30 interviews and distributed a survey in the USA, UK, and the middle East to FM professionals. Analysis of the data revealed that the lack of collaboration results from communication and cultural barriers. Indeed, designers and FM are far apart from each other in the building's life cycle. Once the building is occupied, designers do not welcome criticisms to their design, and FM does not see value in providing feedback at this time since it is "too late." Furthermore, owners see FM/designers collaboration as an additional cost: involving FM in the design is mobilizing another resource and owners are not aware of how this could pay off in the long term.

To foster FM collaboration in design, the researchers proposed a model showing opportunities for FM to collaborate with the design team (Figure 2-10).

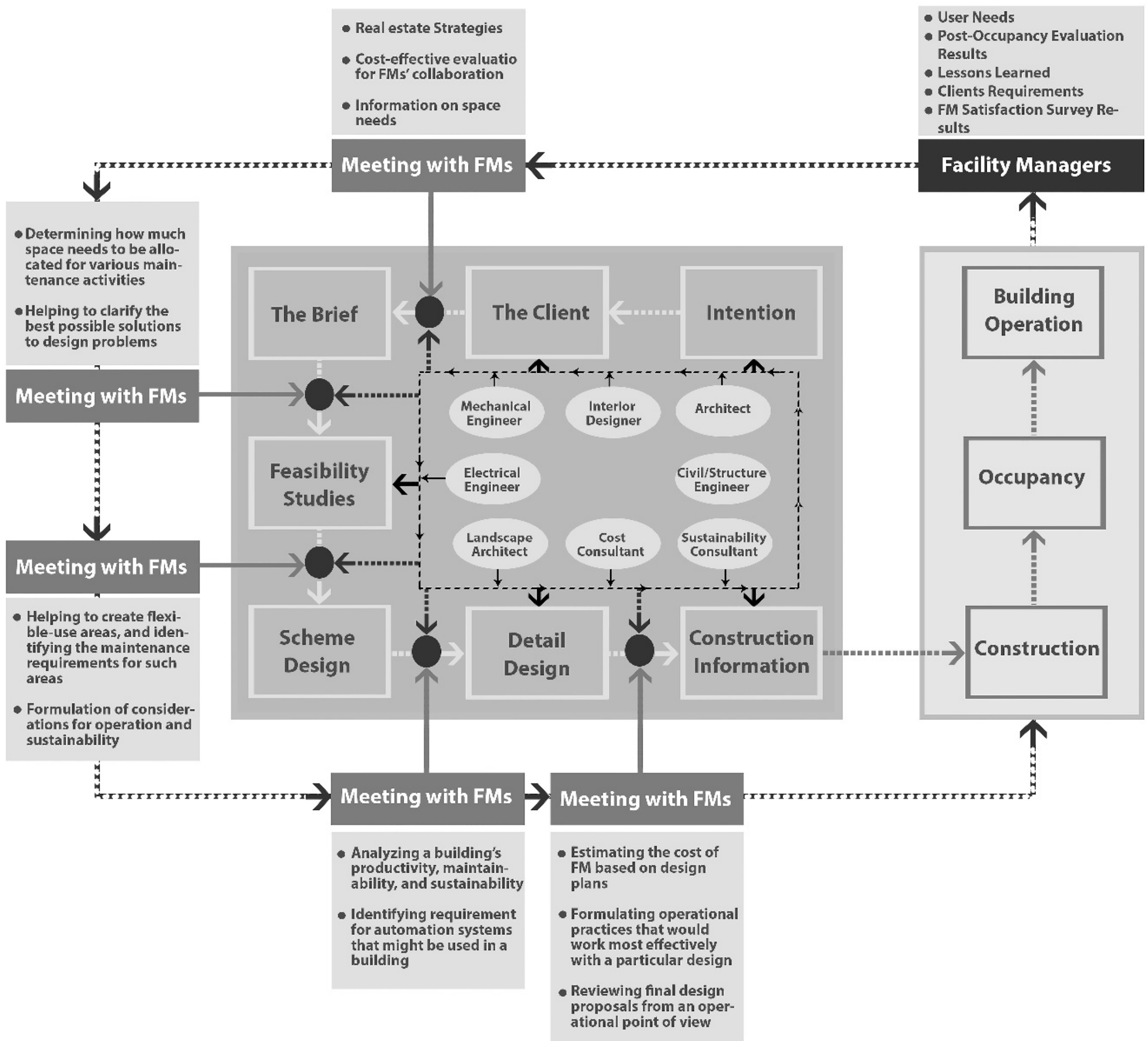


Figure 2-10: Model of Collaboration to Better Integrate the Knowledge from Facility Managers into the Design Process (Figure 9 in Kalantari et al. 2017)

This section made the case for FM early involvement in project delivery. However, is FM early involvement sufficient to prevent buildings from failing and to ensure that they meet customer requirements? The next section answers this question by identifying and classifying how FM fails.

2.4 Classification of FM Failures

For the reasons given in section 2.2.1, the adopted definition of FM is:

"FM is creating an environment that is conducive to the organization's primary processes and activities, taking an integrated view of its services and support infrastructure, and using them to achieve end-user satisfaction and best value through support for, and enhancement of, the core business."

Thus, FM "failure" qualifies situations in which end-user satisfaction and best value are not met due to a lack of support for, or enhancement of, the core business. The researcher classified aspects of FM failures in 5 categories: (1) building systems, (2) people, (3) tools and data, (4) processes, and (5) changes.

2.4.1 Building Systems

Buildings age and deteriorate due to natural wear and tear (Assaf et al. 1996, Grussing and Liu 2014). Building systems also undergo this "inevitable process of decay" (Chew et al. 2004) through what is called functional and technical obsolescence (Clements-Croome 1997, Wong and Chan 2014).

Furthermore, building systems have increased in complexity and density in facilities (Chew et al. 2004, Mohammed and Hassanain 2010, Meng 2013, Lavy and Jawadekar 2014, Domingues et al. 2016). Since facility systems are increasingly more integrated and thus interdependent (ASHRAE 2005), they are also more vulnerable to other systems' failures. Related, Djuric and Novakovic (2007) point out the following concern given this complex context:

"Even though the building complexity is growing, communication/understanding between the participants and the building elements during the building life is poor."

Such problems are exacerbated in building automation systems, where problems at the interface between the system and building occupants remain unresolved (Camacho et al. 2014).

2.4.2 People

Chew et al. (2004) list inappropriate maintenance practices in the reasons for building maintenance failures. The FM profession encompasses many tasks and general curricula such as "engineering" do not prepare students for the wide range of challenges faced in FM. To fill this gap, Watton et al. (1996), and Baglione and del Cerro (2014) propose a more tangible approach to teaching HVAC controls. In order to keep up with a constantly changing technology, FM needs continuous training. Clayton et al. (1999) reported a lack of documents for training. Training documents are provided by the construction team as part of the turnover documents. Related, Song et al. (2002) recommend "JIT training," meaning that training must be done onsite and when needed.

While some studies on building maintainability focus on the need for better FM training, Kalantari et al. (2017) suggest that designers as well could benefit from better training and education "in order to help alleviate communication problems and improve collaboration efforts."

Due to limited resources (Cao et al. 2014), FM must continuously prioritize, hence, make decision (Vanier 2001, Gheisari and Irizarry 2011) but lack of a consistent methodology to make those decisions. Consequences may result in overlooking maintenance needs that should be treated as a priority.

2.4.3 Tools and Data

The lack of quality and structured data about facilities has been documented for years. This data is usually handed over from the design and construction team to the owner during the "turnover process," also called "closeout." Already in 1956, Tidwell (1956) wrote a book titled *How to produce effective operations and maintenance manuals*. Examples of valuable information missing in turnover documents are: design intent (Scarponcini 1996, Clayton et al. 1999) and sequence of operations (Xiao and Wang 2009, Sunnam et al. 2015). In an editorial, Scarponcini (1996) tells the story of designers of a wastewater facility. They refused to provide additional information on why a valve was required, limiting themselves to specify the type, size, and material of the valve as per the contract. Scarponcini (1996) writes:

"Think of the trivial additional cost during design to document this information. Contrast this to the cost to the facility manager who, without this information, has to experimentally discover what the effect of closing this valve will have on the operation of the facility. Multiply this by the number of valves in a $6 billion plant. Next, consider all the other equipment beyond valves and all of the other maintenance/operation-needed, design-known information that is similarly not captured on a traditional set of contract documents."

In fact, the "operations documents issues" that Clayton et al. (1999) listed almost two decades ago are still valid.

However, the information handed over from the design and construction team to the owner is not the only reason for FM failure from a data perspective. Tools hosting this data, namely, data systems are often not integrated: "the building information needs to be integrated or compatible with the FM information systems, such as computerized maintenance management systems (CMMS), electronic document management systems (EDMS), energy management systems (EMS), and building automation systems (BAS)" (Becerik-Gerber et al. 2012). The listed systems are themselves not connected to the building information model. Beyond the lack of integration, researchers report that data is sometimes entered manually in each of these systems (Becerik-Gerber et al. 2012).

The problem of systems' lack of integration stretches out to energy monitoring. Ahmed et al. (2010) write that "the building energy and Facility Management domain exhibits inefficiencies in the availability of consistent and complete building performance data." However, they also suggest that energy inefficiencies are also due to the fact that (when available), the data is not necessarily "actionable."

Even the energy tools used in the design phase present some shortcomings. Ahn et al. (2016) describe the issues encountered in energy simulation models. Among them, they mention that input used for simulation is "grey data": some input values should be stochastic instead of deterministic such as building performance and occupant behavior, other input values are unknown or the information is outdated. In their research, they report the example of a building for which they wanted to create an energy simulation model. They asked the facility manager to provide the information they needed. However, the "information and data provided by the manager were not well-documented and were not up-to-date." Furthermore, the changes (upgrades and other maintenance) that happened to the building after construction had not been documented. Overall, one cannot overlook the "subjective assumptions and judgement" used in modeling, which is one of the reasons of discrepancies between expected energy performance and actual performance.

2.4.4 Process(es)

Buildings fail to meet end-user satisfaction, because architects and designers rely on the representation of user's needs instead of "going to the gemba," which means going on site and seeing for yourself. Aune et al. (2009) support this argument by highlighting the gap between standards and user's thermal comfort in buildings: "occupants are forced to "cope" with thermal discomfort," "meaning that they have to make up for the difference between standards and individual experience." Unfortunately, these observations are made too late in the building life cycle since they happen during "post-occupancy evaluations." However, learning from post-occupancy evaluations seldom takes place: lessons learned do not inform future projects and architects do not receive the feedback. Communication issues and cultural barriers impede FM from fulfilling this role (Kalantari et al. 2017)

Commissioning is conducted in buildings to ensure that systems work as intended. The benefits of commissioning are undermined by a lack of process standardization and the failure to transfer the information collected during commissioning to the owner for operations (Turkalsan-Bulbul and Akin 2006). Even in "continuous commissioning," FM is not systematically involved from the beginning. Kantola and Saari (2014) list the stakeholders involved in each phase of the continuous commissioning process. The researchers fail to involve FM in the "pre-designing phase," "designing phase," "detail designing" and "construction phase." They show FM involvement only in the handover and occupancy phases.

In addition to commissioning, buildings can be retro-commissioned. The purpose of retro-commissioning is "to solve existing problems in buildings where new building commissioning was not conducted and to operate the building efficiently and effectively" (Liu et al. 2003). In other words, retro-commissioning can be considered as a response to the failure of commissioning. Unsurprisingly, Forbes (2013) states that "Commissioning is not well understood by the industry, and is underutilized despite its potential for performance optimization."

Following building commissioning, the turnover process also shows inefficiencies (Clayton et al. 1999, Dunston and Williamson 1999, Mrozowski et al. 2008, Teicholz 2013). The fragmented nature of the construction industry can explain some inefficiencies such as over-processing information, and the absence of "integrated views across functional systems" (Clayton et al. 1999).

2.4.5 Changes

Occupants and business needs' change over time and new needs will emerge as soon as users will start to occupy the building (Alexander 1994, Aune et al. 2009, Wong and Chan 2014). Users' needs can also be conflicting or contradictory (Camacho et al. 2014, Fronczek-Munter 2014). Alexander (1994) defines building users as "producers" and "consumers." Users produce value in alignment with the organization's objectives. They consume the facility and service and have therefore needs. Technology used in buildings evolves fast as well (Evans 1998, Kincaid 2002).

The conceptual model of obsolescence proposed by Thomsen and Van der Flier (2011) includes four quadrants (Figure 9-1 in Appendix). Sources of obsolescence can be endogenous (influences from inside the building), or exogenous (influences from outside the building). They can also result from behavioral or physical processes. Using this model, changes in occupants' needs fall within the "endogenous" and "behavioral" obsolescence quadrant.

Because of obsolescence and frequent changes in needs, processes must be in place to "continuously match the provision of buildings systems and services to changing needs" (Alexander 1994). FM is the "missing link that was already there" between the users and the technology and "who is managing changes of both parts" (Aune et al. 2009).

Given this context, Larssen et al. (2012) developed the viability model, which categorizes buildings with respect to their levels of usability and adaptability. Buildings that have a good usability and adaptability are "fit for purpose" and will be good candidates for future upgrades. Conversely, buildings that have a poor usability and adaptability should be considered for disposal or reconversion.

The next section covers solutions that were developed by academics and practitioners to support FM in ensuring customer satisfaction and best value. It then identifies limitations to the proposed solutions. Limitations are linked to a poor understanding of the nature of FM.

2.5 Proposed Solutions

2.5.1 Description of Solutions

Table 9-17 in Appendix captures solutions that were designed to solve FM failures presented previously. The first column indicates the category (i.e., building systems, people, tools and data, processes, and changes) to which the solution belong. The second column captures the name of the solution. The third column is the description of the solution. The fourth column gives the academic or commercial reference for the solution.

Many solutions exist to support FM. Nonetheless, these solutions have so far either not been fully adopted by practitioners or have not prevented FM from failing. Thus, a question arises: "What are the limitations to these solutions that could account for their lack of adoption or their lack of efficiency in supporting FM?"

2.5.2 Limitations of Proposed Solutions

In the light of the solutions proposed, four observations are shared:

1. Building automation has become ubiquitous, but it still falls short of expectations. First, building automation constitutes the layer on top of building systems (MEP equipment, valves, actuators, etc.). Thus, a prerequisite for building automation to work as expected is that building systems work as expected, which is no easy task given the increasing density of building systems. Second, building automation has yet not resolved conflicts

arising at the interface between the machine and the user. In Ahn et al. (2016), "the authors realized that, even though advanced automatic controls (e.g., enthalpy control, night-purge control) had been installed, the building was discretionally operated by the facility management team. (…) Such irregular operation history has not been documented."

2. From a building life-cycle perspective, most solutions focus on the use phase. However, the influence on cost is greater in earlier phases of the life cycle (Paulson 1976, Figure 9-2 in Appendix).
3. Few solutions capitalize on FM tacit knowledge. Dahl et al. (2005) propose creating a Kanban system to incorporate O&M knowledge into design. Kalantari et al. (2017) proposed a model to integrate FM knowledge in the design.
4. Most solutions are tools and data oriented. Only few solutions address failures falling within the "changes" category. However, changes have been identified as inherent to the building life cycle (section 2.2.3).

These observations reveal a mismatch between the nature of FM and the proposed solutions. Most solutions do not take into account FM tacit knowledge, FM unique relationship with building users, and the role of FM as a feedback loop between users and designers for learning. In fact, solutions either focus on a Transformation, or Flow view of FM. They overlook the Value view of FM (Table 2-1).

Table 2-1: Proposed TFV Definition of FM

Transformation	**Flow**	**Value**
Transitioning from a state A in which building systems and components do not perform as expected to a state B in which building systems and components perform as expected.	Collecting data on the performance of a building or group of buildings to feed decision making or support maintenance operations (see transformation).	Ensuring that the building achieves end-user satisfaction and best value.

The fact that FM still fails despite the solutions made available to them motivated the researcher to better understanding of the nature of FM.

In construction, the Lean community used the Cynefin framework (Kurtz and Snowden 2003) to enhance the Lean theory. Biton and Howell (2013) write that Cynefin "helps decision makers understand what kinds of methods and tools will be likely to work in our particular situation, and those that are unlikely to help."

What could we learn from applying the Cynefin framework to FM? Answering this question is a first step to cast new light on the nature of FM.

2.6 Sense-Making of FM Context using Cynefin

Traditional leadership makes decisions and address situations based on the assumption that the world is ordered and predictable (Snowden and Boone 2007). The Cynefin framework relies on the assumption that some things are not predictable and that some disorder exists in this world. Therefore, not every situation can be simplified (Kurtz and Snowden 2003, Snowden and Boone 2007). Kurtz and Snowden (2003) developed the Cynefin framework to help leaders make decisions by first understanding the context of those (basically, pick from a variety of angles depending on their fitness for the situation). Once the leader has identified the context, the framework gives the decision-making approach that should be followed. Simply put, the Cynefin framework offers a classification of contexts in which decisions must be made. A context is defined by "the nature of the relationship between cause and effect." The next paragraphs describe these different natures.

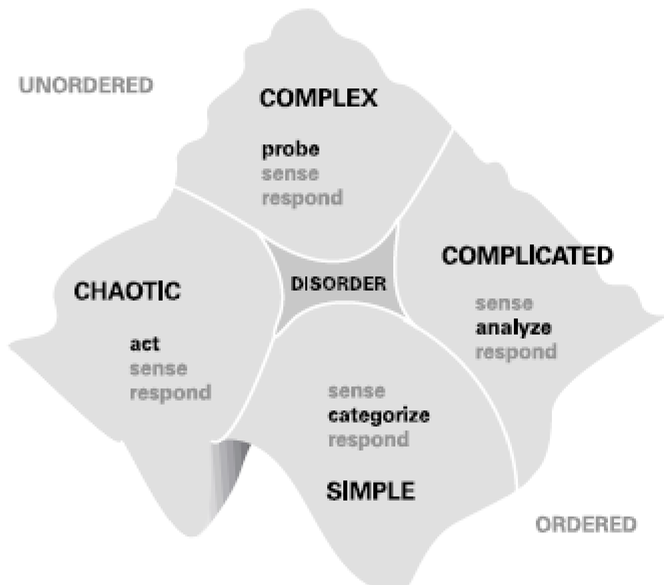


Figure 2-11: The Cynefin Framework (Page 4 in Snowden and Boone 2007)

2.6.1 Simple Context

A simple context is "characterized by stability and clear cause-and-effect relationships that are easily discernible by everyone" (Snowden and Boone 2007). When issues encountered in a simple context involve multiple stakeholders, all stakeholders have the same understanding of the decision to make. In simple contexts, leaders "assess the facts of the situation, categorize them, and then base their response on established practice" (Snowden and Boone 2007).

2.6.2 Complicated Context

In complicated contexts, cause-effect relationships are known, but not by everyone. In comparison with simple contexts, where leaders assess, categorize, and respond, complicated contexts require that the facts are sensed and analyzed. This analysis part requires expertise.

Multiple right answers may exist. The simple and complicated contexts belong to the ordered world, namely, when decision-making can rely on facts.

2.6.3 Complex Context

Complex contexts describe environments that are in constant flux and unpredictable. In complex contexts, cause-effect relationships are not clear but could be observable in retrospect. When looking at a complex context, one can see the emergence of patterns, but patterns are observable only in retrospect. Solutions can emerge too. Therefore, leaders must probe, sense, and respond.

2.6.4 Chaotic Context

Unlike complex contexts, chaotic contexts do not show patterns at first sight, but instead turbulence. In that case, Snowden and Boone (2007) recommend that the leader first:

"act(s) to establish order, then sense(s) where stability is present and from where it is absent, and then respond(s) by working to transform the situation from chaos to complexity, where the identification of patterns can both help prevent future crises and discern new opportunities."

The complex and chaotic contexts belong to the unordered world, namely, when patterns (instead of facts) inform decision-making.

2.6.5 Disorder

The fifth category of contexts, namely disorder, is difficult to assign to a situation due to its nature. However, when leaders are unable to characterize a situation, Snowden and Boone (2007) recommend they break it down into parts and assign each part to its corresponding context (simple, complicated, complex, or chaotic).

Where does FM's decision-making context fit? First, sections 2.2.1, 2.2.2, and 2.2.4 showed that there is no consensus on FM. Second, sections 2.2.5 and 2.2.6 showed that FM makes decisions in a highly dynamic context. Specifically, section 2.2.5 described the evolution of FM involvement in the levels of planning (i.e., operational, tactical, and strategic) from planning for day-to-day operations to forecasting the organization's needs on the long term. Section 2.2.6 emphasized that planning for future needs is a challenge, because the world is in constant flux. This requires that organizations adapt to the changing environment.

Considering the above, the researcher placed FM in the complexity quadrant of the Cynefin framework. This is a first step to better define the nature of FM: FM operates in a complex context during the building use phase. The next section explains how complexity is experienced in project delivery preceding the building use phase.

2.7 Definitions of Complexity

The beginning of research on complexity is often associated with the start of cybernetics research defined as “a theory that (covers) the entire field of control and communication in machines and in living organisms” (Wiener 1948a). Simply put, cybernetics look for properties that are common to complex systems from various fields. Research in cybernetics was motivated by (1) the realization that scholars were becoming increasingly more specialized in their fields of expertise and (2) the conviction that “the most fruitful areas for the growth of the sciences were those which had been neglected as a no man’s land between various established fields” (Wiener 1948b).

2.7.1 Complexity in Critical Infrastructures and Networks

In the field of civil infrastructure, interdependence modeling started to gain momentum ten years ago (Perderson et al. 2006). The California electricity crisis (Rinaldi et al. 2001, Atef and Moselhi 2014) illustrates the importance of interdependence considerations in asset management for civil infrastructures. In 2001, California experienced a decrease in electricity supply, which led to numerous blackouts across the state. Oil and natural gas power plants, refineries, and gasoline distribution were impacted. Consideration of interdependences between civil infrastructure networks was of paramount importance to make informed decisions and mitigate energy shortage risks.

Atef and Moselhi (2014) report that infrastructure interdependence models are commonly developed in disaster management context (Rahman et al. 2006), but less so in asset management, and that research in the latter is lacking. Researchers have also investigated the failures of the electrical grids (Rosato et al. 2008, Laprie et al. 2007). Similarly, researchers used the World Trade Center disaster to show the importance of understanding interdependences to mitigate risk (O’Rourke 2007). Likewise, Tai et al. (2013) value extreme scenarios modeling over accurate systems modeling. They argue that, because no model will be able to accurately capture the true relationships between infrastructure networks, simpler models that focus only on extreme scenarios should be created instead.

At the facility scale, research about systems’ interdependences modeling is scarce. When such research exists, it is more commonly performed for disaster management. For example, network analyses are used to optimize the locations of defibrillators in airports or routes for emergency responses (Liu et al. 2010).

The next section gives an overview of complexity research in construction projects.

2.7.2 Complexity in Construction Projects

Since complex projects are said to be associated with cost overruns, delays, and overall lower performance (and vice versa) more often than on simpler projects, they have been subject to particular attention since the 1960s. In the AEC industry, scholars and practitioners have attempted to define and characterize construction project complexity (Baccarini 1996, Williams 1999, Bertelsen 2003, Whitty and Maylor 2008, Fang and Marle 2013, Steinhaeusser et al. 2013, Brady and Davies 2014, Xiao and Fernandez-Solis 2016).

With over 900 citations reported by Google Scholar, Baccarini's (1996) definition of project complexity is ubiquitous in the relevant traditional project management literature. Baccarini defines project complexity as "consisting of many varied interrelated parts and can be operationalized in terms of differentiation and interdependence." Williams (1999) was among the first to refine the definition of complexity from an architecture/hierarchy perspective: "complexity is concerned with the underlying structure of the project. In this dissertation, we can call this 'Structural Complexity'" in alignment with Simon's (1962) definition of complexity. According to Williams (1999) complexity has two dimensions: "structural uncertainty" and "uncertainty," where "structural uncertainty" is composed of (1) number of elements, (2) interdependence of elements, and "uncertainty" is composed of (1) uncertainty in goals and (2) uncertainty in methods.

In addition to structural complexity, the Lean Construction literature has explored the concept from various angles, including: the Viable System Model (VSM) (emergence, recursion, adaptiveness) (Gregory 2007, Herrmann et al. 2008, Dominici and Palumbo 2010, Steinhaeusser et al. 2013, Elezi et al. 2014), the Cynefin framework (Biton and Howell 2013 developed by Kurtz and Snowden 2003, Tommelein 2014), and the theory of chaos (Bertelsen 2003).

2.7.3 Complex Systems

Simon (1962) gives the following definition of complex systems:

"Roughly, by a complex system I mean one made up of a large number of parts that interact in a non-simple way. In such systems, the whole is more than the sum of the parts […] in the […] sense that, given the properties of the parts and the laws of their interaction, it is not trivial to infer the properties of the whole."

Underlying the quote is the notion of emergence. Emergence refers to the fact that "solutions can't be imposed; rather, they arise from the circumstances" (Snowden and Boone 2007). To explain "complex systems," Simon (1962) adds the notions of hierarchy and near decomposability:

"Empirically, a large proportion of the complex systems we observe in nature exhibit hierarchic structure. On theoretical grounds we could expect complex systems to be hierarchies in a world in which complexity had to evolve from simplicity. In their dynamics, hierarchies have a property, near-decomposability, that greatly simplifies their behavior. Near-decomposability also simplifies the description of a complex system, and makes it easier to understand how the information needed for the development of the system can be stored in reasonable compass."

Simon's definition of complex systems can be also termed "structural complexity" (Browning 2016).

2.7.4 Adopted Definition: Structural Complexity

Koskela's (2000) definition of complex systems that he shares in a footnote of his dissertation, is very much aligned with Simon's.

"vi Since the Second World War, analytical reductionism has been strongly criticized by the systems movement. It is argued that there exist, at certain levels of complexity, properties which are emergent at that level, and which cannot be reduced for explanation at lower levels. The idea is that architecture of complexity is hierarchical (…)."

In this dissertation, complexity will refer to structural complexity as defined by Simon (1962) for complex systems, and as described by Koskela (2000) for project delivery. Considering this definition of complexity, what are interdependences in construction projects? The researcher uses Malone and Crowston's (1990) definition of interdependences as components of coordination along with goals, activities, and actors.

The next section describes how structural complexity is managed in new product development. Practices in new product development are applicable to project delivery due to their similar characteristics: they both qualify as 'wicked problems' (Rittel and Webber 1973).

2.8 Management of Structural Complexity

2.8.1 Value of Complexity in New Product Development

Maurer (2007) states that complexity often exists in a product without adding value to the customer, that is, when it does not fulfill a functionality or a requirement.

However, complexity is not always the enemy as Lindemann et al. (2009) write: "complexity does not represent axiomatically negative characteristics in product design." Indeed, complexity can allow more flexibility for a later development of the product range for example. Wider product ranges give customers more choices and may thereby increase customer satisfaction, similar to Toyota proposing different colors of cars to compete with the black model from Ford. Complexity can thus serve as leverage for later product evolution and customization.

A second advantage is avoiding plagiarism (Maurer 2007). An increase in number of components and interdependences between those components within a product makes plagiarism harder for other manufacturers. If plagiarism is harder, other manufacturers may take more time to achieve the same result, which gives the product inventor some time to develop a new product. As a result, other manufacturers never manage to catch up with the leader's product development speed.

From a functionality perspective, complexity can have a purpose. For example, using different materials can offer new functionalities to the product. Furthermore, in some cases, the desired functionality may be achieved only with a complex structure.

2.8.2 Complexity Modeling

Before attempting to manage complexity, Browning (2001) writes that "the classic approach to increasing understanding about a complex system is to model it." Maurer (2007) lists methodologies borrowed from other research disciplines that are used for modeling complex engineering data. Methodologies include, to name a few: matrix-based approaches (e.g., impact matrices, consistency matrices, DSM, DMM, MDM, house of quality), the use of algorithms (e.g., clustering, partitioning), mathematical simulations, or statistics, but also data visualization, graph theory, and cybernetics models.

2.8.3 Complexity Management with Design Structure Matrix (DSM)

Maurer (2007) recommends three steps to manage complexity: (1) the acquisition and evaluation of complex systems, (2) the avoidance and reduction, and (3) the management and control of complexity. The first step involves defining the complex system boundaries, collecting data, and choosing a method to model complexity (such as using matrix-based approaches). The second step involves removing elements and dependences while maintaining the system functionality using a tearing approach or modularity. Yet, since complexity can also add value to the customer, the third step involves exploring opportunities for increasing complexity in the hope to reach (or approach) an "optimal complexity value of systems" (Puhl 1999, cited in Maurer 2007).

Due to (1) the wide adoption of the DSM methodology to model structural complexity in new product development, (2) the similarities between new product development and the planning of construction projects, and (3) the existence of successful DSM applications in the AEC industry, DSM seems fit for modeling structural complexity in the planning of construction projects. Therefore, chapters 3, 4, and 5 will use the DSM methodology to model structural complexity.

2.8.4 Project Complexity Management

The literature on traditional PM mentions a few methods and tools to manage structural complexity: integration (Baccarini 1996), risk modeling and mitigation strategies (Lehtiranta 2011, Fang and Marle 2013), stakeholder network analysis (Yang et al. 2016), PM training and education (Thomas and Mengel 2008), cultivating adaptability (Brady and Davies 2014). In that respect, Whitty and Maylor (2008) write: "Much theory building and modelling of complex systems has taken place from which we may make successful predictions about the real world, but very few practical tools have been developed to manage or control complex systems." Surprisingly, what remains absent from the traditional project management literature is Lean Construction as a way to manage complexity. The researcher fills this gap by describing how Lean principles and methods could have been used in the two case studies to manage project complexity in chapter 5.

Section 2.7 gave a definition for complexity, that is, structural complexity, considered in this dissertation. Section 2.8 presented how complexity is managed in new product development and construction. To analyze structural complexity in new product development, Maurer (2007) identified four aspects of complexity: (1) product, (2) process, (3) organization, and (4) market. The next section extends Maurer's (2007) classification to help analyze project complexity in high-end facility upgrades.

2.9 Five Aspects of Structural Complexity in High-End Facility Upgrades

2.9.1 Customer Complexity

Customer complexity may emerge from various elements in high-end facility upgrades. Customers can be numerous, and "the greater number of stakeholder agents increases the detailed complexity of the system" (Whelton 2004). For example, customers of a hospital construction project may include: future hospital patients, physicians, nurses, residents living in the same neighborhood, FM, IT, but also donors of funds. The term "customers" may thus involve multiple groups of people, working in different departments within the same- or across multiple- organization(s). Customers use the building in different ways, they have different wants and needs. Those wants and needs may be conflicting or contradictory. For example, touch-free soap dispensers may be preferred by nurses so that germ transmission is reduced thanks to the elimination physical contact between soap dispensers and users' hands, but automatic dispensers require more maintenance, since they rely on batteries, which will need replacement. Customer complexity definitely involves both a numerical and a variational dimension.

2.9.2 Organizational Complexity

Whelton (2004) describes project organizations as complex systems induced or self-inflicted by the project environment, the hierarchical structure of owner's organizations, and people interactions. Although Whelton (2004) does not distinguish customer complexity from organizational complexity, the following excerpt remains relevant:

"Within each stakeholder entity, a hierarchical structure exists, which normally is designed to support the organizational strategy. A hierarchic system is composed of interrelated sub-systems. (…) facility owner organizations are typically made up of hierarchical structures. The owner organization might have a strategic group that makes decisions about their facilities. The owner's operations management provides knowledge about the organization's functions and operational activities. At the lower end of the hierarchy, there are the operators and end users of the facility (…). Ideally these users are supported by strategic and operations management in term of fulfilling the facility-based user needs. Hierarchical structures can exist also within the regulatory agencies and the design specialist groups."

Hierarchical structures are prevalent in organizations presenting a mechanistic structure and are often associated with bureaucracy (Burns and Stalker 1961). In mechanistic structures, decision-making is often centralized and under the responsibility of a few people. For a decision to be made, information feeding the decision must be channeled bottom up. As a result, decision-making (from the time the decision is needed to the time of the actual decision) is likely to take more time than in less hierarchical structures (e.g., organic structures).

Funding mechanisms in large public organizations may also add to the organizational complexity. Funding may come from a different public or private agency. Funding may be uncertain on the long term, and even on a shorter term (from one year to the following), and may involve rules such as "spend it or lose it" that create unintended dependences on how the project is managed.

2.9.3 Process Complexity

In this dissertation, process complexity refers to the structural complexity associated with project delivery phases (i.e., programming, designing, construction, commissioning, use, and decommissioning) of high-end facility upgrades. Work structuring, and planning and coordinating the work are also processes that display the characteristics of structural complexity. For example, the planning and coordination of project delivery phases require that interdependences are managed, since interdependences are components of coordination (Malone and Crowston 1990).

2.9.4 Product Complexity

Product complexity is ubiquitous in high-end facilities. The researcher defined high-end facilities as facilities housing sophisticated systems and/or equipment, which performance is critical to allow the organization to meet its business objectives (e.g., hospital, laboratory, power plant, etc.). Such facilities involve multiple and interdependent mechanical, electrical, plumbing, and controls systems, to name a few. Furthermore, some systems are highly dependent on the weather (i.e., temperature, humidity, wind). This creates more dependences. In addition, high-end facilities house state-of-the-art equipment, which installation requires more coordination from a building systems and structure perspective than common equipment that can be found in residential and regular office buildings for example. To remain up-to-date, pieces of equipment must be upgraded or replaced by newer models. Limitations of simulation tools used by engineers and consultants (e.g., air flow, heat dissipation) contribute to the uncertainty of the behavior that one could "reasonably" expect for the building. The additional complexity in upgrades can also be compounded with the uncertain and unknown condition of equipment and systems within the facility itself or outside the facility, but on which the facility is relying (e.g., utilities connecting two buildings). High-end facilities can also be connected to other buildings, which creates additional dependences and hence complexity.

2.9.5 Market Complexity

Market complexity may emerge from existing or new regulations, competition, and vary depending on the facility's specific attributes such as the activities it supports, location (e.g., earthquake-prone regions). In high-end facility upgrades, changes in building codes and environmental regulations contribute to market complexity.

Although these five aspects of structural complexity have been addressed separately, they all interact with one another and have a compounding effect (Figure 2-12). Chapter 3: Cooling Tower Case Study will expand on this compounding effect.

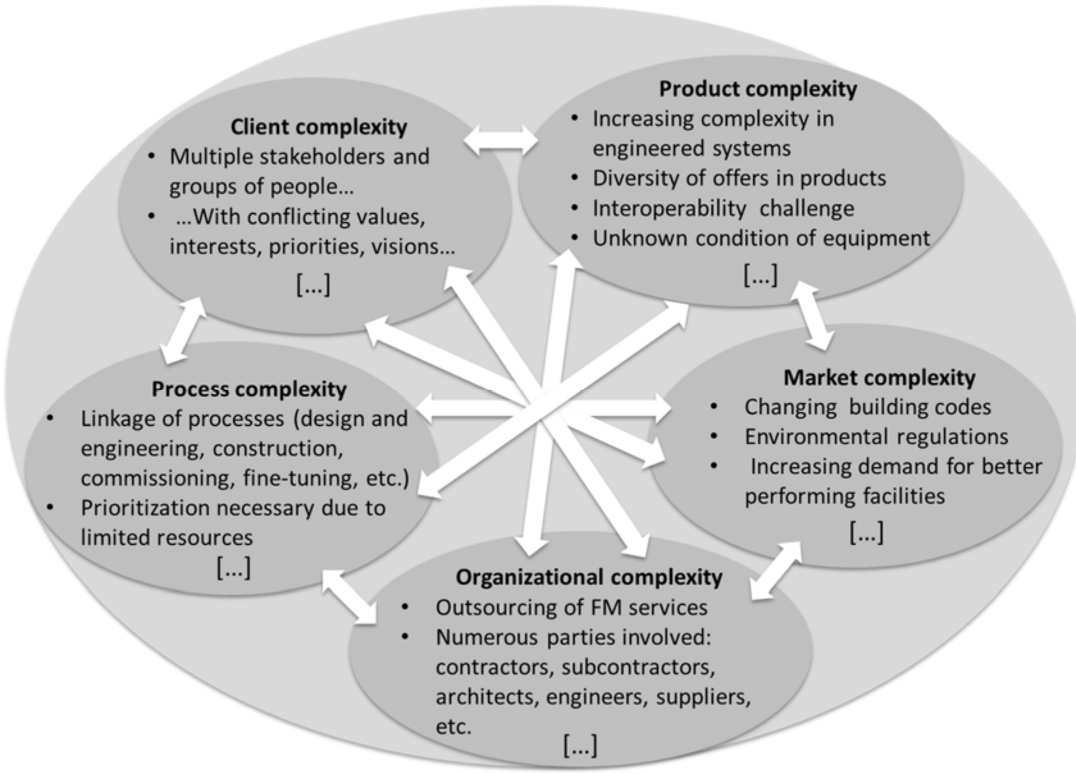


Figure 2-12: Aspects of Structural Complexity in High-End Facility Upgrades (Adapted from Maurer 2007)

The next section describes the tools selected to model structural complexity in the case studies presented in chapters 3 and 4.

2.10 Proposed Tools to Model Complexity in High-End Facility Upgrades

2.10.1 Design Structure Matrix (DSM) Methodology

The DSM methodology is a matrix-based methodology used to manage the design of complex engineering systems (Maurer 2007) by modeling and analyzing the dependences between the elements that compose the system. The approach involves the following steps: (1) define the boundary of the system to study, (2) break down the system into elements at a relevant level of granularity, (3) determine the type(s) of dependence to model, (4) identify the system's dependences, (5) apply the appropriate algorithm (partitioning, clustering) to initiate the analysis.

Different variations of what was first coined "design structure system" by Steward (1981) exist. Elements of the matrix can be: elements that compose the system, people that compose the organization, activities that compose the process (i.e., design, fabrication, assembly), or parameters that describe the system. The types of dependence modeled vary too, depending on the system studied and the purpose of the analysis: precedence between tasks, information flow, people interactions, etc. When elements of the matrix belong to the same domain (respectively two domains), the matrix is called an intra-domain matrix or DSM (respectively an inter-domain matrix or Domain Mapping Matrix (DMM)). A larger matrix called Multi-Domain Matrix (MDM) can be created from assembling DSMs, DMMs, and executing computations

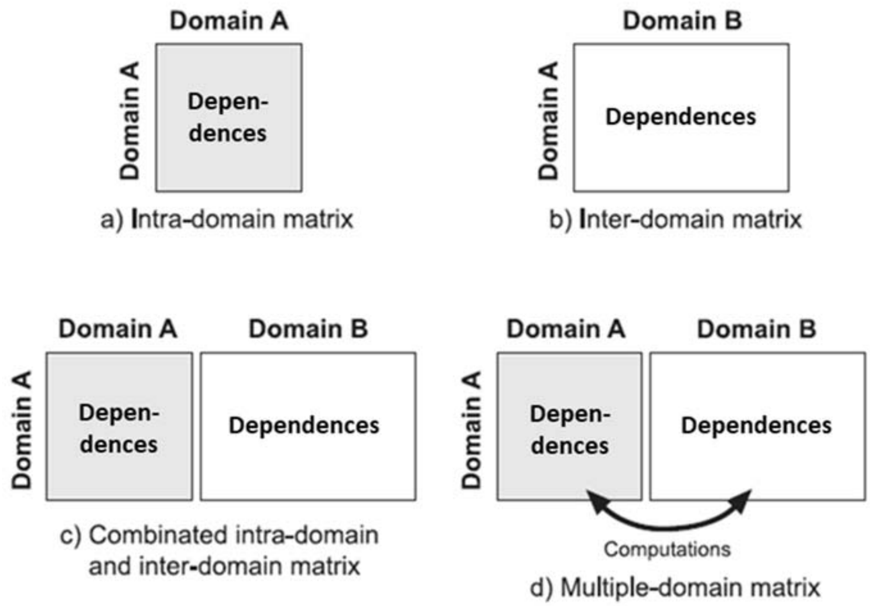


Figure 2-13: Classification of Matrix-Based Method (Figure 3.5 in Lindemann et al. 2009)

The demonstrated benefits of DSM in the manufacturing industry have encouraged researchers and practitioners to explore its applicability to construction. Historical applications of DSM within construction include: identify design units that require close coordination and iterative work (Austin et al. 1994), improve the sequence of design activities (Huovila et al. 1995, Austin et al. 2000, Maheswari et al. 2006, Pektas and Pultar 2006), identify constructability issues (Björnfot and Stehn 2008), plan collaboratively (Baudin 2014), capture unplanned design iteration (Tuholski 2008, Bascoul et al. 2017), improve the reliability of design handoffs and flows (Hammond et al. 2000, Tuholski and Tommelein 2010), re-design an installation process (Furtmeier and Tommelein 2010), explore opportunities for team modularization/reorganization (Krinner et al. 2011). Browning (2016) gives a more extensive list of examples.

The next section presents 5-Whys, a problem-solving technique used in chapter 3 to complement the DSM analysis.

2.10.2 5-Whys

5-Whys is a problem-solving technique that consists of asking why 5 times (or more) successively in order to get to the root cause of the problem (Ohno 1988). Without this recursion, that is, without asking the question more than once or twice, one is likely to remain at the surface of the problem. Thus, when attempting to solve a problem, one will design a solution that hopefully fixes the symptoms (i.e., answer to the first why), but that will not eliminate the re-occurrence of the problem in the long term (i.e., answer to the fifth why). By using 5-Whys, one is able to find the root cause(s) of the problem. Once the root cause found, the design of the solution must aim at eliminating the root cause.

Lean Construction inherited this tool from the TPS (Liker 2004). Tsao (2000, 2005) used the 5-Whys to find the root causes of a door frame installation issue encountered on the construction of a correctional institution. Rybkowski (2009) applied it to find the root cause to the spread of methicillin-resistant Staphylococcus aureus and to demonstrate the value of the tool for evidence-based design for healthcare facilities.

The researcher uses the DSM methodology and 5-Whys to capture structural complexity in the case studies (chapters 3 and 4). The next section presents Choosing-By-Advantages (CBA) and the Lean Project Delivery System (LPDS)-Multi-Domain Matrix (MDM) framework. The researcher recommends that project teams use them to manage project complexity (chapter 5).

2.11 Proposed Framework for Managing Complexity in High-End Facility Upgrades

2.11.1 Choosing-By-Advantages (CBA)

Choosing-By-Advantages (CBA) is a system for making sound decisions that was developed by Jim Suhr during his career as a civil engineer for the US Forest Service. What motivated Suhr to create such system was the realization that: (1) we are all decision-makers, (2) decision-making is not a natural skill: it must be taught, and (3) decision-making methods taught “do not use correct data,” and “they do not use data correctly” (Suhr 1999).

The CBA system requires the use of a shared language. This language is composed of the words: alternative, factor, attribute, advantage, and criterion (Suhr 2008 – Second Essentials):

- An alternative is “two or more persons, things, or plans from which one must be chosen.”
- An attribute is a “characteristic, quality, or consequence of one alternative.”
- An advantage is “a benefit, gain, improvement, or betterment.”
- A factor is “an element, part, or component of a decision.”
- A criterion is “a decision rule, or a guideline- usually either a must or a want.”

Two fundamental principles of the CBA system differentiate this system from other decision-making methods: (1) “decisions must be based on the importance of advantages,” called the fundamental rule of sound decision making, and (2) “decisions must be anchored to the relevant facts,” which is the anchoring principle. CBA implementation involves 8 steps, which are:

1. Identify Alternatives
2. Define Factors
3. Define the “Must” and “Want to Have” Criteria for Each Factor
4. Summarize the Attributes of Each Alternative
5. Decide the Advantages of Each Alternative
6. Decide the Importance of Each Advantage
7. Evaluate Cost Data

8. Reconsideration Phase

The AEC industry has implemented CBA to make different decisions, to name a few: landscape architect and green roof consultant selection (Parrish et al. 2009), wall system selection, insulation material selection, sustainable ceiling tile selection, HVAC system selection, building design selection (Arroyo 2014), and formwork selection (Martinez 2015).

While the use of CBA for decision-making is common practice within the Lean community, the revised LPDS-MDM framework presented next is not.

2.11.2 LPDS-MDM Framework

2.11.2.1 Overview of the LPDS

The Lean Construction Institute (LCI 2017a) defines IPD as "a delivery system that seeks to align interests, objectives and practices, even in a single business, through a team-based approach. The primary team members would include the architect, key technical consultants, as well as a general contractor and key subcontractors. It creates an organization able to apply the principles and practices of the Lean Project Delivery System."

Unlike traditional project management that sees projects mainly as networks activities, Lean Construction sees projects as social systems around which temporary organizations take shape. The delivery of the project is the result of people interacting to take individual and joint decisions during the design and construction phases. The nature of the interaction is shaped after the characteristics of the project delivery system (Hickethier et al. 2013). Characteristics include (1) the organization, (2) the contract or commercial terms, and (3) the operating system. They constitute the three edges of the LCI triangle (Figure 2-14).

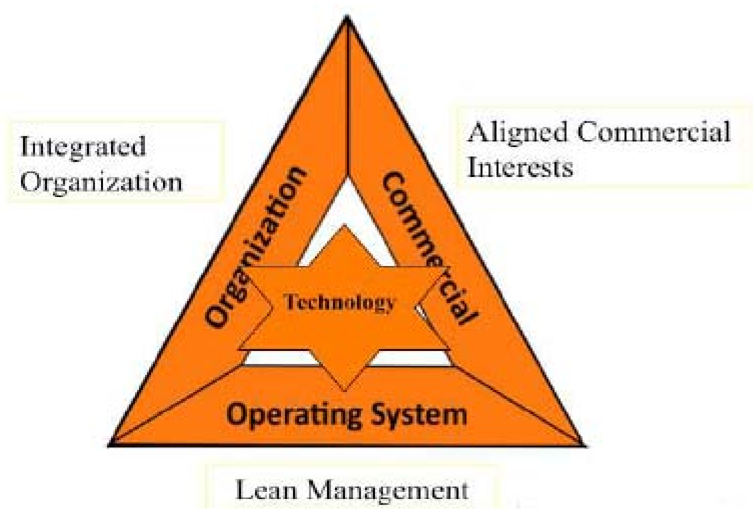


Figure 2-14: LCI Triangle (LCI 2017b)

Figure 2-15 represents the Lean Project Delivery System (LPDS) (Ballard 2000a, 2008). The LPDS is composed of 11 modules, which are in turn grouped in 5 triads: "project definition," "lean design," "lean supply," "lean assembly," and "use," the production control module, the work structure module, and the learning loops (i.e., post-occupancy evaluations).

Unlike traditional project delivery systems, the LPDS highlights the interdependences of the modules.

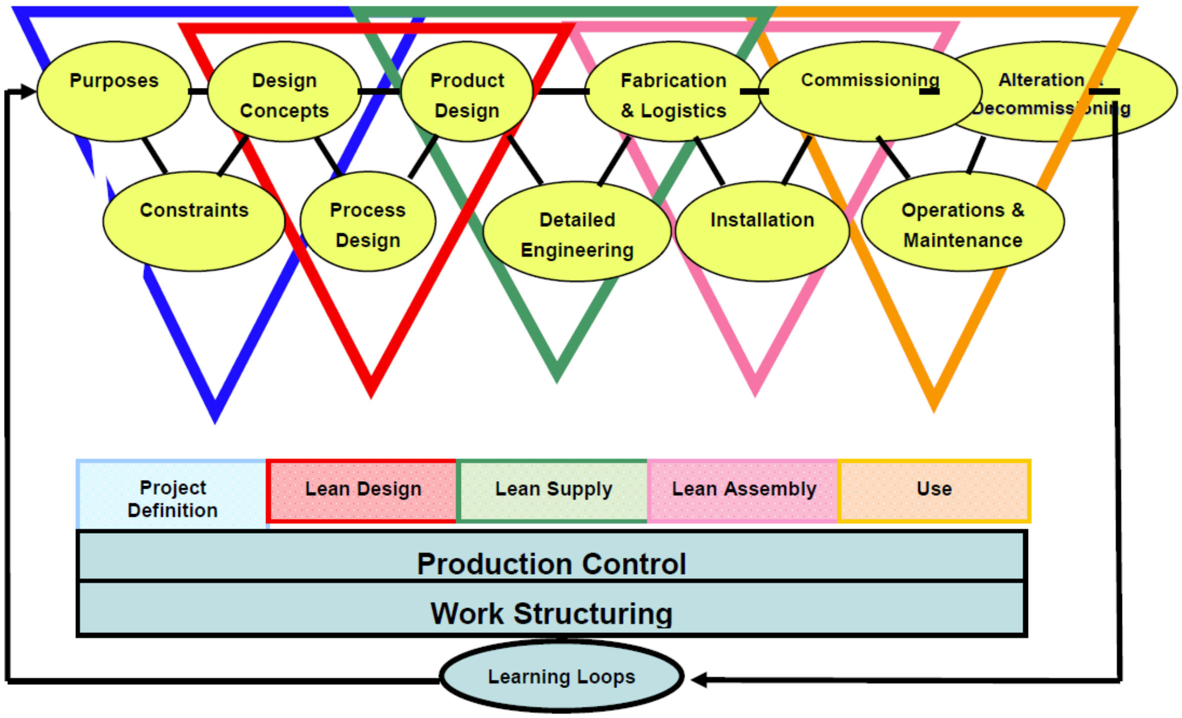


Figure 2-15: The LPDS Schematic (Figure 3 in Ballard 2008)

2.11.2.2 Translation of the LPDS into MDM (3 pages)

The LPDS is a project delivery representation envisioned by the Lean Construction Institute (Ballard 2000, 2008). Tuholski (2008) introduced the LPDS-MDM framework to make more visible the interconnection of the Transformation-Flow-Value (TFV) views of production, with the objectives of "formaliz[ing] their interconnection" and "deepen[ing] understanding of their mutual dependence." Tuholski's (2008) framework (Figure 2-16) is differs from what Figure 2-17 shows. Figure 2-16 captures the 5 triads from the LPDS framework (project definition, Lean design, Lean supply, Lean assembly, and product use) in DSMs along the diagonal of the large MDM matrix. To the 5 LPDS triads, Tuholski (2008) adds the information DSM between the Lean design and the Lean supply and the material DSM after the 5th triad (product use).

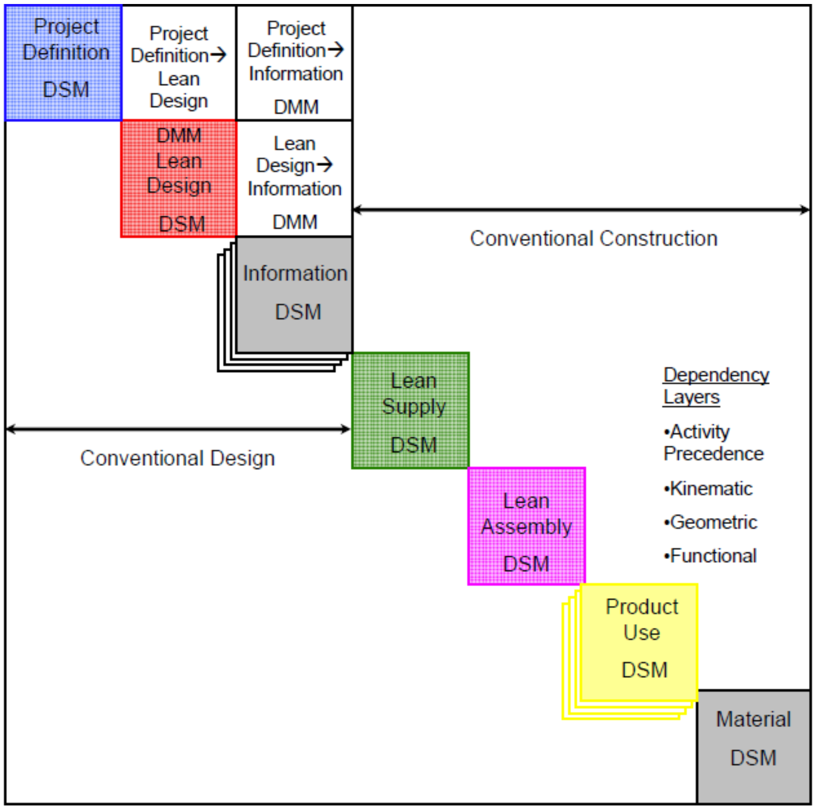


Figure 2-16: Original LPDS-MDM Framework (Figure 6.1 in Tuholski 2008)

To show the interconnection between TFV and the LPDS, Tuholski (2008) associates the Lean design, the Lean supply and the Lean assembly triads with Transformation, the project definition and product use triads with Value generation, and the information and material additional DSMs (DSMs and not "triads" because these are not represented in Ballard's framework) with Flow (Table 2-2).

Table 2-2: Interconnection between LPDS Triads and TFV (after Tuholski 2008)

DSM	Production Model	DSM-Type
Lean design Lean supply Lean assembly	Transformation	Activity
Project definition Product use	Value	Component
Information Material	Flow	Activity, Kinematic, Geometric, Functional

The researcher proposes 3 adjustments to this model based on the following observations. First, the framework does not stop at a fine enough level of granularity to convey project structural complexity. “How complex or simple a structure is depends critically upon the way in which we describe it” (Simon 1962). The level of granularity a shown does not convey effectively how interdependent the triads are. A correction would be to stop at a recursion level of “decomposition” that is fit for looking at project complexity. Second, because the framework stops at a too high level of granularity, the interpretation of the LPDS-MDM framework into the TFV model of production is not so clear. Consider the Lean Design triad for example. Tuholski (2008) associates it with the Transformation view on production (Table 2-2). However, when looking at the next level of the hierarchic structure, Lean Design comprises 3 modules (see Ballard 2008): concept design, process design, and product design. As shown, these 3 modules are, according to Tuholski (2008), Transformations. While process design can be interpreted as a transformation of information into a sequence of operations, process design also encompasses (or at least, should) the design of work-, materials-, and information- flows for example. Thus, Lean Design should also belong to the Flow view on production. Third, the framework does not show learning feedback loops that links the triads.

Given these observations, classifying triads by production view seems unfit for understanding and managing structural complexity. Instead, considering that each triad pertains to all three views on production seems more relevant. As a result, the researcher proposes a revised LPDS-MDM framework (Figure 2-17), that goes one level deeper into the hierarchic structure of the LPDS schematic: it shows the 11 modules grouped in 5 triads. Each module corresponds to a DSM domain. Relationships between elements across modules are captured in the 55 DMMs (shown in gray in Figure 2-17) below the diagonal. The resulting MDM illustrates well project structural complexity.

Figure 2-17 captures the Transformation view along the diagonal of the MDM. Traditional PM focuses on the activities shown in the diagonal and corresponding contractual deliverables. Figure 2-17 shows the Flow view encompassing work-, information, and material- flows in the lower diagonal part of the matrix. For example, the interdependences between project purposes and design criteria and how these evolve with time could be captured in the p * cr DMM. Figure 2-17 captures the Value view by feedback loops linking DSMs and DMMs in the Product Use triads to those in the Project Definition triad.

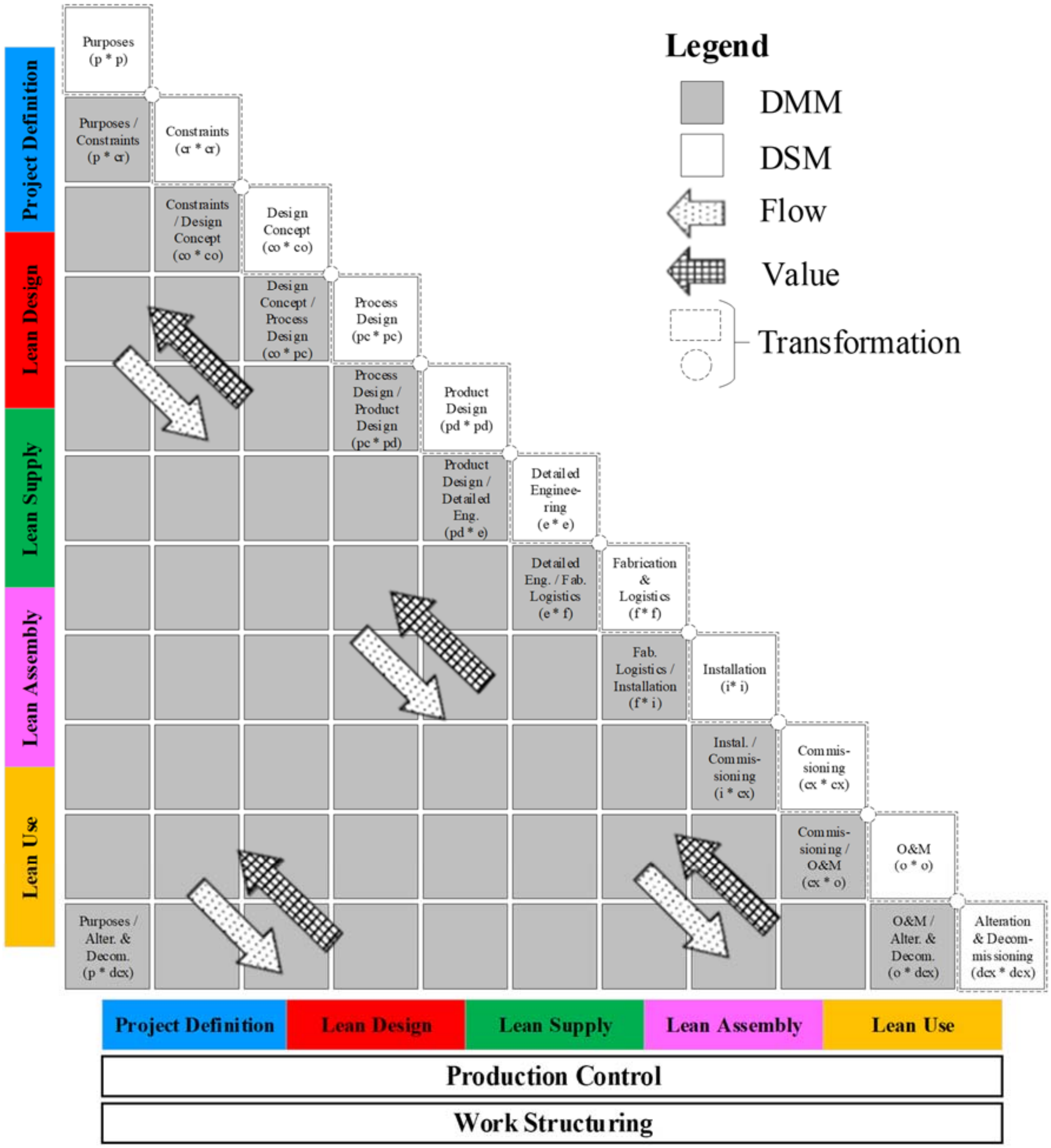


Figure 2-17: Revised LPDS-MDM Framework

2.11.3 Hoshin Kanri

Hoshin Kanri is a process used by organizations for strategic and business planning, whose historical evolution has been documented during the past twenty-five years (Lee and Dale 1998, Tennant and Roberts 2001, Jolayemi 2008, Nicholas 2016). The success of Hoshin Kanri implementation in large organizations and the reaped benefits promises success in application in FM as well.

With respect to the origin and meaning of the two words, Watson (1991) writes that Hoshin is the contraction of two Chinese words "ho" and "shin." While "ho" means method, "shin" means compass. Together, “Hoshin” means “a methodology for strategic direction setting.” Simplistically, Lee and Dale (1998) equate Hoshin Kanri to the sum of a target and the means to achieve the target.

Although Hoshin planning is not semantically strictly equivalent to “policy deployment,” the two are used interchangeably in the literature. Lee and Dale (1998) emphasize that the mere translation of Hoshin Kanri into “policy deployment” does not capture the importance of “feedback” that is stressed in Hoshin Kanri; and as a consequence, “can lead to inadequate application of the method and unsatisfactory results” (Lee and Dale 1998). Furthermore, in the literature, only few texts specify that Hoshin Kanri is specifically a “systems approach to management of change” (Watson 1991).

In the 1950s, Japan saw the emergence of Management by Objectives; while at the same time, the work of Juran and Ishikawa paved the way for quality management leveraging Deming’s previous work on statistical control. Juran, known for his Quality Control Handbook (1951), insisted on the role of management in driving and implementing quality in the company; Ishikawa stressed the importance of total quality control. However, it is the Bridgestone Tire Company that looked into how to standardize Hoshin planning after visiting Deming prize winners. As a result, the Bridgestone Tire Company gathered its findings in a report that was published in 1965 (Lee and Dale 1998). In the mid-1970s, Hoshin Kanri was already adopted in Japan, and was imported in the US through Japanese subsidiaries a few years later (Lee and Dale 1998). Unlike the US, Europe saw the appearance of Hoshin Kanri much later (90s) following Dale’s (1990) publication.

Today, Hoshin Kanri remains an important pillar of Total Quality Management (TQM) (Meier et al. 2010). Well-known Hoshin Kanri users include: Hewlett-Packard, NEC Japan, Procter and Gamble, Xerox, to name a few.

Researchers have compared Hoshin Kanri to other planning processes: Fortuna and Vaziri (1992) compared Hoshin Kanri to MBO; Mulligan et al. (1996) compared Hoshin Kanri to 3 other planning processes (“Issue-based,” “Formal strategic,” and “Strategic assumption analysis-dialectic inquiry”). Lee and Dale (1998) emphasize the following specificities of Hoshin Kanri:

- Unlike other planning processes, Hoshin Kanri is a pillar to TQM, also compared to the “glue” for TQM (Tennant and Roberts 2001).

- Unlike other planning processes, Hoshin Kanri is based on “a cascade and catchball process”; and nemawashi. Nemawashi is a Japanese word used to describe how Japanese build consensus to reach an agreement on how to proceed with an action before acting on it (Witcher and Butterworth 2001).

- Unlike other planning processes, feedback from employees creates a closed loop in policy deployment (Bititci et al. 1997).

- Unlike other planning processes, each employee in the company knows how he/she contributes on a daily basis to the tactical and strategic objectives of the organization (Watson 1991). As a consequence, it increases the buy-in and involvement of employees.

- The Plan-Do-Check-Act cycle is integral to Hoshin Kanri.

To conclude, this literature review presented the requisite background on Facility Management (FM), structural complexity, Lean Construction. At the organizational level, it qualified the context in which FM makes decision as complex (cf. Cynefin). At the project level, it identified five aspects of complexity in high-end facility upgrades.

Chapters 3 and 4 illustrate five aspects of complexity with two case studies: the cooling tower case and the supercomputer facility case. The researcher used the DSM methodology and 5-Whys to model project complexity.

Chapter 5 shows an application of the LPDS-MDM framework on the cooling tower case. The researcher used it to make recommendations for managing project complexity.

Chapter 6 explores synergies between DSM and Hoshin Kanri to integrate FM into project delivery.

3. COOLING TOWER CASE

The goal of this chapter is to document a case study, that is, the cooling tower project at the Lawrence Berkeley National Laboratory (LBNL) and analyze how it failed to deliver value to occupants. It describes how the lack of management of structural complexity contributed to FM failure through an in-depth analysis of the planning process and the cooling tower selection.

The chapter is organized as follows. Section 3.1 introduces the project background. Section 3.2 describes the research methodology followed, namely case-study research, to collect data and analyze the cooling tower case. Section 3.3 illustrates five aspects of structural complexity met on the cooling tower case. Sections 3.4 and 3.5 analyze in depth two instantiations of structural complexity encountered on the project. Section 3.6 presents the application of Lean Project Delivery System-Multi-Domain Matrix (LPDS-MDM) framework to the cooling tower case. Last, section 3.7 concludes this chapter.

3.1 Project Background

3.1.1 Project Overview and Objectives

The project concerns building 37 (B37), a facility plant that supplies low conductivity water (LCW) and treated water (TW) to 13 buildings spread across LBNL's campus. Figure 3-1 shows the facility plant and the 13 buildings that it serves.

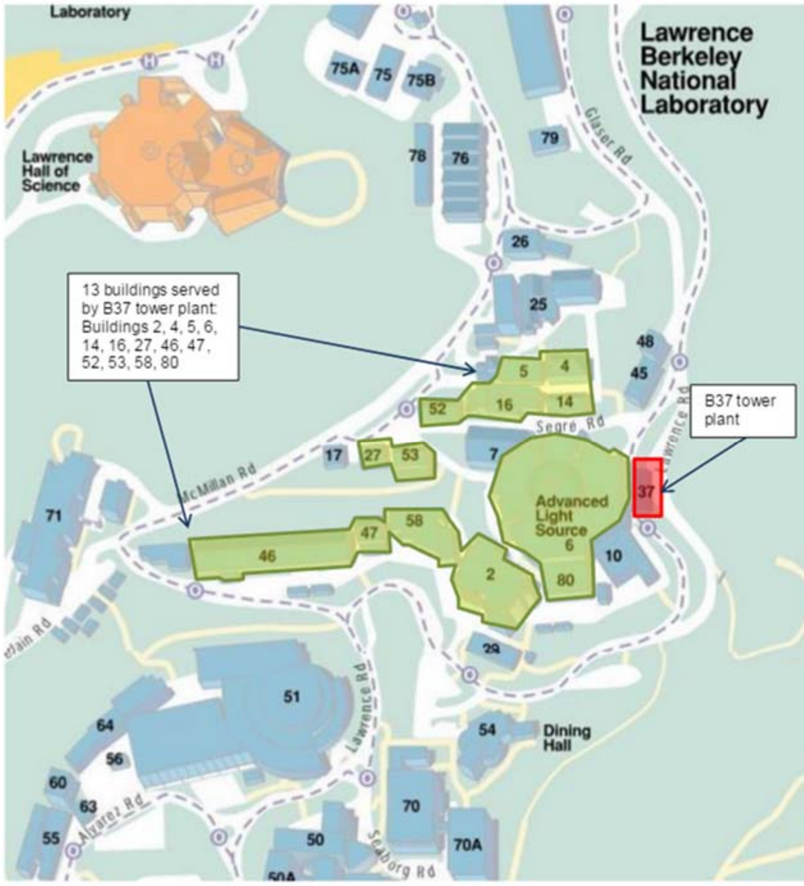


Figure 3-1: Map of Buildings Served by B37 Facility Plant (LBNL 2016)

Most importantly, one of these buildings is the Advanced Light Source (ALS) (Building 6 (B6)) that must run 24 hours, 7 days except in the case of planned shutdowns. ALS shutdowns are planned six months in advance. They allow the staff to do maintenance work on the beamlines and other supporting systems. The main and longest planned shutdown occurs in the winter and is followed by two-day shutdowns every other week.

B37 was originally constructed in 1959. The term 'originally' means that the building has, since then, continuously been upgraded (e.g., the building did not have cooling towers in 1959). The two-story concrete building accommodates various pieces of equipment ranging from pumps, through heat exchangers, an indoor generator, a fuel tank, a sand filter, TW loop, LCW loop, to electrical equipment. Furthermore, the roof supports two existing 1,000-ton wooden cooling towers (Figure 3-2), TW surge tank, LCW surge tank, nitrogen tank, and an electrical load bank.

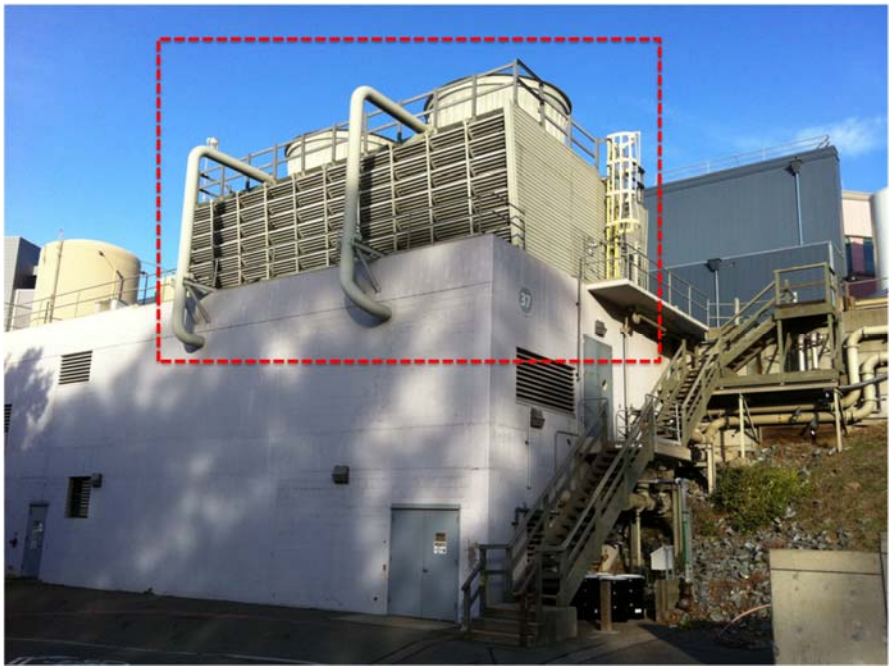


Figure 3-2: Existing Wooden Cooling Towers at LBNL (Taylor Engineering 2016)

The objective for this project is to ensure the operational stability and reliability of ALS. The project must therefore address the issues and concerns that threaten this objective. The first issue is the poor condition of the existing cooling towers. The commissioning agent has reported them to lean 2 inches toward Lawrence road. The concern is that the cooling tower threatens to collapse in case of an earthquake (frequent in California). The second issue is the vibrations that are induced by some ranges of fan speed. The concern is that vibrations pose a stability problem to the leaning cooling towers. The third issue lies in the uneven distribution of water flow between the two towers, because of the poor condition of the top deck of the cooling tower. The concern is that the uneven distribution of water leads to an uneven deterioration of the two cooling towers.

Thus, the scope of the project includes: demolition of the two old cooling towers installation of two new cooling towers; and replacement of the heat exchangers, the filtration unit, the TW expansion tank, and the pumps.

3.1.2 Past Projects

Concerns about the sustained, long-term performance of B37 began to be addressed in 2010 with the upgrade of the LCW pumps for higher flow. One year later, the installation of new equipment connected to the Automated Logic Controls platform required changes in the controls that were carried out the same year. In 2013, a controls system retrofit transferred the remainder of ALS running with the Barrington controls system to the Automated Logic Controls platform. In addition, variable speed drives were added to all tower pumps in B37.

3.1.3 Adjacent Projects

Concurrently with the cooling tower project, LBNL is executing two projects affecting B37: (1) B37 generator and (2) ALS HVAC controls. With respect to the first, the scope is to upgrade the generator and this work is conducted as a change order to the cooling tower project. With respect to the second, the scope is to upgrade the controls (hardware and software) in several buildings, namely ALS, B34, B37, and B80.

3.1.4 Project Team, Structure, and Project Delivery Method

The owner is LBNL. The owner dedicated (full-time) or made available (part-time) the following people to the project: a program director, a project manager, a construction manager, a safety manager, an office coordinator and various Subject Matter Experts (SME) (mechanical and plumbing, energy management, controls, structural, among others).

The project delivery method used is the Construction Manager/General Contractor (CM/GC) process. The owner has a contractual relationship (Figure 3-3) with the commissioning agent, Taylor Engineering, under a fixed price contract following a prequalification process. The commissioning agent's scope of work includes: the commissioning of the mechanical equipment, the review of the submittals along with the engineer of record, and the documentation of the system performance.

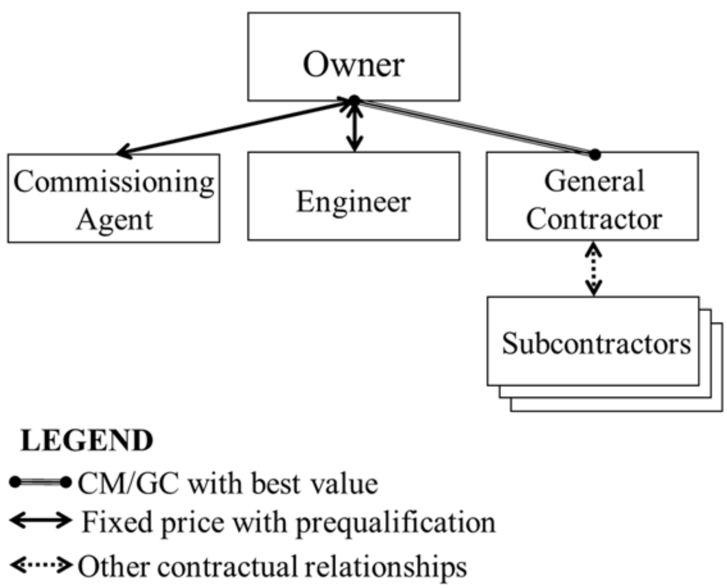


Figure 3-3: Structure of the Cooling Tower Project Organization

LBNL also has a contractual relationship with the mechanical, electrical, and plumbing (MEP) engineer, YEI Engineering (Figure 3-3), under a fixed price contract following a prequalification process. The MEP engineer's scope of work includes: the design of the project, the recommendation of products for selection, and the phasing of the project. The MEP engineer subcontracted the structural portion of the design to a different firm, and the architectural portion of the design to another firm.

The owner has a contractual relationship with the General Contractor (GC), WEL Lyons (Figure 3-3), under a best value contract. The GC's scope of work includes: value engineering, planning the work, hiring subcontractors to perform the work, coordinating the work, etc.

All three contractors had prior work experience with LBNL, which means that they were familiar with LBNL's work environment (i.e., campus-specific regulations, internal processes, etc.) and some project customers.

3.1.5 Project Timeline

Figure 3-4 shows the project design phases, ALS major shutdowns and three milestones: (1) the cooling tower selection, (2) the notice to proceed for the GC, and (3) the original project end date. Figure 3-4 does not show the two-day maintenance windows that ALS scheduled every other week following the long winter shutdown.

The engineer served as a consultant from March 1, 2016 to March 31, 2016. During that time, the owner, the engineer, and the commissioning agent (project team) jointly developed a document called "Current Facility Requirements" (CFR) and selected the cooling tower model. The CFR describes the performance requirements of the facility "where practical and known." The project team selected the cooling tower March 30, 2016. They finalized the CFR mid-April 2016.

The owner contracted with the engineer for the design and engineering of the project mid-March. Thus, the engineer started the design of the project right after the cooling tower selection. The engineer submitted the 50% preliminary design April 29, 2016, and the 100% preliminary design two months later June 30, 2016. The engineer submitted the 90% final design drawings August 19, 2016. LBNL selected the GC late August 2016 but the CM/GC contract was issued early December 2016. From August to December, the GC provided CM services upon LBNL's request. When CM services were needed, LBNL made the request through a letter describing the CM work scope and giving a lump sum. Eventually, the engineer submitted the 100% final design drawings (issued for bid) September 23, 2016. The engineer issued the phasing matrix to prove the feasibility of the proposed design August 26, 2016.

The goal of the phasing was to complete as much work as possible during ALS shutdown windows. In this respect, as of September 2016, the ALS maintenance schedule showed a no-LCW flow period from January 6, 2017 to January 19, 2017 as well as no temperature control on TW and LCW from January 6, 2017 to February 12, 2017. Following these no flow periods, the ALS maintenance schedule showed two-day maintenance windows every other week.

LBNL sent a letter to the GC to allow it to proceed with work installation December 13, 2016. The letter specified a project end date (later referred to as the "original" project end date in this dissertation) of August 22, 2017.

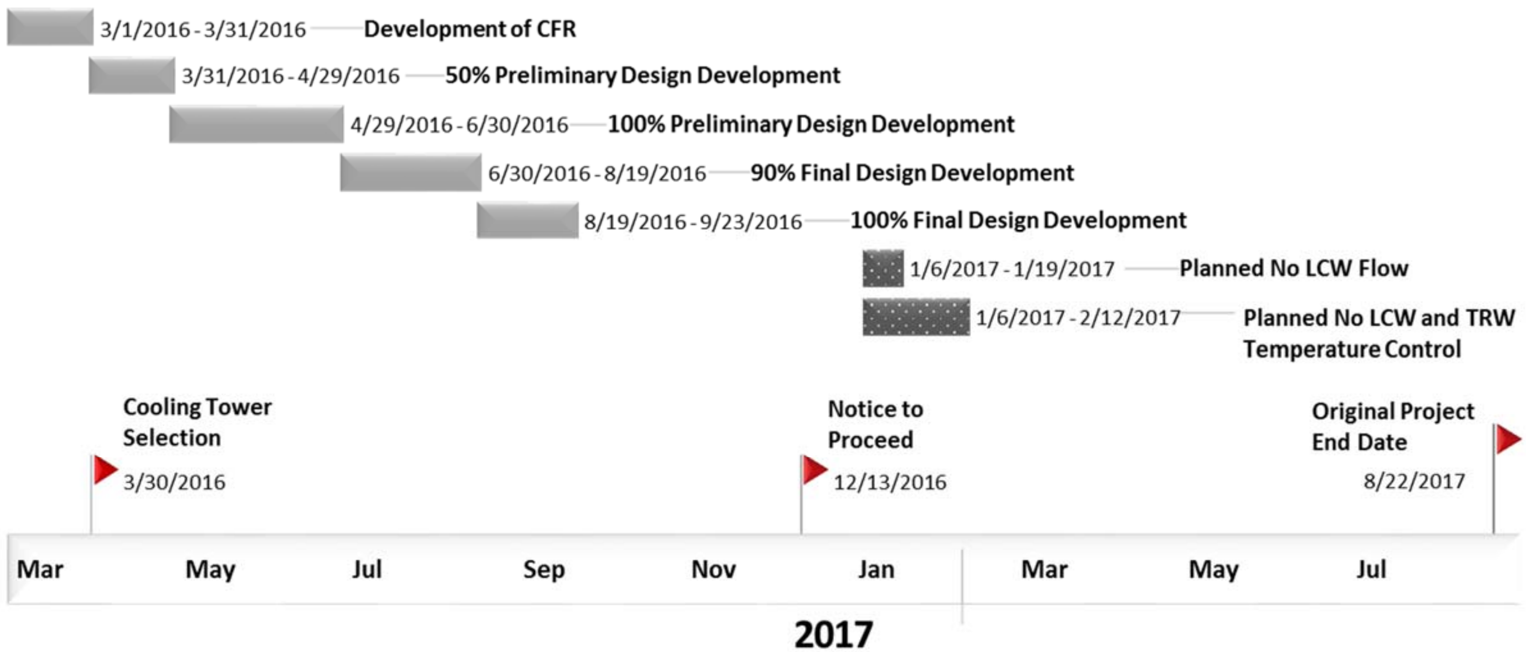


Figure 3-4: Project Timeline

3.2 Research Methodology

The researcher used case-study research to create knowledge from the cooling tower replacement project. The researcher worked at LBNL as a Graduate Student Research Assistant from January 10, 2017 to December 15, 2017, which facilitated data collection and analysis.

In terms of data collection, the researcher had easy access to project information and visited B37 construction site regularly thanks to her employment within LBNL Facilities Division. From April 2017 to November 2017, LBNL upper management asked the project team to copy the researcher on all emails related to the project. In addition to emails, the researcher had access to all project documentation on the shared network at LBNL, which allowed her to retrace the project history preceding January 2017. In addition, the researcher had access to the commissioning agent's online documents repository.

In terms of phasing, the case-study research took place in two phases: (1) an exploratory phase and (2) an explanatory phase. The exploratory phase lasted from January 2017 to mid-April 2017 and the explanatory phase from mid-April 2017 to October 2017. The goals of the exploratory phase were to refine the research questions and verify their relevance while the researcher became familiar with the project. During this phase, the researcher consulted the project documentation, attended construction progress meetings, and observed field work. The goals of the explanatory phase were to characterize aspects of structural complexity on the project, test DSM to make sense of the structural complexity encountered on the project, and gain insight into waste caused by the late involvement of FM on the project.

The goal for the next sections is to answer the question: "How did five aspects of structural complexity manifest themselves in the cooling tower case?" In fact, answering this question reveals that (1) some elements contributing to project structural complexity could have been managed and (2) failure to meet customer requirements is caused by a lack of management of structural complexity.

3.3 Aspects of Structural Complexity on the Project

LBNL supports the Office of Science, which is a DOE's program office (DOE 2017). DOE itself qualifies its projects as 'complex' (DOE 1999). Aware of the shortcomings of its project management practices, DOE has conducted internal audits to improve on them. In this respect, an excerpt from a DOE's (1999) report reads:

"DOE's problems in completing many projects on time and on budget can be partially attributed to the complexity, uniqueness, and frequent changes in these projects, but these difficulties are exacerbated by DOE's shortcomings in project management. Among the deficiencies are an organizational structure unsuited to managing projects, inadequate techniques for planning and executing projects, (…)."

The next sections focus on the project structural complexity manifested in the cooling tower case.

With respect to the terminology used in the remainder of the chapter, "customers" or "project stakeholders" refer to the group of individuals composed of: (1) LBNL personnel using the facilities served by B37 (researchers, engineers, and support staff), (2) individuals invited by LBNL to use the facilities served by B37 (visiting scholars), (3) LBNL personnel managing the maintenance of or directly maintaining B37 (LBNL Facilities Division), and (4) the Department of Energy (DOE). The "project team" refers to: (1) LBNL Facilities Division, (2) the commissioning agent, (3) the engineer, (4) the GC, and (5) the GC's subcontractors. It is worth pointing out that the Facilities Division is both a customer and a project team member.

3.3.1 Customer Complexity

In the cooling tower case, the customer aspect of the project structural complexity arises from: (1) the high number and diversity of customers and (2) the resulting diversity of operating needs.

In terms of customers, each building houses one or more research programs (researchers and staff), laboratories, and more or less sensitive equipment. As previously mentioned, the occupants of the 13 buildings constitute only a subset of the customers of the plant upgrade project. Other customers include FM, DOE, etc.

In terms of operating needs, the cooled TW serves a multitude of HVAC pieces of equipment (compressors, chillers, etc.) in buildings. The HVAC equipment helps to modulate the temperature in those buildings, which is critical for smooth operations. Indeed, certain equipment in laboratories can operate only within tight temperature ranges and react poorly to variations in temperatures. For example, the temperature swing tolerance at ALS is +/- 0.1 ^{o}F.

Obviously, the TW and LCW demand from each building varies with time and the aggregate increases during hot days. LBNL energy managers can make rough predictions in the aggregate demand using historic data collected by onsite meters. However, the limited cooling capacity makes meeting the demand from all served buildings difficult. Since both the LCW and the TW loops are cooled by the tower water loop, an increase in demand reduces the cooling available. As a result, LBNL has prioritized the LCW loop over the TW loop when the two loops are competing for cooling. In this respect, the CFR (see section 3.1.6 Timeline) reads "if there is a shortage of cooling capacity, the control system will reduce cooling to the TW stream in order to meet LCW setpoints." Hence, excessive demand in cooling capacity and a limited cooling capacity makes satisfying a customer's need happen at the expense of another customer's.

In addition to guaranteeing a specific temperature and temperature stability, ALS adds two constraints to the cooling tower replacement project: (1) guarantee continuous operations and (2) minimize vibrations because of ALS equipment sensitivity to vibrations.

With respect to the first constraint, "guarantee continuous operations" requires that the phasing of the project aligns with ALS' scheduled shutdown windows. ALS plans for maintenance 6 months in advance: it has an annual planned shutdown in the winter, and a 2-day maintenance window every other week following the winter shutdown. If an exceptional shutdown should occur, ALS requires to be informed in advance so that the ALS maintenance team can seize the opportunity to get some work done as well.

With respect to the second constraint, "minimize vibrations" requires that construction activities potentially generating vibrations take place during ALS shutdowns only.

3.3.2 Organizational Complexity

In the cooling tower case, the organizational aspect of the project's structural complexity arises from: (1) the rigidity of the communication channels between project stakeholders, (2) the lack of a formal project documents tracking system, and (3) the inflexible project funding mechanism.

First, the rigidity of the communication channels stems from the mechanistic structure of the organization (LBNL) (Burns and Stalker 1961). Characteristics of mechanistic structures are, for example: (1) a high specialization of employees, (2) an attachment to hierarchy, and (3) a centralized decision-making system, to name a few. Unlike mechanistic structures, organic structures are based on: (1) multi-tasking and joint specialization of employees, (2) self-forming teams, and (3) a decentralized decision-making system, to name a few. Each one of these two types of structures have advantages depending on the context in which they are used. Table 3-1 presents a compilation of these advantages relative to the other (Hatch and Cunliffe 2006).

Table 3-1: Mechanistic vs. Organic Structures Choosing-By-Advantages (CBA) Two-Alternative Table

Mechanistic Structure	**Organic Structure**
Employees have a deep technical expertise and knowledge.	Employees multi-task often; they have general knowledge and are flexible.
The structure performs well in certain and stable environments.	The structure performs well in uncertain environments.
The hierarchy makes the chain of command clear; authority is well defined and centralized.	Decision-making is decentralized and lateral, which empowers employees.
The primary communication pattern is top-down.	The primary communication pattern is lateral.
The structure has a rigorous control mechanism.	The structure is adaptable to changing environments and objectives.

The next paragraphs expand on these rigid communication channels.

On the project, the commissioning agent (external to LBNL), the construction manager, and the subject matter experts (internal to LBNL) report to the project manager. If deemed important by the project manager, the project manager communicates the piece of information to their supervisor, namely the project director. If deemed important by the project director, the project director informs the deputy director. If clarification is needed, the deputy director asks the project director for additional information, who in turn asks the project manager. Furthermore, in the case where the piece of shared information must be communicated to ALS, the project director informs ALS. In the case where the piece of information shared must be communicated to any building other than ALS, the project manager informs FM, and FM in turn involves these other customers in the conversation.

Figure 3-5 illustrates the prevalent communications channels used to share information about the cooling tower project. The black dotted lines symbolize LBNL Facilities Division's internal groups.

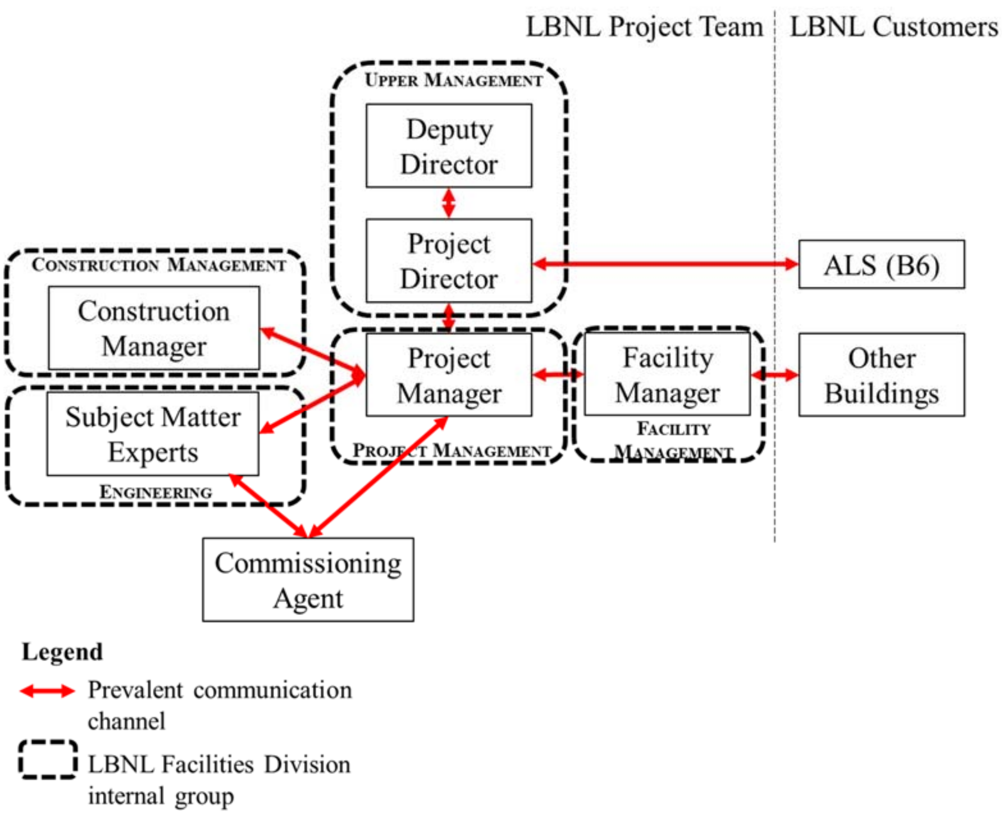


Figure 3-5: Prevalent Communication Channels

In the light of this description, two observations stand out.

First, information concerning ALS is channeled differently than information concerning any other building and some communication channels are long. The first observation shows that ALS ranks first in the order of importance in the buildings served by B37.

Second, the project lacked a formal project document tracking system. The project team exchanged Requests for Information (RFI) and submittals, through emails only. Benefits of using document tracking software are to be able to keep a "single version of truth," route documents consistently, and increase information transparency. The GC reported multiple times on the project not having been returned an RFI when they actually had.

Third, the inflexible funding mechanism contributes to the organizational complexity of the project., Funding mechanisms vary depending on the project type (i.e., Institutional General Plant Projects (IGPP), General Plant Projects (GPP), and line-item projects). Project initiation approval from DOE is required for projects in which capital property, plant, or equipment items are purchased, constructed, or fabricated, including major modifications or improvements.

When a project duration exceeds the span of a year, LBNL earmarks funding per fiscal year (in addition to committing to a total project cost). Consequently, the spend profile acts as a baseline as to how much money can be spent (sometimes when preconstruction has barely started) during each fiscal year.

On the cooling tower project (IGPP type), if spending on a project exceeds by +/-10% the total project costs, the project team must submit a 'mod' (modification) to the Construction Directive Authorization. Such a request may or may not be granted. Conversely, if spending on a project is less than what was budgeted for the current fiscal year, the money not spent (= budgeted spending – actual spending) creates a 'mortgage' into the next year. Since the project still needs to complete, the estimate to completion is mortgaged against the following's year budget. This creates an opportunity cost, because those funds cannot be used for other projects that the division had initially planned to perform.

Overall, the funding mechanism "use it or lose it" impacts decisions made at LBNL concerning planning, designing, and executing the work, since it becomes a factor to take into account in decisions. The benefit of a 'use it or lose it' funding mechanism is to create fiscal accountability on an annual basis.

3.3.3 Process Complexity

In the cooling tower case, the process aspect of the project structural complexity stems from: (1) the densely occupied construction space and (2) poor work structuring.

Riley and Sanvido (1995) proposed that construction space is composed of: (1) unoccupied space, (2) space occupied by construction processes, and (3) space occupied by constructed product, so-called product space. They broke down the space occupied by construction processes in 12 process space types including: layout area, unload area, work area, staging area, etc.

The plant's footprint is approximately 100 feet (30 meters) by 35 feet (11 meters). Its two floors and roof are densely loaded with mechanical and electrical equipment, with unoccupied space accounting for less than 20% of the total building footprint. For example, the second floor had some unoccupied space between the gridlines 3-4:B-C (Figure 3-6), while the roof did not have any in its existing condition (Figure 3-8). Therefore, the installation of new equipment could take place only after its installation location was freed up.

In some cases, the footprint of a new piece of equipment - called "product space" in Riley and Sanvido (1995) - was the same as the piece of equipment it was replacing: e.g., the existing heat exchangers in 4-6:B-C (Figure 3-6) were being replaced with new heat exchangers in 4-6:B-C (Figure 3-7). In other cases, the product space of a new piece of equipment was different from the piece of equipment it was replacing: e.g., the new cooling tower 1 in 3-4:B-C (Figure 3-9) was actually replacing existing cooling tower 1 in 4-5:B-C (Figure 3-8). The two locations being different, it required that existing concrete pads be removed beforehand in 3-4:B-C (Figure 3-8).

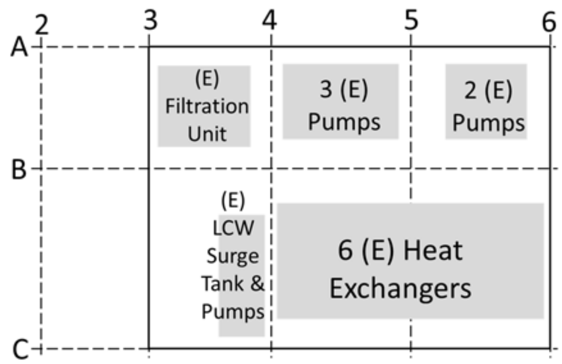


Figure 3-6: Equipment Layout on 2nd Floor: Existing (E) Conditions (Bascoul et al. 2017)

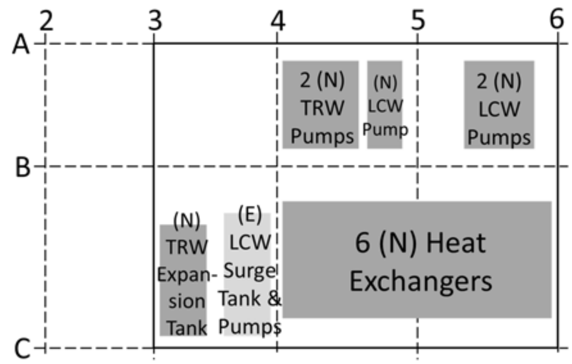


Figure 3-7: Equipment Layout on 2nd Floor: New (N) Work (Bascoul et al. 2017)

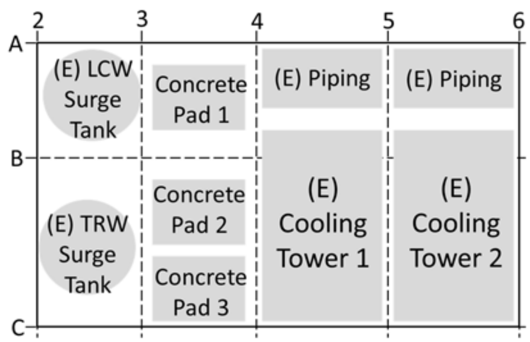


Figure 3-8: Equipment Layout on Roof: Existing (E) Conditions (Bascoul et al. 2017)

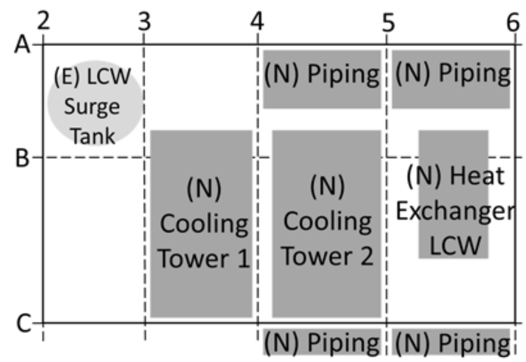


Figure 3-9: Equipment Layout on Roof: New (N) Work (Bascoul et al. 2017)

The engineer was tasked with the phasing of the work to demonstrate the feasibility of the plan he proposed. Then, the engineer handed over the design and the phasing of the work to the GC. Figure 3-10 illustrates the production system design on the cooling tower case. Production system design is also called work structuring.

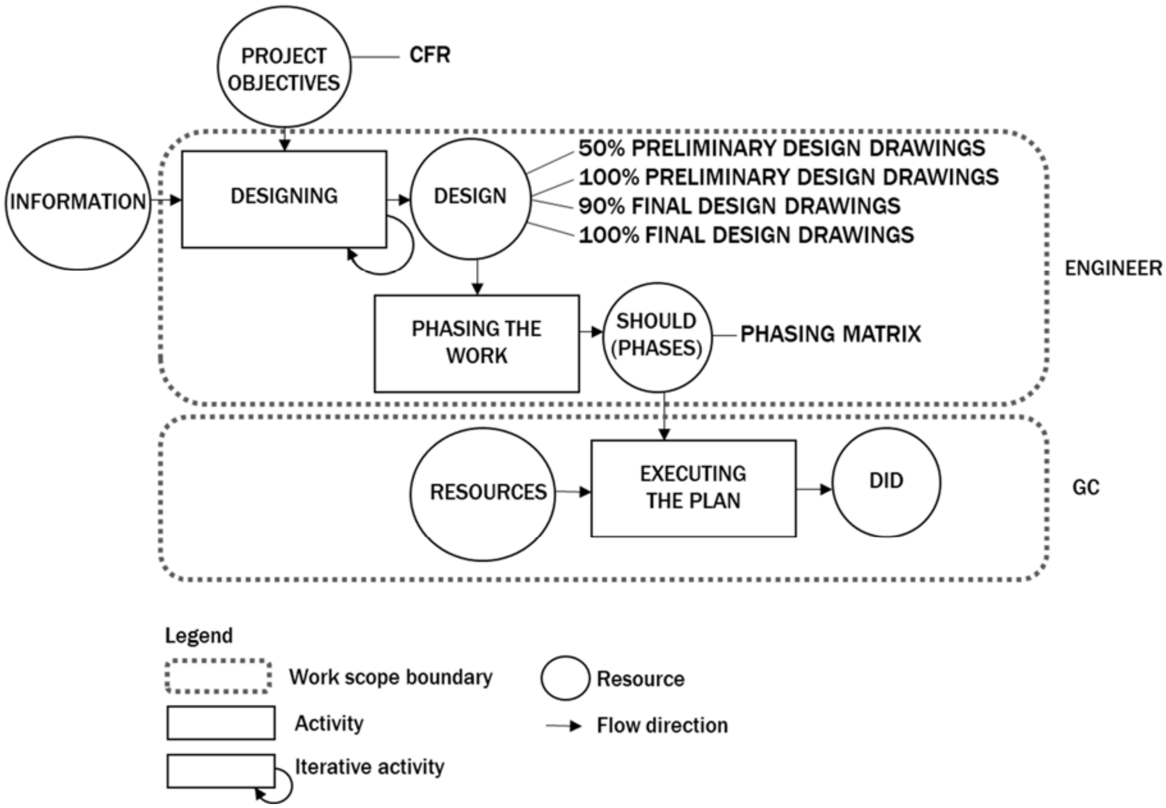


Figure 3-10: B37 Traditional Production System Design (adapted from Ballard 2000b)

In traditional project management, decisions about means and methods to use are often made very early. In this respect, Tsao and Tommelein (2004) write: "Project participants brought into the project at a later time will then feel an obligation to work within the previously established Work Structuring direction." Changes on the project thus result from overdefining the "What?" before developing the "How?"

In this case study, the phasing of the work removed flexibility in the planning of the work and the selection of means and methods to execute the work, due to the product complexity, the density of the equipment, and ALS' continuous operations. A question arises: "Could the GC have provided input to the engineer on the phasing of the work?"

First, the GC did not get on board early enough in the project. The procurement process for the GC on the project happened relatively late in the preconstruction phase. While the engineer started to be involved in February 2016, LBNL sent out a Request for Qualifications to select a GC in May 2016. GCs submitted their prequalification proposal in June 2016, and their final proposal at the end of August 2016. The GC selected by LBNL was awarded the contract in December 2016 due to the long and rigid procurement process at LBNL.

Second, designing and phasing had to be done concurrently to guarantee continuous operations. Indeed, shutting down all buildings supported by B37 over the total project duration was not an acceptable plan, which left two alternatives. The first alternative was to rent a temporary cooling tower, which would have allowed the team to do the work in B37 without the need to align the construction schedule with ALS shutdowns. The second alternative was to align the construction schedule with ALS shutdowns. The team selected the second alternative. This alternative created a tight linkage between ALS shutdown, the design of the project, its phasing, and the sequencing of activities. The design informed the phasing and vice versa. This interdependence encouraged the owner to task the engineer with the phasing of the project due to the anticipated late involvement of the GC.

3.3.4 Product Complexity

In the cooling tower case, the product aspect of the project structural complexity arises from: (1) the interdependence of the systems in B37, (2) the uncertain or unknown condition of the systems and components in B37 (i.e., remaining useful life of the existing cooling towers), (3) the interdependence of B37 with the buildings it serves, (4) the uncertain or unknown location and condition of underground network components, (5) the dependency of the demand from the buildings served on the weather, and (6) the limitations of engineering tools to model and calculate cooling loads and systems behaviors in response to these loads. The next sections expand on these factors.

B37 houses multiple interdependent systems. B37 cools down a TW loop and a LCW loop via two cooling towers (Figure 3-11).

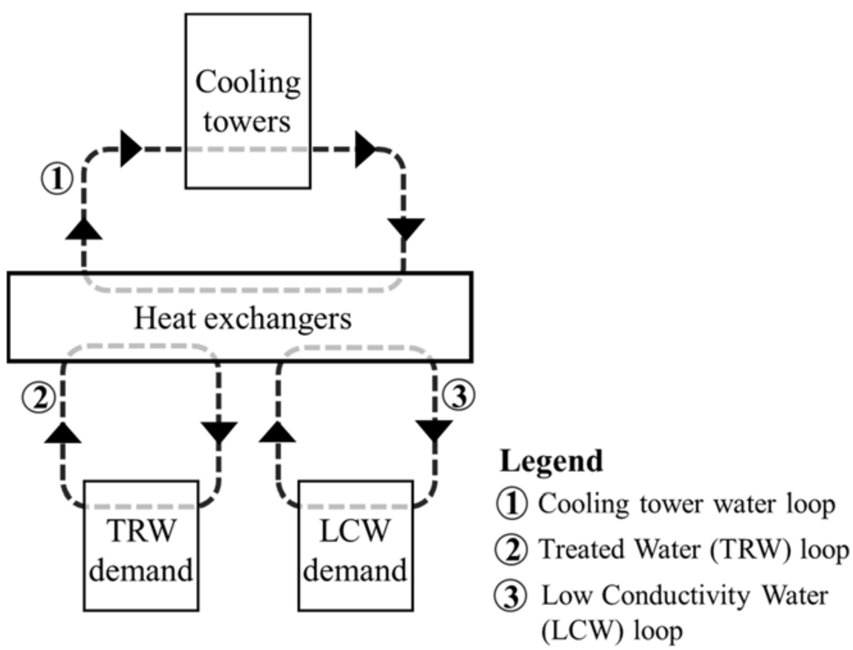


Figure 3-11: Schematic of Water Loops in B37

In the cooling tower water loop, water is cooled down when getting through the cooling tower and is then pumped to go through the 6 heat exchangers (Figure 3-12).

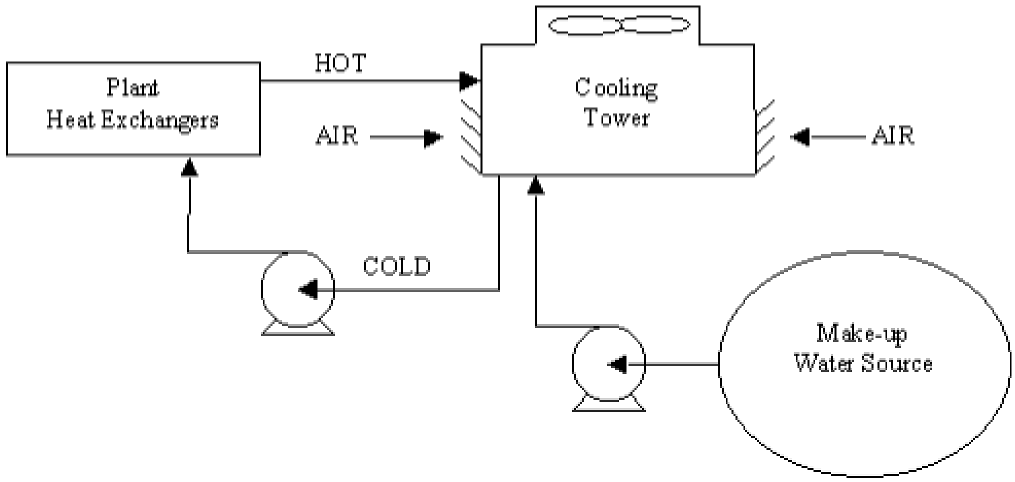


Figure 3-12: Typical Cooling Tower Water Loop (Figure 7.1 in Bureau of Energy Efficiency (2015))

The tower water that runs through the heat exchangers cools down the TW and LCW loops, and eventually returns to the cooling tower. In reality, the TW and the LCW loops are not physically separated in the piping that conducts water to the heat exchangers. Instead, a system of valves (either automatically actuated by a program, digitally actuated through a BMS by an engineer, or manually turned by maintenance staff) routes portions of the water flow to the TW loop and the LCW loop. By choice, when B37 experiences an increase in cooling demand that cannot be met because of the available cooling capacity, the LCW loop takes precedence over the TW loop. The reason for this is that the LCW loop serves to cool down the beamlines at ALS, and ALS generates more revenues than any other building served by the TW loop. As a result, the engineer (manual operation) or the controls program (automated operation) would position the valves so that enough cooled water is directed to the LCW loop. This description demonstrates how the two loops are interdependent and what is currently done to mitigate this interdependence.

This product complexity made assessing the impact of the demolition and installation of pieces of equipment here and there difficult for anyone without the technical expertise in fluid dynamics, controls, and mechanical equipment in general. For example, even the SMEs and the engineer on the project disagreed on how the phase 1 temporary transition from the old cooling towers to the first of the two new ones would impact the water level in the sumps, and at which level the float levels should be placed in the sump to avoid water overflow. The issue was first brought up in November 2016 and was eventually resolved 3 months later.

The unknown condition of the aging B37 equipment and systems also contributed to the product complexity (as a reminder, B37 was initially built in 1959), because predicting equipment behavior is difficult when its condition is unknown (is it about to fail? Is it reliable? Etc.). The existing cooling towers are a case in point. Although the engineer's scope of work included the assessment of the existing cooling towers conditions, the engineer could not guarantee exactly how much longer the cooling towers could operate. In its recommendation, the engineer advised that the cooling towers be replaced in the very near future. The cooling towers are only one example among many pieces of equipment which the condition was unknown.

Furthermore, the numerous interdependences of B37 and other buildings contributed to the product complexity. By serving 13 buildings on the LBNL campus, B37 is at the heart of a network. Each building houses different research groups and activities. The research groups and their corresponding needs change with time. Although onsite metering and historical demand data allow the building energy manager to forecast aggregate demand, the numbers obtained may not be enough to predict future needs, because they do not take into account the dynamics of the changing environment and requirements (changes in research programs, equipment used, etc.). Since among the 13 buildings served, 3 buildings constituted most of the demand, the engineer focused on their demand when developing the design and selecting the cooling tower. Section 3.4 expands on the cooling tower selection as an instantiation of product complexity.

In addition, the project team did not have access to comprehensive and up-to-date as-builts of LBNL's site. The lack of up-to-date as-builts is a recurrent problem in large organizations that grow incrementally over the years. To address this issue, LBNL recently hired a resource to create a comprehensive database of as-builts. The lack of knowledge on how other buildings are connected to B37 added uncertainty to the design process and troubleshooting that occurred due to unexpected performance undergone in phase 1.

Since the B37 cooling towers use ambient air to cool water, their cooling capacity is dependent on the ambient air. Unsurprisingly, average temperatures at the location of the cooling tower constitute a design parameter in the selection of the cooling tower (more to read in section 3.4).

3.3.5 Market Complexity

Federal- and state- specific construction regulations and building codes are numerous. As an example, the cooling tower project BOD listed 26 different building codes and legislations that the design had to comply with (Table 9-18 in Appendix). Some of these are difficult to interpret or even conflicting. Furthermore, complying to code does not only apply during design development but also when changes occur on the project. The cooling tower steel support structure redesign is a case in point. The change in the steel design resulted in the creation of a platform below the cooling tower. Code requires that when a walkable platform is 30-inch (76.2 cm) high or more, rails must be added to the platform for fall protection. In the B37 case, LBNL's SME considered that the platform was not meant for maintenance, so it did not need additional rails for fall protection.

Thus, section 3.3 brought some light on the research question: "How is structural complexity manifested in facility upgrades?" by describing how structural complexity is manifested in the cooling tower case. Sections 3.4, and 3.5 look at instantiations of product, process, and organizational complexity. The shared goals of these sections are to: (1) explore whether DSM can be applied to facility upgrades work (and if so, how?) and (2) assess the fitness of DSM to model structural complexity in facility upgrades work.

3.4 Instantiation of Process Complexity: Work Sequence and Iterations

3.4.1 Iterations

In highly competitive industries such as car manufacturing and aerospace engineering, teams strive to reduce NPD lead times. Research efforts in these domains have significantly advanced the understanding of the NPD process. Overall the literature concurs on the non-linear (Kline 1985) and dynamic (Cho and Eppinger 2005) aspects of the design process, recognizing that iteration is inherent to the design process especially of complex products.

What qualifies as "iteration" is subjective, so the classification of design iteration needs further discussion (Smith and Eppinger 1997). Taxonomies of iteration include: (1) a function-based taxonomy by Wynn and Eckert (2017), (2) the dualism of small versus large iteration by Krehmer et al. (2008), and (3) the dichotomy of value-added versus non-value-value added iteration by Ballard (2000c). In that regard, Wynn and Eckert (2017) build on Smith and Eppinger's (1997) work by proposing a taxonomy based on the three iterative functions: (1) progressive iteration, (2) corrective iteration, and (3) coordinative iteration. Krehmer et al. (2008) differentiate small from large iteration. Small iteration is defined as "quantitative approximations" whereas large iteration is defined as "changing of requirements or of information basis respectively". The adjective "small" qualifies iteration that involves one or very few steps in case of a fallback; the adjective "large" those that are induced by a change in requirements, which entails either the full redesign of the product or at least iterating through a large number of design steps to ensure that the product remains fully integrated. In lean construction, Ballard (2000c) writes that in "the designing," iteration can add value ("positive iteration) or be waste ("negative iteration"), whereas in "the making" (construction), iteration is always waste (and is termed "rework"). Iteration can hence be desirable or undesirable (also termed "unnecessary" by Roelofsen et al. 2008). The goal is therefore to accelerate value-adding iteration and eliminate non-value adding iteration where iteration is, put simply, "the rework of a task caused by the execution of other tasks" (Cho and Eppinger 2005). Before exploring how this could be done, the next section reviews causes for wasteful iteration.

In NPD, the division of labor (Krehmer et al. 2008), the induced lack of communication (Krehmer et al. 2008), the lack of understanding of dependencies and interdependences between tasks, the early start of an activity without all required input (Cho and Eppinger 2005) contribute to uncertainty associated with the design process. Lévárdy and Browning (2005) define uncertainty by the "known unknowns in the process," which is what this section is about.

Drawing parallels with design and construction, project planning is no different than NPD planning with respect to uncertainty and interdependence (Crichton 1966): different technical groups make up the delivery team, communication channels are not trivial, interfaces between the different trades are difficult to understand (Gil et al. 2008), and trades are pressured to "make-do," that is start an activity without all required input (Koskela 2004).

3.4.2 Methodology

In the following case study, we assembled three task-based DSMs: (1) the sequence of activities devised by the Engineer in the pre-construction phase, (2) the sequence of activities proposed by the General Contractor (GC) before starting construction, and (3) the observed sequence of construction. For the first, we used the phasing matrix submitted by the Engineer with the finalized construction drawings. For the second, we used the master schedule submitted by the GC before construction. For the third, we used the minutes from the weekly coordination meetings and on-site field observations. Before building the DSMs, we flowcharted the corresponding sequences of activities. We then codified the activities across the 3 cases using letters from "A" to "Z," "AA" to "AZ," and "BA" to "BU". This step revealed significant differences in semantics used in schedules depending on their author. When an activity description from one plan could not be strictly matched with any activities from the two other plans, we used unique codes. This explains why a code may appear in only one of the three DSMs (e.g., "B" showing in Figure 8 but not in Figure 6 or 7). When an activity description matched across plans, we used the same code (e.g., "E" showing in Figures 6-8). When an activity was broken down at a finer level of granularity, we added an index to the activity code. We then translated the flowcharts into DSMs following the rules in Figure 1. The next section describes the case study and the 3 DSMs obtained following this methodology.

3.4.3 Results

The task-based DSMs only capture the Phase 1 portion of the work. Specifically, the DSM in Figure 3-13 captures the sequence of activities as planned by the Engineer, the DSM in Figure 3-14 captures the sequence of activities as planned by the GC. The DSM in Figure 3-15 captures the observed sequence of activities. Although capturing the sequence of activities for the same project, the 3 DSMs diverge significantly by their size and number of diagonal blocks.

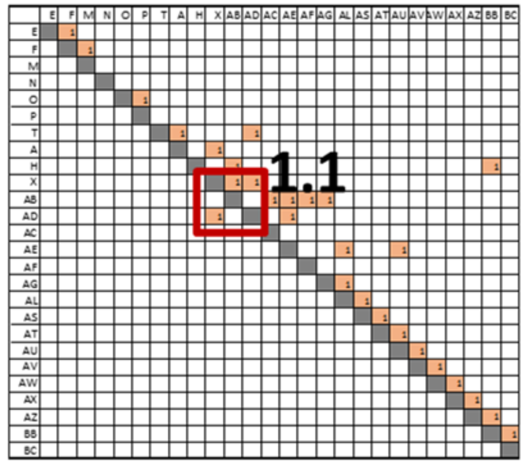


Figure 3-13: DSM showing Sequence of Activities as Planned by the Engineer (Bascoul et al. 2017)

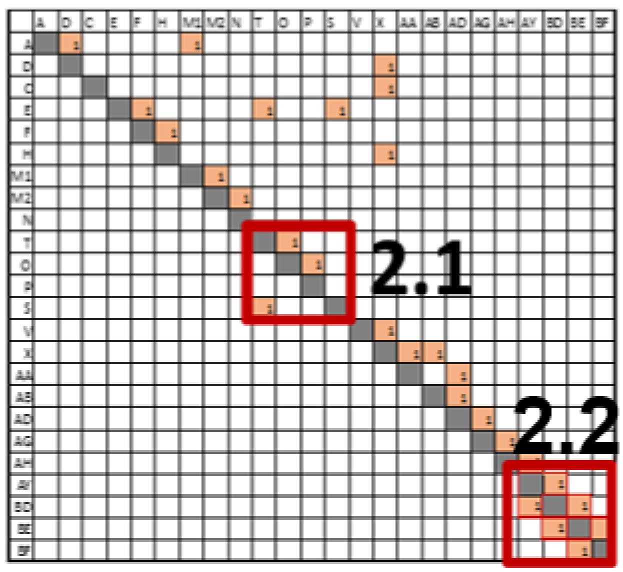


Figure 3-14: DSM showing Sequence of Activities as Planned by the GC (Bascoul et al. 2017)

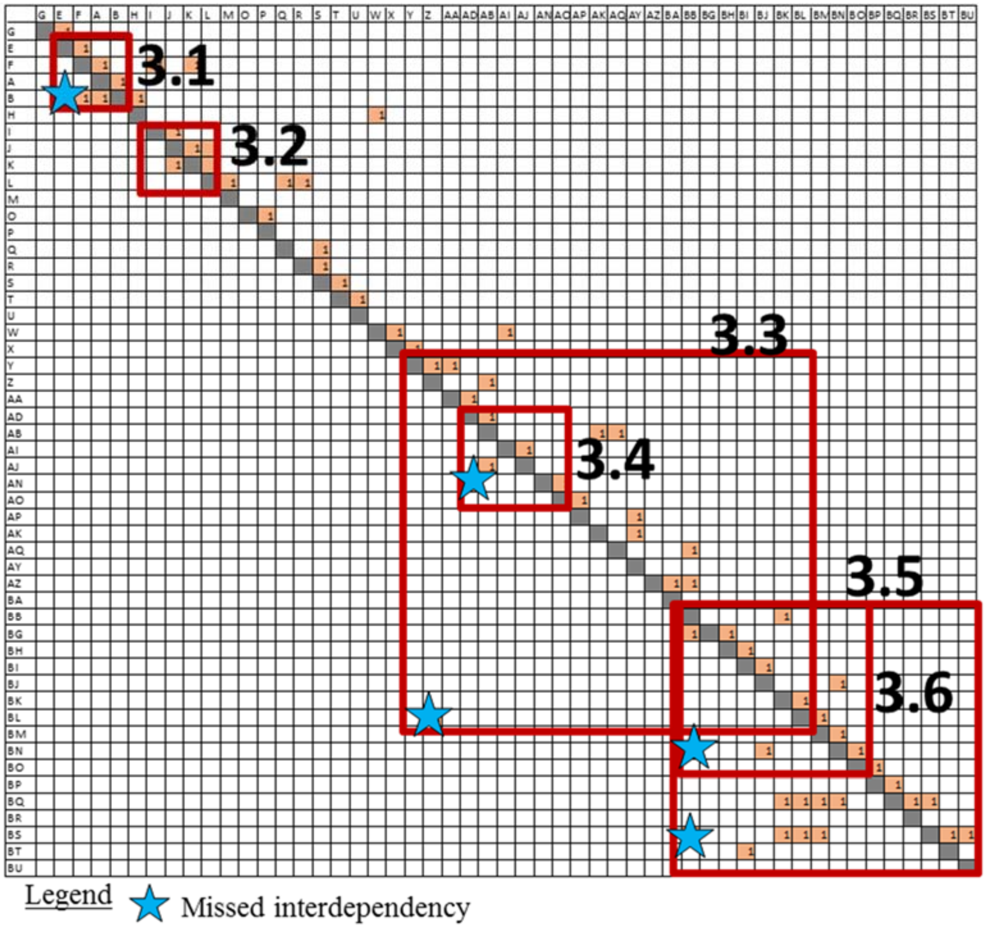


Figure 3-15: DSM showing Observed Sequence of Work (Bascoul et al. 2017)

Table 3-2 classifies the blocks revealed in the DSMs in Figures 6, 7, and 8 in two groups: (1) concurrent activities loops and (2) iteration. It also reports the missed interdependences causing the design iteration.

Table 3-2: Summary of Blocks: Concurrent Activities vs. Iterations (Bascoul et al. 2017)

Block Number	Concurrency	Iteration	Missed Interdependence
1.1	x		N/A
2.1	x		N/A
2.2	x		N/A
3.1		x	High density of conduits and poor results of scanning made anchoring of steel structure to roof unsafe.
3.2	x		N/A
3.3		x	Cooling tower isolators had to be adjusted prior to vibration testing.
3.4		x	Location of new tower water supply pipe prevented from reverting back to old cooling towers as fallback plan, because it obstructed old cooling tower's maintenance.
3.5		x	Re-design of pipe location in Block 3.4 made reverting back to old cooling towers possible. Reverting back to old cooling towers is a process iteration.
3.6		x	Float levels in the existing sumps had to be adjusted for the flow transfer from old cooling towers to new one to prevent water overflow.

3.4.4 Closer Look at the Steel Support Structure Re-Design

Block 3.1 (Figure 3-15) shows iteration resulting from the infeasibility of the structural steel installation. Figure 3-16 magnifies the DSM of Block 3.1, where A represents the first pass, B the missed interdependence, and C the second pass. This magnification helps gain a better understanding of the number of tasks involved in the iteration.

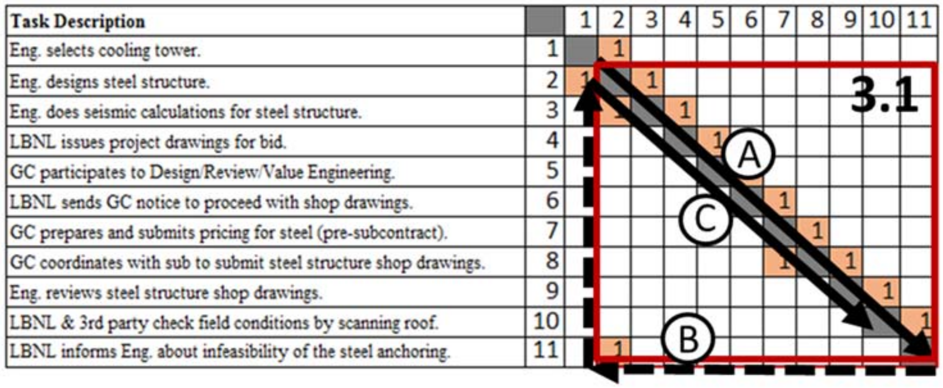


Figure 3-16: Magnified DSM of Block 3.1 (Bascoul et al. 2017)

The installation of the support structure for the new cooling towers required that the steel structure be anchored in 64 locations to the roof, that was composed of structural slab with two layers of rebar, embedded 220V electrical conduit, and a topping slab reinforced with welded wire fabric (Figure 3-17, Figure 3-18, Figure 3-19, Figure 3-20).

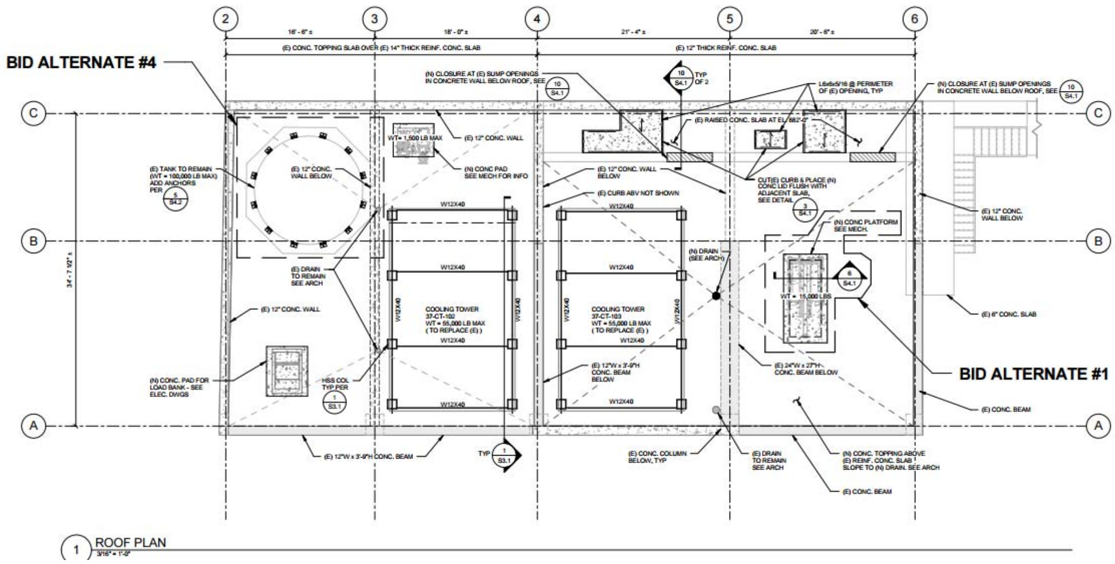


Figure 3-17: Roof of Design Drawing Issued for Bid (YEI 2016)

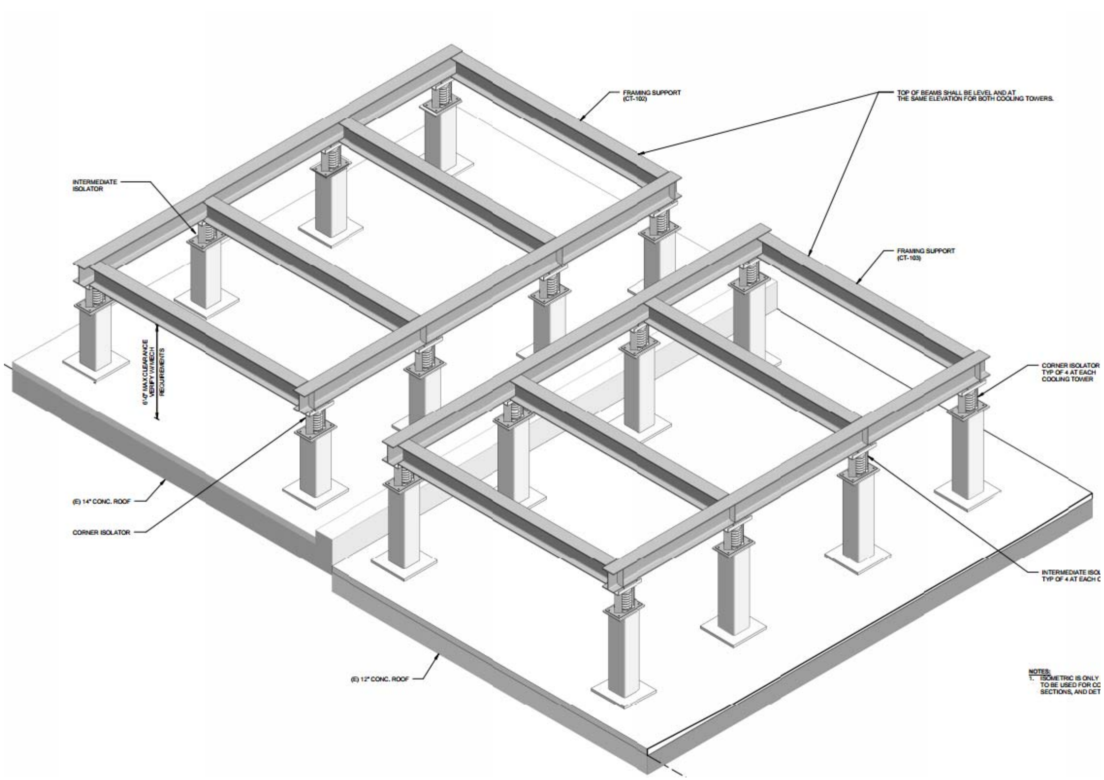


Figure 3-18: Steel Structure on Design Drawing Issued for Bid (YEI 2016)

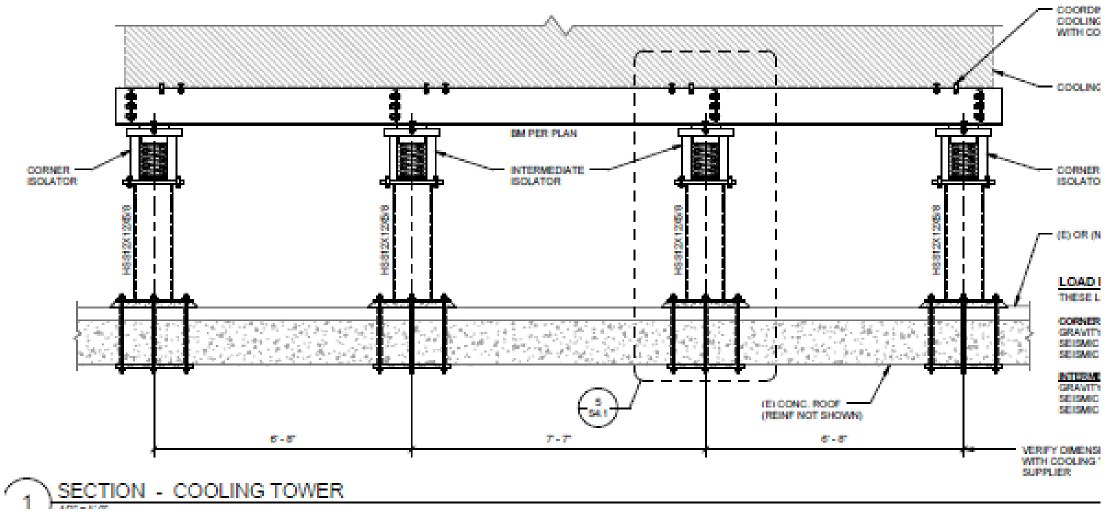


Figure 3-19: Steel Structure Column Detail (YEI 2016)

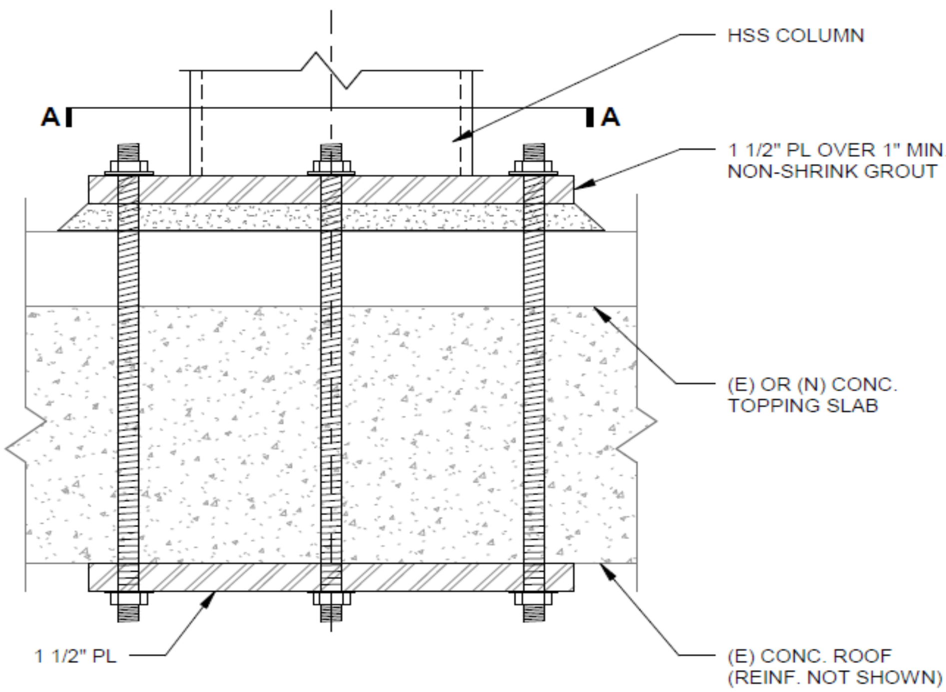


Figure 3-20: Steel Structure Column Anchoring Detail (YEI 2016)

Therefore, to ensure that the anchors would not hit the rebar or conduit, the Engineer included the activity "Scan the roof slab to ***check*** field conditions for placement of the new cooling tower support system" as a predecessor to the anchoring of the support structure. During the drawing review process, LBNL expressed concern but did not ask the Engineer to propose an alternative to the design. Instead, LBNL placed a work order to request internal staff to scan the roof, but this took longer than expected.

The qualitative results of the scan showed significant complexity in the multi-layer slab system and also indicated that the embedded conduit would be very difficult to avoid. LBNL management expressed concern over worker safety given this plan and requested the contractor to closely review the field conditions. The GC agreed there was too great a risk to drill through the slab while the plant was operational and the electrical conduits were energized. Eventually, LBNL directed the Engineer to re-design the steel structure based on the joint LBNL/GC decision, but at the time, the GC had already started to work on the steel shop drawings with its manufacturer, which created rework. The re-designed structural steel system was resting on the perimeter walls of the building. The next section investigates decisions leading to this design iteration.

From a root cause perspective, a first question arises: "why didn't the Engineer suggest this solution initially?" The first solution proposed required less steel than the second one, and was consequently cheaper in material cost, so it represented a local optimization worth doing in the eye of the Engineer. Additionally, the Engineer did not understand LBNL's risk acceptance levels, which is a symptom of traditional project delivery systems in which contracts are seen as transactional rather than relational. Finally, the Engineer did not bear the risk of worker safety during installation as that typically falls on the GC under "means and methods." The contractual barrier between the Owner, Engineer, and GC contributed to the late identification of installation risk inherent with the first design.

In the light of the magnified Block 3.1, a second question arises: "Why did scanning of the roof not happen earlier to inform the design?" LBNL could not proceed with scanning (and the preliminary removal of equipment) before the bid drawings were issued by the Engineer. However, the use of the "iteration masking language" (Tuholski 2008) as in "scan (…) to ***check*** field conditions (…)" should have raised a red flag. The words "revise," "confirm," "check," "verify" call for iteration.

Eventually, the third question arises: "Could the Engineer have released the bid drawings earlier?" The Engineer was hired in May and issued the bid drawings 6 months later with a great level of detail. In the construction industry, engineers are not always tasked with and compensated for exploring and communicating design alternatives with project teams. Instead, they take early decisions (rather than at the last responsible moment) for the design following a point-based design approach and then spend extensive time developing the design into greater detail (in this case, even showing paint details), which contributed to the late discovery of the inconstructible anchoring detail.

3.4.5 Discussion on Fitness of DSM for Iteration Representation

In this case study and in general, task-based DSM offers a visually effective means to represent unplanned design iteration. However, its interpretation can be ambiguous for two reasons. First, diagonal blocks do not systematically represent iteration. Some diagonal blocks may be induced by the concurrency of different activities. Hence task-based DSM users must be aware of the project context to infer the meaning of the diagonal blocks, which makes the exploration of other representations for iteration worthwhile. Second, not showing the time dimension in the DSM makes quantifying the magnitude of any impact difficult and comparison between blocks irrelevant as blocks containing activities shown in more detail may give the erroneous impression of a larger impact than blocks with lesser activities.

In conclusion, the steel structure re-design is a manifestation of process complexity encountered on the project. Its analysis allowed to identify opportunities for LBNL to manage this aspect of complexity in the future.

Similar to the previous section, the next section analyzes the cooling tower selection as a manifestation of product complexity in order to identify opportunities for product complexity management.

3.5 Instantiation of Product Complexity: Cooling Tower Selection

The cooling towers were selected March 30, 2016 and procured at the end of July 2016. The first one was installed early March 2017 and the second one was installed in the end of September. The reported underperformance of the cooling tower by LBNL Facilities Division during the transition phase motivated the researcher to analyze what happened. The purpose of this section is not to approve or not the cooling tower selection, but rather capture how complexity manifested itself in the decision-making process.

3.5.1 Methodology

The researcher studied the cooling tower selection among the many instantiations of product complexity on this project, because cooling towers are a central piece to the project and sufficient data was available to retrace the history of their selection.

To make sense of the data collected, the research's first step was to conduct a literature review to acquire technical knowledge on this piece of equipment. The second step was to consult project documentation, available on (1) LBNL's shared drive and (2) the commissioning agent's online documents repository, to retrace the cooling tower selection timeline and context. The purpose of the third step was to answer these questions:

- What did LBNL value in the cooling tower replacement project? (Objectives to meet). How were the objectives formulated?
- How were the objectives translated into the basis of design, the technical performance criteria, and other project specifications?
- How were technical performance criteria translated into design criteria/parameters?
- How was the cooling tower model sized and selected?
- How does the project process compare with industry practices (manufacturer's recommendations)?
- How did the technical performance criteria (if formulated) compare with the actual performance of the cooling tower?

The final step was to apply the structural complexity framework to analyze the case study and answer these questions:

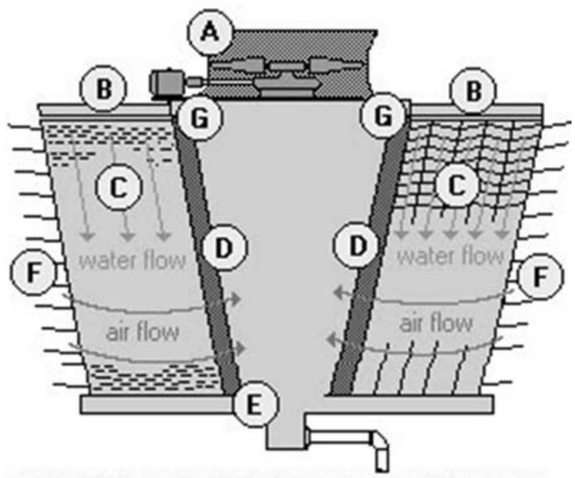
- How does structural complexity manifest itself in cooling tower sizing?

- Can DSM be applied to cooling tower sizing? If so, how? What could be learned from doing so?

3.5.2 Cooling Tower Configurations

A cooling tower is a piece of mechanical equipment that cools down incoming water by evaporative cooling: when falling through the tower, the warm water supplied to the tower comes in contact with a cooler air that cools it down by heat transfer and makes some of it evaporate. Two configurations of cooling towers exist: (1) crossflow and (2) counterflow cooling towers. The difference between the two comes from the direction of air flow relative to water flow.

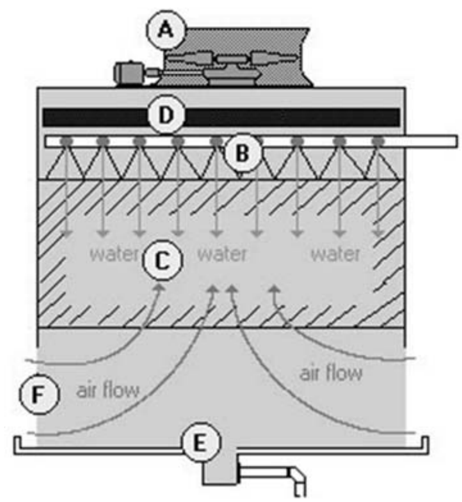
In a crossflow cooling tower, the air flows perpendicular to the water (Figure 3-21). Gravity makes water flow perpendicularly through the fill. In a counterflow cooling tower, the air flows the direction opposite to the water, that is, vertically upwards (Figure 3-22). Spray nozzles at the top of the counterflow cooling tower spray the water in a "rain-like pattern" (SPX Cooling Technologies 2016b) to expose more water surface area to the air. The counterflow system design is more efficient than the crossflow system design, because the "coldest water comes in contact with the coolest and most dry air, optimizing the heat transfer" (GTPL 2011).



Legend

A - Mechanical Equipment
B - Water Distribution
C - Fill Packing
D - Drift Eliminators
E - Cold Water Basin
F - Air Inlet Louvers
G - Redistribution Area

Figure 3-21: Crossflow Cooling Tower (Industrial Water Cooling 2016)



Legend

A - Mechanical Equipment
B - Water Distribution
C - Fill Packing
D - Drift Eliminators
E - Cold Water Basin
F - No Inlet Louvers

Figure 3-22: Counterflow Cooling Tower (Industrial Water Cooling 2016)

Janssen (2012) recommends to choose crossflow cooling towers if the client seeks to: minimize pump heard, minimize pumping and piping cost, minimize operating cost, reduce noise, account for variance in hot water flow, minimize maintenance. Conversely, Janssen (2012) recommends counterflow when space is limited, when there is a risk for icing, or when pumping is desired for additional pressure drop.

The next section summarizes the cooling tower selection timeline.

3.5.3 Cooling Tower Selection Timeline

Figure 3-23 illustrates the cooling tower selection timeline.

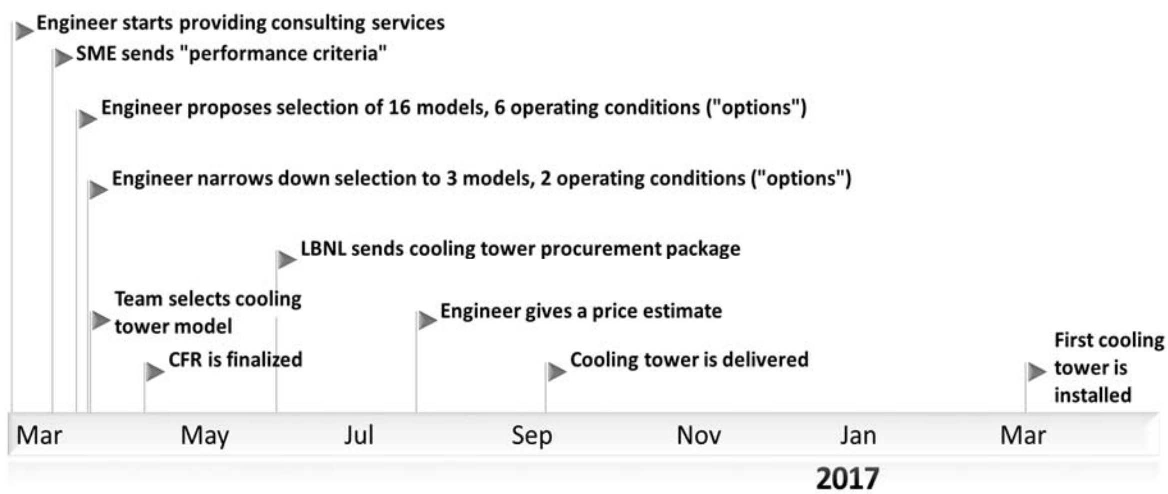


Figure 3-23: Cooling Tower Selection Timeline

LBNL contracted with the Engineer to provide consulting service from March 1, 2016 to March 31, 2016. On March 16, 2016, the SME sent an email to give the engineer "the performance criteria for the new B037 cooling towers." In addition, the SME asked the engineer to "send […] some preliminary selections for both the crossflow and counterflow options" and to "outline the advantages and disadvantages of each selection."

On March 25, 2016, the engineer proposed a selection of 13 models, of which performance was described for 6 operating conditions that the engineer called "options." The 13 models included both crossflow and counterflow configurations. The engineer narrowed down the selection to three models under two "options" (namely operating conditions – as clarified in the next sections) and sent the information to LBNL on March 29, 2016. The project team held the cooling tower selection meeting March 30, 2016.

Concurrently with the cooling tower selection, the engineer, the commissioning agent, and LBNL jointly developed the Current Facility Requirements (CFR) document that they finalized April 19, 2016, that is, **after** the selection of the cooling tower.

Following the cooling tower selection, the engineer kept exploring solutions to guarantee that the facility plant would be able to consistently cool down the TW and LCW loops ("consistently" means even during very hot days). He formulated and shared three alternatives with LBNL in early April 2016. He gave a price estimate at the end of July 2016. In early August, LBNL requested the engineer to separate the alternative solutions from the main bid and propose them under "alternate bids." The intent behind reducing the scope (removing some from the main bid) was to guarantee that work could be undertaken in the same fiscal year and that the work scope would not exceed the available funds. The funding mechanism is further explained in Section 3.3.2.

LBNL sent the cooling tower procurement package to the vendor in early July 2016. They finalized the purchase in late July 2016. The cooling towers arrived mid-September 2016, but due to lack of staging space, the cooling tower installer (GC's subcontractor) staged them offsite. The GC (along with its subcontractor) installed the first cooling tower in early March 2017.

The next section explains how the cooling tower selection was impacted by a lack of awareness of structural complexity.

3.5.4 Problem Encountered

During commissioning, the commissioning agent and LBNL FM (including the building energy manager) reported that the new cooling tower lacked cooling capacity. This raised concerns among the project participants. The team spent the three following months diagnosing the problem, which postponed the start of the second phase of the project. The team even turned off B2 chillers and B43 compressors to reduce the TW load and prioritize the LCW load, namely ALS, during the diagnosis time due to the apparent lack of cooling capacity. This severely impacted the operations in B2 as its laboratory operations require the chillers to be on (experiments must be run at a specific temperature). When the temporary solution (at the expense of B2 and B43) was insufficient to reach the required LCW supply temperature and stability, the team injected city water directly into the system. Injecting city water into the system was a last resort for two reasons: it incurred (1) an environmental impact and (2) extra cost. Regarding the first reason, the system needed a significant amount of city water to help cool down the LCW load and B37 did not have any installation that would allow to recycle the injected city water, which therefore ended up being wasted. Regarding the second reason, LBNL incurred additional costs of $30,000 per day during which city water was injected into the system.

The project team brought up multiple reasons to account for the lack of cooling capacity. Among those reasons, they questioned the cooling tower capability. Consequently, the next paragraph explains how practitioners size cooling towers, and the trade-offs that are inherent to this design decision-making process.

3.5.5 Cooling Tower Sizing

Seven cooling tower design parameters matter for cooling tower sizing: (1) weather, (2) process, (3) tower flow rate, (4) range, (5) approach, (6) wet-bulb temperature, and (7) heat load. The next paragraph defines those parameters and describes their relationships. The information will be used to populate a DSM (Figure 3-27) to illustrate product complexity.

Since a cooling tower uses ambient air to cool down water, the (1) **weather** directly influences how the cooling tower must operate to cool down the incoming water flow. The higher the level of humidity in the air, the less the air is able to absorb water, and therefore the less evaporative cooling works. The (1) **weather** is interdependent with the (6) **wet-bulb temperature**, which is defined as "the temperature of the air if it were saturated with water" (SPX Cooling Technologies 2016b). The wet-bulb temperature can be inferred from the dry-bulb temperature (ambient air temperature) and the relative air humidity via a psychometric chart (Figure 3-24).

To read the wet-bulb temperature at a given dry-bulb temperature (ambient air temperature) and relative humidity, one first looks for the intersection between the dry-bulb temperature shown in the horizontal axis and the relative humidity curves (drawn from 0% to 100% in 10% increments). One then draws a line going through the point of intersection and parallel to the diagonal lines of enthalpy. The intersection between this line and the 100% relative humidity curve gives the wet-bulb temperature (the wet-bulb temperature scale is in 10°F increments in Figure 3-24).

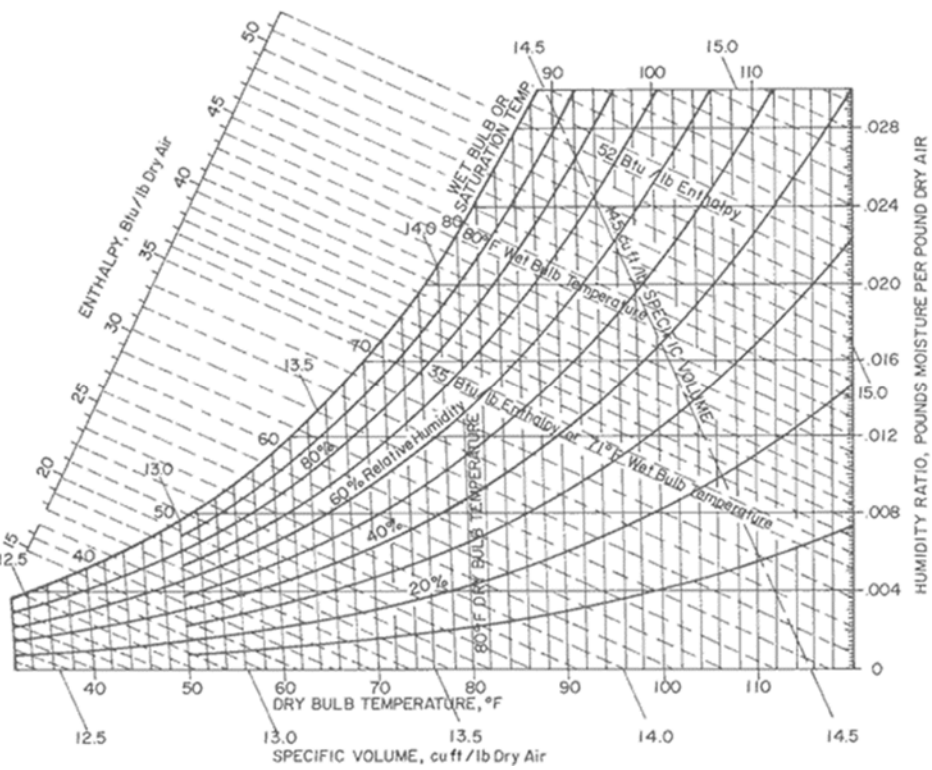


Figure 3-24: Psychometric Chart (Carrier 2017)

However, the parameter (6) **wet-bulb temperature** used as a parameter in cooling tower sizing is actually different from the definition given above, although it is conventionally named this way by practitioners and manufacturers for brevity. Instead, what they actually mean is "design wet-bulb temperature," also more accurately called "mean coincident wet-bulb temperature" (MCWB). The MCWB is associated with a percentage of annual cumulative frequency of occurrence for a specific location. For example, if the 2% MCWB is 62.4°F at Oakland, it means that the actual wet-bulb temperature in Oakland exceeds 62.4°F by 2% of the year, which is 175.2 hrs per year, or 7.3 days. Table 3-3, an excerpt from ASHRAE (2013b), shows how MCWB varies spatially in relatively close-by cities.

Table 3-3: Mean Coincident Wet-Bulb (MCWB) Temperatures (°F) in Livermore, Oakland and Stockton (ASHRAE 2013b)

City	0.4% MCWB	1% MCWB	2% MCWB
Livermore	67.8	66.6	65.1
Oakland	64.3	63.2	62.4
Stockton	69.9	68.9	68.2

The (5) **approach** is "the temperature difference between the temperature of the cold water leaving the tower and the surrounding air wet-bulb temperature" (Morvay and Gvozdenac 2008). The approach is therefore interdependent with the actual wet-bulb temperature and the MCWB temperature. The "approach […] is fixed by the size and efficiency of the cooling tower" (SPX Cooling Technologies 2009).

The (4) **cooling range** is "the temperature difference between the hot water coming to the cooling tower and the temperature of the cold water leaving the tower" (Morvay and Gvozdenac 2008). The (4) **cooling range** depends on the heat load and the tower flow rate, where the tower flow rate is the amount of water passing through the tower water loop per unit of time. The range depends on the heat load and the water circulated through the heat exchanger and toward the cooling tower. The heat load is the amount of heat generated by the processes served, heat that must be exchanged with the cooler tower water flow. The processes served by the cooling towers are multiple as described in section 3.3.1 Customer Complexity. The heat load therefore depends on the process. The heat load per hour can be calculated as follows in imperial units (for water):

$$Q\left[\frac{Btu}{hr}\right] = Flow\ rate\left[\frac{gal}{min}\right]\left[\frac{ft^3}{7.48\ gal}\right] * \left[\frac{60\ min}{hr}\right] * 62.34\left[\frac{lb}{ft^3}\right] * 1\ [\frac{Btu}{lb * °\mathrm{F}}] * \ \Delta T[°\mathrm{F}]$$

$$Q\ \left[\frac{Btu}{hr}\right] = Flow\ rate\left[\frac{gal}{min}\right] *\ 500\left[\frac{Btu *\ min}{hr * gal *\ °\mathrm{F}}\right] *\ \Delta T[°\mathrm{F}]$$

Where:

- Q is the heat rate in Btu/hr
- Flow rate is the amount of hot water that passes through the heat exchanger in gal/min
- ΔT is the temperature difference between the hot and the cold water in °F

The heat load per second can be calculated as follows in SI-units (for water):

$$Q\ \left[\frac{kJ}{s}\right] = Flow\ rate\left[\frac{m^3}{s}\right] * 1000\ \left[\frac{kg}{m^3}\right]\ * 4.2\left[\frac{kJ}{kg * °\mathrm{C}}\right] *\ \Delta T[°\mathrm{C}]$$

$$Q\left[\frac{kJ}{s}\right] = Flow\ rate\left[\frac{m^3}{s}\right] * 4200\left[\frac{kJ}{m^3 * °C}\right] * \Delta T[°C]$$

The approach is therefore related to the cooling tower efficiency. Figure 3-25 shows which locations are used to calculate the range and the approach in a typical cooling tower loop.

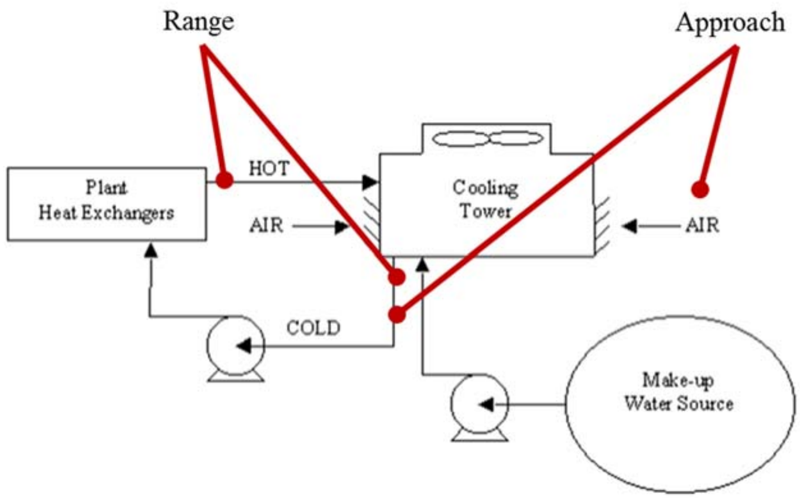


Figure 3-25: Illustration of Range and Approach on Simplified Cooling Tower Water Loop (Adapted from Figure 7.1 in Bureau of Energy Efficiency (2015))

Figure 3-26 captures the relationship between the **wet-bulb temperature**, the **approach**, and the **range**.

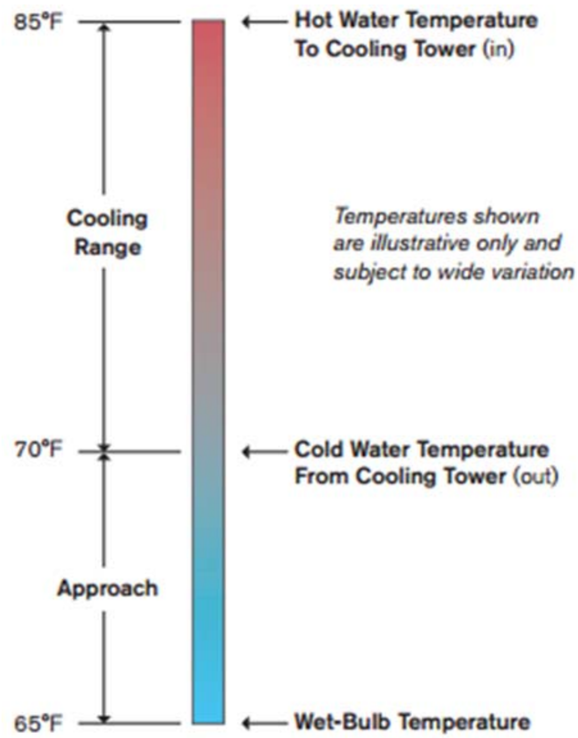


Figure 3-26: Relationship between Wet-Bulb Temperature, Approach, and Cooling Range in Cooling Tower Operation (Figure 1 in SPX Cooling Technologies (2016a))

Last, **cooling capacity** is "the heat rejected, given as product of mass flow rate of water, specific heat and temperature difference" (Bureau of Energy Efficiency 2015).

From those definitions, a few observations stand out.

First, the LCW and TW supply temperatures cannot be inferior to the temperature of the cold water coming from the cooling tower. Usually, these supply temperatures will even be a few degree Fahrenheit (Celsius) more than the approach depending on the rate "q" at which heat is transferred in the heat exchanger. This rate can be calculated as follows (imperial units):

$$q\left[\frac{Btu}{hr}\right] = U\left[\frac{Btu}{hr * ft^2 * °\mathrm{F}}\right] * MTD[°\mathrm{F}] * A[ft^2]$$

Where:

- q is the load in Btu/hr
- U is the design overall heat transfer coefficient in BTU/(hr.ft^2.°F)
- MTD is the mean temperature difference between hot and cold fluids in °F
- A is the effective outside area of tubes in ft^2.

The same formula with SI-units is:

$$q\left[\frac{kJ}{s}\right] = U\left[\frac{kJ}{s * cm^2 * °\mathrm{C}}\right] * MTD[°\mathrm{C}] * A[cm^2]$$

Therefore, if the LCW supplied temperature must be 72°F (22.2°C) and the wet-bulb temperature is 75°F, the cooling tower will not be able to reach the 72°F (22.2°C) without additional pieces of equipment.

Second, the equation of the heat exchanger brings up another interdependence: the heat exchanger's characteristics (variable "A" in the equation, for example) are used to calculate how much heat can be dissipated through the system. Hence, the heat exchanger is part of the problem to solve. If the heat exchangers are changed after the cooling tower is selected, the cooling tower may no longer be a good solution to the problem.

To make product complexity visual concerning cooling tower sizing, the researcher captured previous information in a parameter-based DSM (Figure 3-27). The density of the shaded cells shows how the design parameters are intertwined and make sizing the cooling tower complex. Hence, quantifying each of them appears to be the first (and critical!) step to select a cooling tower that can meet the demand. Yet, quantifying these terms may require the engineer to make some assumptions (assumptions that should be validated by the project team) and to answer preliminary questions such as: "Will the MCWB vary significantly within the next 10 years due to global warming?" or "Will the heat exchangers be replaced after the project has started?"

Beyond the uncertainty surrounding the quantification of certain design parameters, cooling tower sizing poses another challenge: the trade-off between the size and the cooling capacity. The larger the demand (heat load), the larger the cooling tower will have to be, which adds a new difficulty: ensure that the cooling tower can fit within the available space and that B37 can support its weight from a seismic regulation perspective. This constraint counters the inclination to over-design the cooling tower and thus add some buffer cooling capacity. In structural engineering for example, over-designing is common practice. The use of safety factors helps remove some variables (and hence interdependences) in the problem to solve.

Figure 3-27 is a DSM capturing interdependences between seven design parameters involved in cooling tower design.

Cooling Tower Design Parameters	Weather	Process	Tower flow rate	Range	Approach	Wet-bulb T	Heat load	Cooling capability
Weather	1				1	1		
Process		1					1	
Tower flow rate			1					1
Range				1			1	
Approach	1				1	1		1
Wet-bulb T	1				1	1		
Heat load		1		1			1	
Cooling capability			1		1			1

Legend

1 Parameter row i influences parameter column j.

Figure 3-27: Static DSM of Cooling Tower Design Parameters

If three of these four parameters: (4) range, (5) approach, and (6) wet-bulb temperature, and (7) heat load are held constant, changing the fourth will affect the cooling tower size as shown in Figure 3-28. The researcher populated Figure 3-28 based on information extracted from Figure 9-3 to Figure 9-6 in Appendix.

- If the range, the approach, and the wet-bulb temperature are held constant, and the heat load increases, the size of the cooling tower must increase. This could happen if for the given system, ALS adds new equipment that must be cooled with LCW.
- If the heat load, the approach, and the wet-bulb temperature are held constant, and the range increases, the cooling tower size must increase. This could happen if the heat exchanger is changed with a less efficient one.
- If the heat load, range, and wet-bulb temperature are held constant, and the approach decreases, the cooling tower size must increase.
- If the heat load, range, and approach are held constant, and the design wet-bulb temperature increases, the cooling tower size decreases.

Cooling Tower Sizing Relationships	Heat load	Range	Approach	Wet-bulb temperature	Cooling tower size
Heat load					α
Range					α
Approach					1/α
Wet-bulb temperature					1/α
Cooling tower size	α	α	1/α	1/α	

Legend

α	Parameter row i increases when parameter row j increases
1/α	Parameter row i increases when parameter row j decreases (and vice-versa)

Figure 3-28: Relationships between Heat Load, Range, Approach, Wet-Bulb Temperature, and Cooling Tower Size

The next section describes the steps that led to the selection of the cooling tower model on the project.

3.5.6 Actual Decision-Making Steps

The researcher was not able to identify a formal decision-making system or a methodology used for the cooling tower selection. Nonetheless, the researcher was able to identify 6 steps that led to the final selection. The steps are: (1) determine factors, (2) select alternatives, (3) narrow down the set of alternatives, (4) list advantages and disadvantages, (5) express preference, and (6) meet to select the final cooling tower model. Cost did not drive the decision for the selection, since the price difference between the different models was marginal, according to the project director.

3.5.6.1 Determine Factors

The list of factors that the SME initially proposed in an email sent to the engineer March 16, 2016 included: (1) the capacity, (2) the return temperature, (3) the supply temperature, and (4) the wet-bulb temperature. The SME also specified values for each factor in the same email. For clarity and consistency, the researcher will refer to these values as "want criteria," term commonly used in CBA. The interested reader can refer to section 2.11.1 to read more about CBA and its terminology.

Thus, the want criteria proposed by the SME were:

- Capacity: 1,200 short tons (1088.6 metric tons)

- Return temperature: 80°F (26.7°C)
- Supply temperature: 70°F (21.1°C)
- Wet-bulb temperature: 65°F (18.3°C)

Interestingly, the proposed factors were all performance-related. They did not cover maintenance needs, vibrations limitations, sizes, etc. However, the engineer added some of those maintenance-related factors when he suggested a first set of alternatives, as described in the next paragraph.

3.5.6.2 Select Alternatives

The engineer proposed a selection of 8 crossflow cooling tower models and 5 counterflow cooling tower models March 25, 2016. The engineer formatted the information in two tables with identical column headings (Table 9-19 to Table 9-24 in Appendix). The first table covered the crossflow- and the second covered the counterflow cooling tower models. Each row of the two tables contained a different model. The main column headings listed 6 "Options": "Option A: 67/77/87" same as "Option B: 67/77/87," "Option C: 65/75/87" same as "Option D: 65/75/87," "Option E: 65/75/85," "Option F: 67/75/85," where numbers meant: MCWB/Approach/Range in degrees Fahrenheit. The ambiguity of the term "Option" is explained later.

The reason why, in some instances, the same values were listed under two different options (such as A and B, and C and D) is because some cooling tower models could perform at a given MCWB/approach/range for multiple flow rates and motor horsepowers. Thus, for example, models that could perform at 67/77/87 at a flow rate of 3,600 US gpm (13.6 m^3/min) (resp. 3,000 US gpm (11.3 m^3/min)) were listed under Option A (resp. Option B). Hence, the same model could be listed under both Option A and Option B.

In addition to the factors proposed by the SME (capacity, wet-bulb temperature, range, approach), the engineer populated the following information for each model: the flow rate, weight, dimensions, motor horsepower, and efficiency per ASHRAE 90.1 standards.

3.5.6.3 Short-List Alternatives

The engineer narrowed down the initial selection of 13 cooling tower models to three (one crossflow, two counterflow) and presented the information in a table that he sent to LBNL March 29, 2016 (Table 9-25 to Table 9-28). The project documentation did not include the correspondence motivating the engineer to narrow down the selection. Furthermore, the want and must criteria used to eliminate some alternatives were not made explicit in the table. However, the researcher was able to infer two probable "must" criteria used for the elimination of: crossflow models 3, 4, 5, 6, 7, 8 and counterflow models 1, 3, 5, as well as the "must" criterion used for the elimination of counterflow model 1. The researcher was not able to infer the must criterion motivating the eliminations of crossflow model 2 and counterflow model 4.

Table 3-4 links the cooling tower models eliminated with the inferred must criterion when identified.

Table 3-4: Inferred Must Criteria used by Engineer

Criterion Category	Criterion Description	Eliminated Model (Cumulative)
Must	Load induced by the weight of the cooling tower must not exceed the allowable load on the roof.	Crossflow: 1, 2, ~~3~~, ~~4~~, ~~5~~, ~~6~~, ~~7~~, ~~8~~ Counterflow: 1, 2, 3, 4, ~~5~~
Must	Model must fit within available space.	Crossflow: 1, 2, ~~3~~, ~~4~~, ~~5~~, ~~6~~, ~~7~~, ~~8~~ Counterflow: 1, 2, 3, 4, ~~5~~
Must	Model must be able to operate with a 65°F (18.3°C) wet-bulb temperature.	Crossflow: 1, 2, ~~3~~, ~~4~~, ~~5~~, ~~6~~, ~~7~~, ~~8~~ Counterflow: ~~1~~, 2, 3, 4, ~~5~~
The rationale for the elimination of crossflow model 2 was not documented.		Crossflow: 1, ~~2~~, ~~3~~, ~~4~~, ~~5~~, ~~6~~, ~~7~~, ~~8~~ Counterflow: ~~1~~, 2, 3, 4, ~~5~~

The next section describes the advantages and disadvantages listed for the short-listed alternatives and the shortcoming resulting from this decision-making step.

3.5.6.4 List Advantages and Disadvantages

As mentioned, the remaining alternatives included: one crossflow model and two counterflow models. They were listed under “Option C” and “Option D,” which differed in flow rates (3,000 US gpm (11.3 m^3/min) and 3,500 US gpm (13.2 m^3/min)) but were equal in terms of wet-bulb temperature, approach, and range: <65/75/87>. While the crossflow model could operate under the two options, one counterflow model could operate only under “Option C,” and the other only under “Option D.”

The engineer listed the advantages and disadvantages for each of them. However, the advantages and disadvantages revolved around the differences between crossflow and counterflow configurations, such as in “less maintenance required than counterflow cooling tower due to use of gravity flow in lieu of spray nozzles for the counterflow cooling tower.,” or also “more efficient than the counterflow cooling tower.” Advantages did not address the differences in operating conditions and the reliability of each model for the given operating conditions.

As a result of listing both “advantages” and “disadvantages,” the advantages for the counterflow model were also listed as disadvantages in the crossflow model and vice versa, such as in the advantage: “Less footprint than the counterflow cooling tower.” for the crossflow model, which became the disadvantage: “More space required than the crossflow cooling tower.” for the counterflow model. This example illustrates a flaw of the decision-making system being used: the practice of double counting.

Figure 3-29 is a graphical representation of the table listing the advantages and disadvantages for each model. Each advantage and disadvantage is represented by a numbered shaded square. A straight line between two advantages means that the advantages were the same. A straight line between an advantage and a disadvantage means that the advantage for one model was counted as a disadvantage for the compared model.

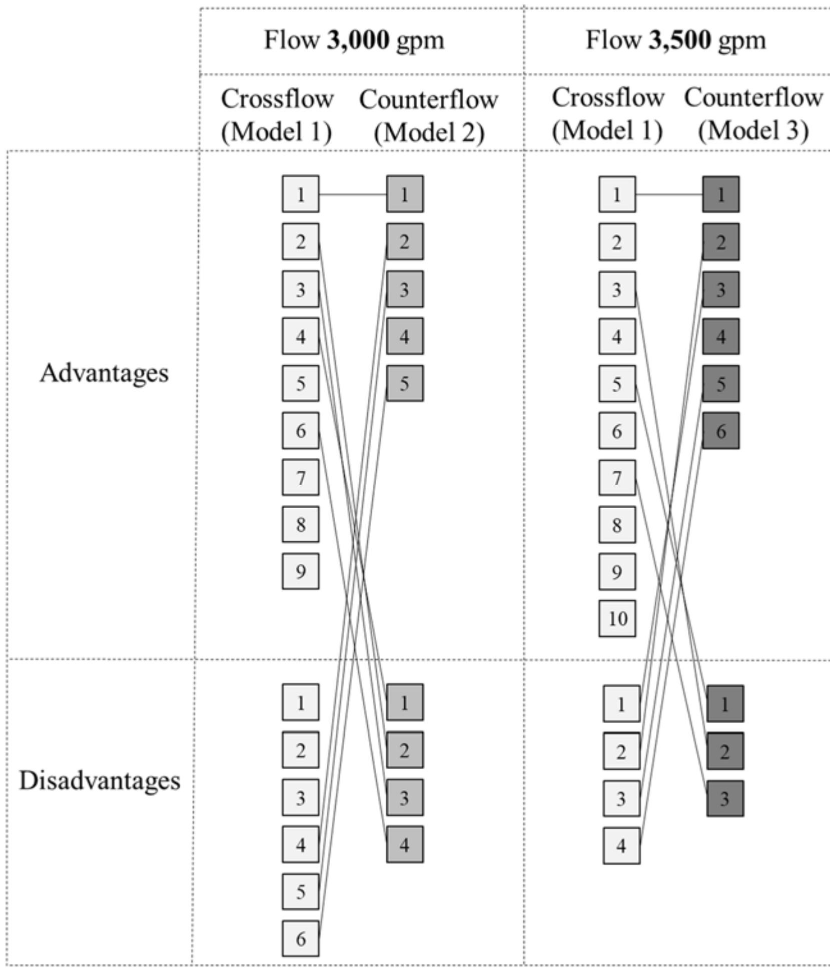


Figure 3-29: Advantages and Disadvantages in Short-Listed Cooling Tower Models

Figure 3-29 makes visible how many advantages were double-counted in the process.

3.5.6.5 Express Preference

In the same email describing the shortlist of cooling tower models, the engineer wrote “There are so many pros and cons on the selections. However, without looking at the cost, my recommendation is Option D – [crossflow] Marley NC8414 with 1400-ton capacity and 100 horsepower fan motor since this will provide you with more options to increase your load capacity in the future.”

Thus, the engineer expressed a preference for the selection of the cooling tower. The preference seems to be primarily based on the model's potential to accommodate more load in the future. Thus, two observations stand out: (1) this factor had so far not been formulated explicitly in the tables or in the relevant correspondence (not even in the SME's specifications), (2) the advantage of this attribute is deemed the most important by the engineer among the "many pros and cons on the selections."

3.5.6.6 Meet to Select Final Cooling Tower Model

Table 3-5 lists the number of meeting attendees per LBNL team group to the exception of the Engineer (external to LBNL). The various groups illustrate the diversity of the audience. Among this diversity, one could wonder: "How many people did have a deep understanding of how cooling towers worked?" and "How many people were aware of the interdependences between the various design parameters playing a role in the cooling tower selection?"

In addition, it is worth pointing out that only one customer representative (ALS) attended the meeting. From the meeting sign-in sheet, it appears that other customers (than ALS) did not attend the meeting. The researcher speculates that they may not have been invited to the meeting maybe because ALS was deemed as the most important customer. As a result, it did not allow other customers to question the decision made.

Attendees chose option D, as recommended by the engineer.

Table 3-5: Attendees of the Cooling Tower Selection Meeting

Group	**Number of People**
Engineer (External to LBNL)	1
LBNL ALS (Customer)	1
LBNL Upper Management	2
LBNL Facilities Operations	1
LBNL Procurement	1
LBNL Fire Marshall	1
LBNL Engineering (SME)	3
LBNL Commissioning	1
LBNL Project Management	1
LBNL Construction Management	1
Total	13

The next section identifies some flaws in the implemented decision-making system.

3.5.7 Shortcomings of the Implemented Decision-Making System

The lack of formality of the implemented decision-making system had the following consequences: (1) project stakeholders did not share the same language, (2) they had different views on the problem to solve, and (3) the progression from one decision step to the following lacked transparency.

First, the terms used in the emails and the correspondence pertaining to the cooling tower selection was confusing at best. For example, the SME first asked the engineer to provide a few “crossflow and counterflow options.” What he actually meant was “models” instead of “options.” In his response, the engineer used the word “option” to refer to different operating conditions. The word “option” is misleading as operating conditions result from (1) assumptions made on the MCWB and (2) actual calculations to infer the needed cooling approach. The researcher speculates that the wording used made stakeholders believe that all the proposed models would meet the actual demand, which is not certain at all. A better word could have been “alternative” to refer to the cooling tower models (and not their operating conditions).

Second, project stakeholders had different views on the problem to solve (or objectives to achieve) at the time the cooling tower was selected. LBNL internal groups each have a different hierarchy of objectives to meet; a second-tier objective for one group may be a top-tier for another group and vice versa. For example, on the one hand, LBNL FM wants to maximize customer’s satisfaction, thus minimize risks of shutdowns for ALS but also all the other buildings served by B37 (e.g., B2, B43) and guarantee that the aggregate cooling demand is consistently met (not only ALS’s demand). On the other hand, ALS wants that their cooling demand is met in priority and that all construction activities take place in planned shutdown windows; objectives that are also different from LBNL Facilities upper management’s. Facilities upper management wants the B37 project completed as planned in the project planning guide (formal document) approved by DOE.

Related, the CFR document, which summarized the project’s objectives and requirements, was finalized (April 19, 2016) after the cooling tower was selected (March 30, 2016). The CFR document was jointly written by LBNL, the commissioning agent, and the engineer. The CFR documented the following project requirements:

- “LCW in particular needs to be provided within close temperature and pressure parameters.
- In addition to the temperatures and tolerances listed, there will be a priority of control that gives precedence to meeting LCW setpoints over meeting TW setpoints. That means if there is a shortage of cooling capacity, the control system will reduce cooling to the TW stream in order to meet LCW setpoints.
- Efficiency will remain as-is.
- Reliability of main equipment should be exceptionally high, to support 24/7 operations. Unscheduled shut-downs due to equipment failure are potentially disastrous since they may shut down ongoing research, which is the core activity of the Lawrence Berkeley Laboratory.”

Interestingly, the CFR document reads that "while temperature stability is more important than the absolute temperature of LCW, the loss of temperature control on warm days raises concerns, especially in the light of ongoing global warming and its changes on the tower response." Although not being able to meet the demand on certain hot days "raises concerns" at LBNL, the same document also reads that this scenario "is currently acceptable." However, the "acceptability" of the scenario in the long term never appeared in the list of factors used to make a decision. Most importantly, the CFR provided a table describing the current operating conditions. The existing cooling towers performance would have been useful to be compared against for each selected model. Additionally, the appendices included historical data collected by various sensors in the system. They also pointed out instances of unusual operating conditions. For example, in December 2010 and February 2011, there were sudden temperature spikes as the result of failing control valves on the heat exchangers serving the TW circuits. Thus, the CFR provided a wealth of information that could have been useful at the time the cooling tower was selected.

Third, the progression from one decision step to the next lacked transparency. As a first example, Table 3-6 shows how values used for cooling tower sizing varied across time. It is worth pointing out that even very small differences in numbers have significant impact on the cooling tower size. The project documentation does not include the rationale for the change in values. However, the researcher speculates that upon submission of the values by the SME, the engineer realized that such small cooling approach was difficult to reach with respect to the available space (the smaller the approach, the bigger the cooling tower).

Table 3-6: Changes in Values of Parameters used for Cooling Tower Sizing

	SME	**Engineer, 1st selection**	**Engineer, 2nd selection**
	03/16/2016	03/25/2016	03/29/2016
Range (°F)	80	85, 87	87
Approach (°F)	70	75, 77	75
"Wet-bulb temperature" (MCWB) (°F)	65	65, 67	65

As a second example, the relationships between the project objectives and the factors used for the cooling tower selection remain unclear. For example, the project requirement related to "efficiency," which was formulated as "Efficiency will remain as is" in the CFR document, was translated into ASHRAE 90.1 standard. The researcher was not able to find evidence showing that the engineer compared the proposed models against the current cooling towers' efficiency. Doing so would have brought valuable information to the project.

The next section follows the 5-Whys problem solving technique to understand why the decision was questioned after the start-up of the new cooling tower.

3.5.8 5-Whys on Cooling Tower Selection

The interested reader is invited to consult section 2.10.2 in Chapter 2 to know more about the 5-Whys.

After the first cooling tower was installed, the project team started to question the cooling tower selection.

W1. Why was the cooling tower selection questioned during phase 1?

The cooling tower selection was questioned following the start-up of the first cooling tower, because the team did not expect the experienced behavior of the cooling tower, as attested by this email: "Today May 01, 2017 ALS had to go offline during user operations due to high LCW temperatures. This is a pretty significant failure of this system and it's supposed to get worse tomorrow. Here's a picture of the current conditions. Note that the LCW LOAD calculation is inaccurate because it uses a static supply temperature of 73°F (22.8°C) for the calculation and we are far above that."

The "significant failure of this system" stems from the fact that the project team expected more cooling capacity even in the unusual warm conditions on that day. The LCW temperature hit 75.3°F (24°C) with only 80 short tons (72.6 metric tons) on the TW system. This first answer brings the following question:

W2. Why was the behavior of the cooling tower unexpected?

The behavior of the cooling tower was unexpected, because the project team believed that the installed cooling tower would be able to meet the demand during the transition phase. The transition phase refers to the period of time during which only the new cooling tower installed operates.

W3. Why did the team think that the installed cooling tower would be able to meet the demand during the transition phase?

From the reviewed project documentation, it seems that the reliability of a single cooling tower during the "transition phase" was never discussed during the cooling tower selection. Reliability never appeared as a factor for selection. At the time, the design of the project had barely started, and the phasing of the project had not even been thought through. In fact, project documentation and memos show that the project team had not eliminated the use of a temporary cooling tower during the transition phase either. The temporary cooling tower would have allowed some flexibility in the execution of the plan. Selecting the cooling tower model before exploring alternatives such as the use of a temporary cooling tower can be summarized by "defining the What before understanding the How." Furthermore, the lack of shared language led to confusion in terms of what "capacity" (in US tons) meant, what risks were associated with each "option," and the consequences of choosing a "wet-bulb temperature" of 65°F (18.3°C) against 67°F (19.4°C) for example. In fact, the project team did not seem to be aware of the interdependences between the design parameters and trade-off between size and cooling capacity. This third level of root causes identification brings the two following questions:

(1) why was the team unaware of (i) the interdependences between the design parameters and (ii) the trade-off between size and cooling capacity? and (2) why was the cooling tower selected before having a better understanding of what the project phasing would be? The next two paragraphs answer question (1) in W4.1 and W4.2 and the fifth level of 5-Whys stemming from question (1) in W5.

W4.1. Why was the team unaware of (i) the interdependences between the design parameters and (ii) the trade-off between size and cooling capacity?

The team was unaware of the interdependences between the design parameters, because either understanding them was not part of their scope, or they did not have time to look at them, or they did not have the mechanical expertise themselves to understand the system. Furthermore, the interdependences were not communicated or made visible to them. The same applies to the trade-off between size and cooling capacity. This fourth level of root cause identification brings the following question:

W5. Why were interdependences between design parameters not made visible to project team members?

Making interdependences explicit and modeling them is not common practice in engineering for two reasons. First, the AEC industry simply lacks awareness about the importance of understanding and managing structural complexity in engineering design. Second, the AEC industry is not familiar nor educated about the use of tools such as DSM to model interdependences.

W4.2 Why was the cooling tower selected before phasing the project?

First, the organizational complexity induced by the project funding mechanism encouraged the project team to use the money allocated for that purpose before the end of the fiscal year. This way, the team avoided running the risk of not having the same amount of money allocated in the following year in case of delayed cooling tower selection/purchase. Second, the project team bought the cooling tower ahead of time to mitigate the impact of unreliable procurement time of the cooling tower through a time buffer. As a result, the project team did not fully assess whether a single cooling tower would be able to handle all the demand during the transition phase.

The next section summarizes how the product complexity experienced in the cooling tower selection was compounded by four other aspects of structural complexity.

3.5.9 Compounding Effect of Structural Complexity

The cooling tower selection is a case in point of product complexity experienced on the project. However, impacts of product complexity were amplified by the customer-, organizational, process- and market- aspects of complexity.

Table 3-7 captures how each implemented decision step was impacted by structural complexity. The implemented decision steps are compared against CBA steps, which is used here as a baseline.

Table 3-7: Impact of Structural Complexity on Decision-Making Steps (1/3)

CBA steps (used as baseline)		Step 1: Identify alternatives	Step 2: Define factors	Step 3: Define the "must" and "want to have" criteria for each factor
Actual decision-making steps			(1) Determine factors (2) Select alternatives	
Factors	Customer complexity	Unknown/uncertain future development needs and environment. Different views on problem to solve.	High variety of customers. Design rationale and interdependences between design parameters not captured and communicated. Lack of customer engagement.	High variety of customers. No group validation.
	Organiza-tional complexity	Project funding mechanism.	Mechanistic structure Vertical organization and centralized decision making	Rigid communication channels. Lack of stakeholders' participation in decision.
	Process complexity	Work structuring. GC not involved at the time cooling tower is selected.	Management by results.	Work structuring. Lack of sound decision-making system. Commercial terms.
	Market complexity	Unknown/uncertain future development needs. Unknown/uncertain future regulations (energy efficiency, water use, etc.).	Diversity of cooling tower types and models. Engineering as a commodity.	High variety of applicable building codes and regulations. Climate change.

Table 3-8: Impact of Structural Complexity on Decision-Making Steps (2/3)

CBA steps (used as baseline)		Step 4: Summarize the attributes of each alternative	Step 5: Decide the advantages of each alternative	Step 6: Decide the importance of each advantage
Actual decision-making steps		(3) Narrow down the set of alternatives	(4) List advantages and disadvantages (leads to double counting)	(5) Express preference and add considerations
Factors	Customer complexity	Lack of transparency in criteria used for elimination.		
	Organiza-tional complexity	Lengthy procurement process encourages the acceleration of the decision-making process. Unreliable lead times of LBNL internal processes.		
	Process complexity	Lack of sound decision-making system.	Lack of sound decision-making system (double-counting). Received traditions.	Lack of sound decision-making system. Received traditions.
	Market complexity	Manufacturers' data does not facilitate comparison across brands.		

Table 3-9: Impact of Structural Complexity on Decision-Making Steps (3/3)

CBA steps (used as baseline)		Step 7: Evaluate cost data	Step 8: Reconsideration phase
Actual decision-making steps			(6) Meet to select the final cooling tower model
Factors	Customer complexity	Best value is not necessarily a driver when the entity that funds the project (DOE) is not the same as the entity that manages it (LBNL).	Reliance on expertise.
	Organizational complexity		
	Process complexity	Lack of sound decision-making system.	Work structuring. Lack of sound decision-making system.
	Market complexity		

3.6 Application of LPDS-MDM Framework to Explore Opportunities for Managing Complexity

The lack of management of structural complexity on facility upgrade projects can impact project performance. In section 3.3, the researcher classified the factors contributing to the project complexity in five aspects: customer, process, product, organizational, and market. In sections 3.4 and 3.5, the researcher first identified an instantiation of structural complexity for a specific aspect and then explored how the instantiation was impacted by the four other aspects of complexity. Findings show that aspects of complexity can have a compounding effect when their interdependence is not managed. This section uses the LPDS-MDM framework to summarize those findings and describe opportunities to manage complexity.

The value for project delivery teams in using the LPDS-MDM framework is that it offers a comprehensive and simple view of the interdependences between project delivery modules. For clarity, the next section uses the simplified representation of the framework (the full representation is in Chapter 2, section 2.11.2).

3.6.1 Project Structural Complexity Made Visual

The goal of this section is to show how delivery teams could use the LPDS-MDM framework in anticipation or retrospect to visualize structural complexity on the project. Section 2.11.2 describes the framework in more details. The terminology used in the framework is defined in the 'Definitions' section. The research shaded the cells of the framework that are the most impacted by the aspect of complexity considered. However, complexity being in the 'eyes of the beholder,' the decision on which cell(s) to shade is subjective. Therefore, the shaded cells are likely to vary from one team member to the next. This visual tool could thus support conversations about how to manage project complexity within the team.

Figure 3-30 illustrates customer complexity in simplified LPDS-MDM framework. The shaded cells indicate which elements of the project delivery were directly impacted by customer complexity (as analyzed in retrospect and in the eyes of the researcher). As mentioned in section 3.3.1, the high number of customers and operating needs made the identification of project purposes difficult. Furthermore, one customer, ALS, had stringent requirements on the commissioning of the cooling towers. Accordingly, the row "commissioning" was also shaded in Figure 3-30. The fact that the facility serves numerous buildings and the fact that there is a prioritization in meeting their needs (ALS having priority) contributes to the complexity of the operations. For this reason, the row "operations" was also shaded in Figure 3-30.

The LPDS-MDM framework helps to visualize customer complexity on the project, but most importantly to increase awareness on how complexity impacts (snowball effect) numerous project delivery modules. Customer complexity mainly impacted the identification of project purposes, the commissioning, the operations, and the decommissioning. It also affected the definition of design criteria, the design concept, the process design, product design, engineering, fabrication and installation (Figure 3 30).

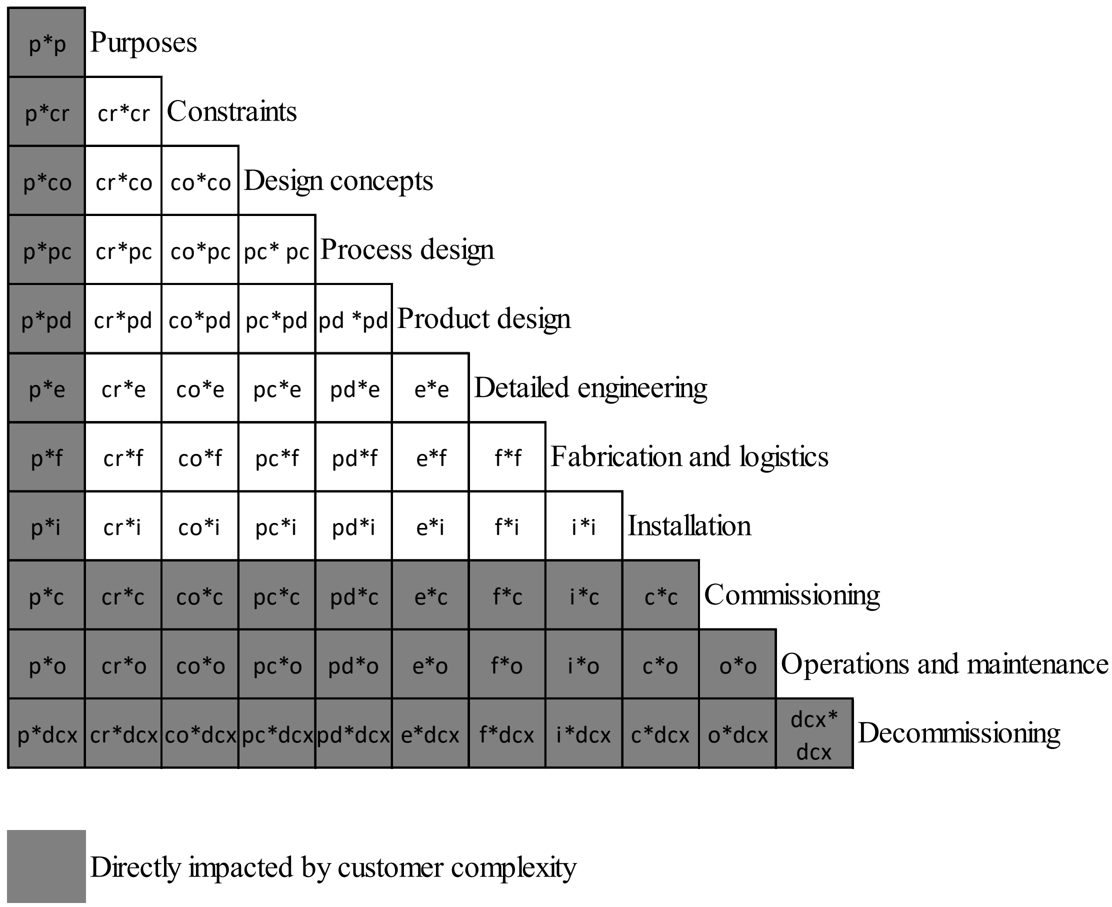


Figure 3-30: Customer Complexity in Simplified LPDS-MDM Framework

Figure 3-31 illustrates product complexity in simplified LPDS-MDM framework. The shaded cells indicate which elements of the project delivery were directly impacted by product complexity. As mentioned in section 3.4 covering the cooling tower selection, sizing a cooling tower is complex. Cooling tower parameters are highly interdependent and rely on input values that are sometimes estimated with a lot of uncertainty (such as the anticipated changes of the mean coincident wet-bulb temperature over the next 10 years due to global warming) on the project. In addition, planning the behavior of the system during the transition phase was complex for multiple reasons. First, the two existing cooling towers had been built as a single entity (sharing the same basin). In that respect, the construction manager was comparing them to “a pair of lungs”; the metaphor emphasized the fact that the existing cooling towers were operating together as a pair. Yet, during the transition phase, only one cooling tower was operating in a system that had been designed and built for a pair of cooling towers. The team’s doubt on the cooling tower capacity and the long period of troubleshooting following the start-up of the cooling tower are examples of how product complexity was experienced on the project.

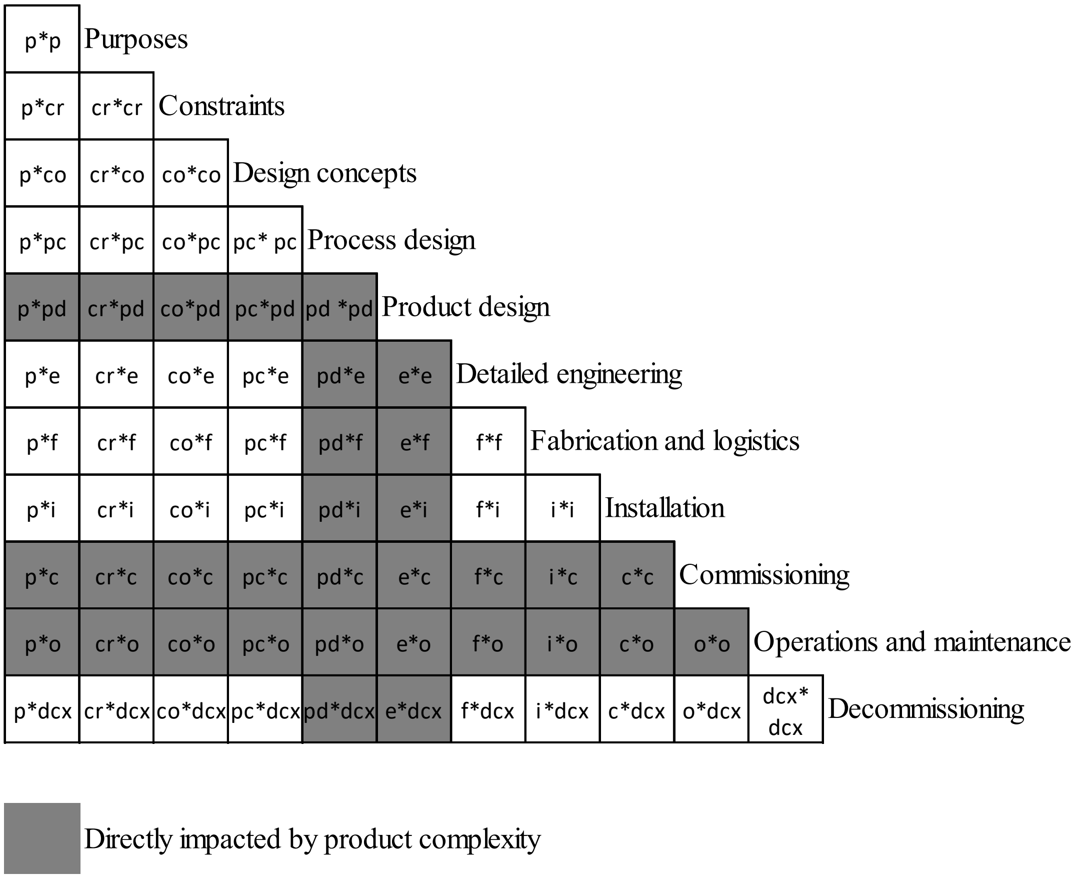


Figure 3-31: Product Complexity in Simplified LPDS-MDM Framework

Figure 3-32 illustrates process complexity in simplified LPDS-MDM framework. The shaded cells indicate which elements of the project delivery were directly impacted by process complexity. As mentioned in section 3.4 covering work sequencing as an instantiation of process complexity, poor work structuring negatively impacted project performance (commissioning and operations). Indeed, the engineer was the only one tasked with project phasing (process design). Because the GC was involved on the project much later, the engineer did not receive input on the feasibility and risks associated with the proposed phasing. In addition, the cooling tower model was selected before the project was phased, and most importantly, **before** the purposes of the project were clearly identified.

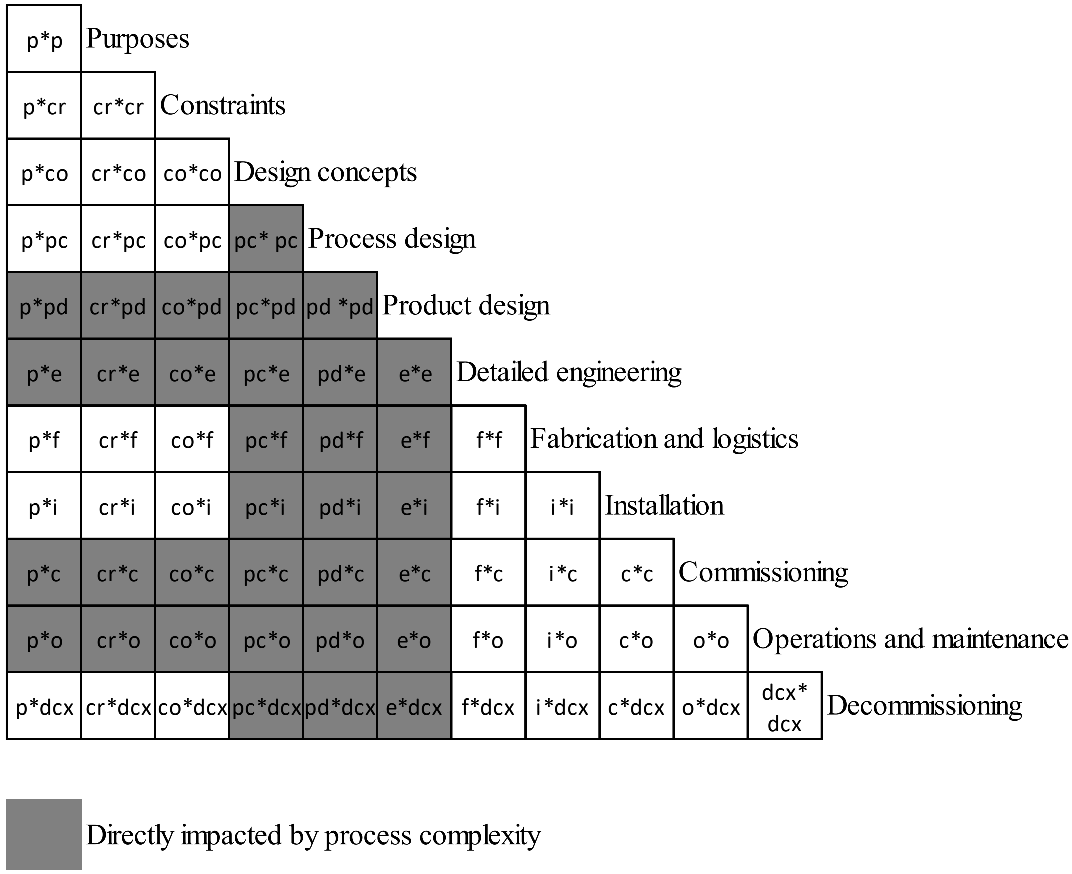


Figure 3-32: Process Complexity in Simplified LPDS-MDM Framework

Figure 3-33 illustrates organizational complexity in simplified LPDS-MDM framework. The shaded cells indicate which elements of the project delivery were directly impacted by organizational complexity. As mentioned in section 3.3.2, the organizational complexity on the project resulting mainly from the mechanistic structure of the owner's organization and the project funding mechanism imposed by DOE. In this respect, the project funding mechanism encouraged the early selection and purchase of the cooling tower (product design and engineering), which preceded the finalization of the CFR document. The objective was to capture the project purpose and requirements (purposes). The funding mechanism played a role in how decisions were made on the project: postponing activities to mitigate risk was not considered as an alternative, because the team would have run the risk of not being allocated the same amount of money the following year.

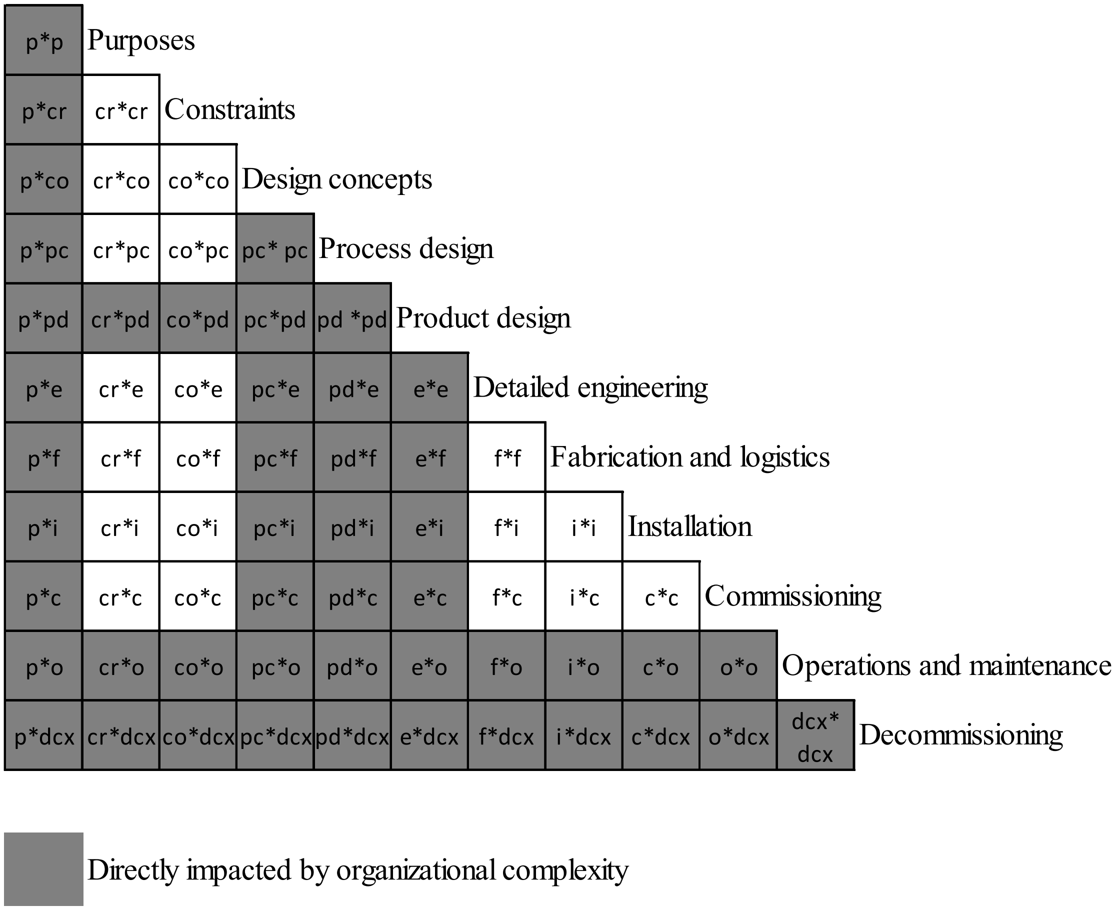


Figure 3-33: Organizational Complexity in Simplified LPDS-MDM Framework

Figure 3-34 illustrates market complexity in simplified LPDS-MDM framework. The shaded cells indicate which elements of the project delivery were directly impacted by market complexity. As mentioned in section 3.3.5, the stringent and fast evolving (at least in California) environmental regulations made the identification of purposes and constraints complex. In addition, the wide variety of cooling tower configurations, models, and brands contributed made product design and engineering complex as well.

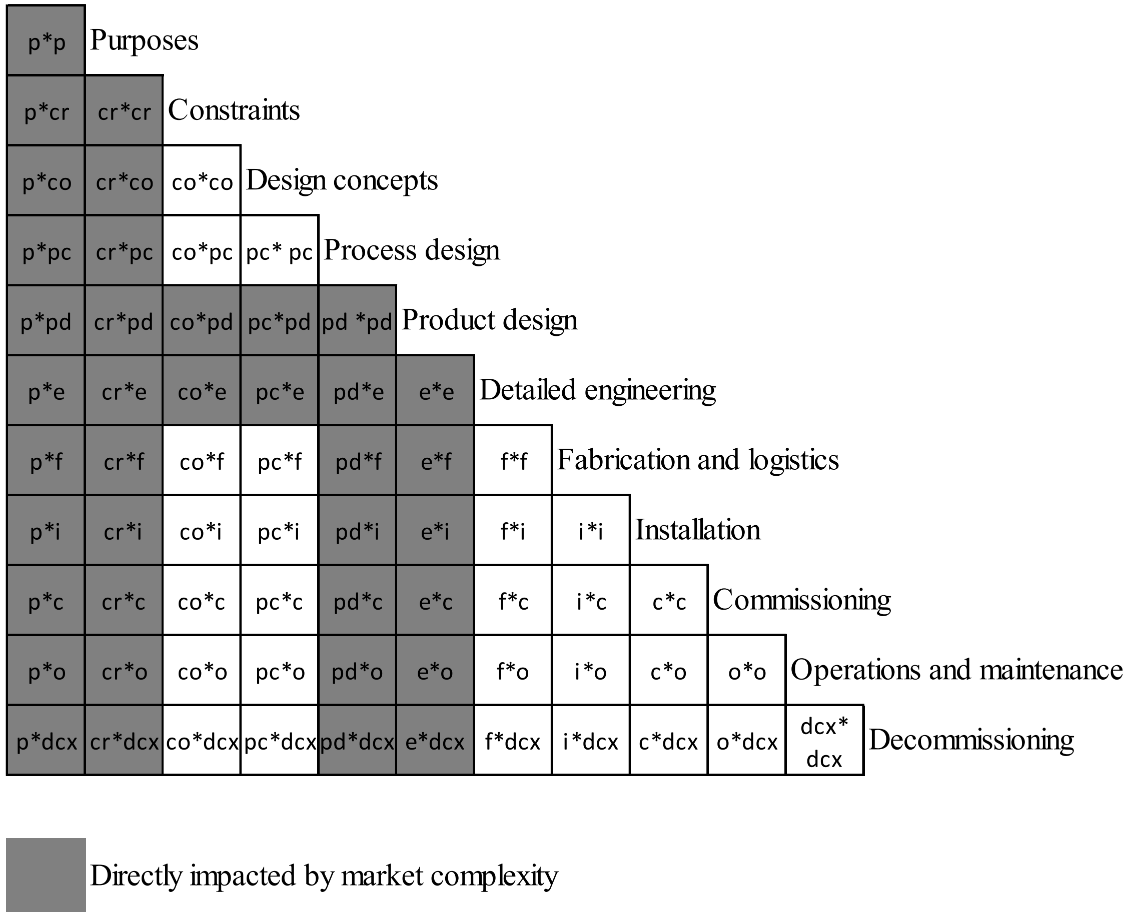


Figure 3-34: Market Complexity in Simplified LPDS-MDM Framework

The previous figures help make the case that complexity is not self-contained in one DSM or MDM, instead it spreads across multiple DSMs and MDMs (representing project delivery modules). The framework conveys the idea that lack of complexity management has consequences on the entire project delivery (as opposed to having consequences on a single project delivery module).

The previous figures also make the case that the different aspects of complexity can have a compounding effect. For example, the MDM pd * e (that is, process design * detailed engineering) is affected by product complexity (Figure 3-31), process complexity (Figure 3-32), organizational complexity (Figure 3-33), and market complexity (Figure 3-34).

In conclusion, the use of the LPDS-MDM framework can have 3 purposes: (1) learn, (2) communicate, and (3) manage. In terms of learning, the framework makes visual the mechanism of project structural complexity. In terms of communicating, the framework helps the 'observers of complexity' to communicate about it and create shared understanding about it. In terms of managing, the framework can trigger the conversations about how the project team can eliminate the non-value adding complexity and monitor the value-adding complexity.

Regarding the management of project structural complexity, the next section explores principles and tools that could have been used to mitigate the impact of structural complexity on the project.

3.6.2 LPDS Principles to Manage Complexity

The LPDS representation comprises five triads: (1) project definition, (2) lean design, (3) lean supply, (4) lean assembly, and (5) lean use (Ballard 2008).

Table 3-10 lists principles from the LPDS benchmark that are particularly applicable to the cooling tower case. Principles are from the LPDS benchmark from Ballard (2000). Columns 1-5 show to which (of the five) triad(s) a principle belongs. Column 6 formulates the principle. Columns 7 and 8 indicate which of the cooling tower selection or the steel structure re-design would have significantly benefited from implementing the principle. Column 9 describes how the principle could have been applied.

Table 3-10: LPDS Principles Applicable to Managing Structural Complexity on Cooling Tower Case

LPDS Triad	**Principle (LPDS benchmark by Ballard 2000)**	**Cooling Tower Selection**	**Comment**
Project Definition	Design criteria for both product and process will be produced.	Cooling Tower Selection	In the cooling tower selection, the Ends had not been discussed sufficiently in depth. Examples of questions that were unanswered include: "Did the project team aim at guaranteeing cooling capacity in very hot days?" "And for which level of relative humidity (since the MCWB depends on it)?" "What amount of flow is expected during the transition phase?"
Project Definition	Multiple conceptual designs will be generated and evaluated. When appropriate, more than one will be carried into the Lean Design phase	Sequencing and Steel Re-Design	The engineer presented only one design to the stakeholders. The engineer did not propose a few alternatives for how the steel structure would be anchored to the roof. Had multiple conceptual designs been generated, the project team could have been able to evaluate the risks associated with each design and thereby maybe avoid negative iteration.
Project Definition	The project definition process will include an explicit information collection and documentation process.	Sequencing and Steel Re-Design	The development of the conceptual design was carried out before gathering information on the existing field conditions (such as rebar and conduits location in the roof slab).

LPDS Triad	**Principle** **(LPDS benchmark by Ballard 2000)**	**Cooling Tower Selection**	**Comment**
Project Definition	Collaborative production and decision making will include clients and stakeholders; e.g., design and construction specialists; suppliers of materials, equipment, and services; facility operators, maintainers, and users; representatives of financiers, insurers, regulators, and inspectors.	Sequencing and Steel Re-Design	Had the GC been involved earlier in the project, it could have been able to provide feedback on the feasibility of the anchoring the steel structure into the slab in more than 80 locations. Furthermore, the involvement of the building energy manager in the phasing of the cooling tower installation would have helped the engineer and the GC identify activities that were more subject to risk, such as the tuning of the new cooling tower and vibration testing.
Project Definition	Work structuring will be applied in the project definition phase in the production of rough cut strategies and plans for project execution, linked to product architecture options, in advance of the more detailed integration of product and process design to be accomplished in subsequent phases.	Sequencing and Steel Re-Design	The significant differences between the planning DSMs and the observed-work DSM are symptoms of a lack of collaboration of project team members during the project definition phase.
Project Definition	Product and process design decisions are made simultaneously rather than first producing a design for the product, then trying to produce a satisfactory design for the process of designing and making that product.	Sequencing and Steel Re-Design	The fact that the design of the system did not allow the project team to revert back to the old cooling towers (in case of a failing new cooling tower) results from designing the product and designing the process sequentially.

LPDS Triad	**Principle** **(LPDS benchmark by Ballard 2000)**	**Cooling Tower Selection**	**Comment**
Lean Design	The Design Structure Matrix will be used to re-sequence design tasks in order to reduce needless iteration.	Sequencing and Steel Re-Design	Section 3.4 addresses this principle in depth.
Lean Design	Specialty contractors will either serve as designers or will participate in the design process, assisting with selection of equipment and components and with process design.	Cooling Tower Selection	The cooling tower manufacturer was not involved during the selection of the cooling tower.
Lean Design	Design decisions will be deferred until the last responsible moment if doing so offers an opportunity to increase customer value.	Cooling Tower Selection	The cooling tower selection happened very early on the project. At the time, the project team and stakeholders had still not made other decisions that were interdependent with the choice of cooling tower (such as sizing new heat exchangers).
Lean Design	Process design will have addressed buffer type, location, and sizing. That will be further detailed and then controlled in this phase, in which the ’iterative’ relationship among the modules within the phase are more like continuous adjustment than like the generative conversation characteristic of design proper.	Sequencing and Steel Re-Design	The DSMs representing the sequences of activities as planned by the engineer and the GC did not take into account any time buffers. As a result, the observed sequence of work significantly differed from the plans.

LPDS Triad	Principle (LPDS benchmark by Ballard 2000)	Cooling Tower Selection	Comment
Lean Supply	We will develop the technique of in-process inspection both in shops and at sites.	Sequencing and Steel Re-Design	Because the team did not expect the experienced performance of the cooling tower, they tried to identify the reason for the deviation in performance. In the troubleshooting process, they questioned whether or not the recently installed pumps had been actually delivered with the right impellers. As a result, they took advantage of a 2-day shutdown window to disassemble the pumps and check their impellers, all of this to realize that the right impellers were installed. This inspection could have happened upstream of the supply chain, before the installation of the pumps.
Lean Assembly	We will encourage incorporation of First Run Studies into assembly lookahead processes, measure their benefits, and link feedback to project definition, design, and supply	Cooling Tower Selection	The duration of the activities related to the start-up of the old cooling towers were unknown to the project team. Those could have been measured prior to proceeding with the transition from the old cooling towers to the new one (during an ALS shutdown window for example).

3.6.3 Discussion on the LPDS-MDM Framework

The LPDS-MDM framework offers a visual and concise view of the interdependences between the 13 modules that constitute the LPDS. The MDM is composed of 66 matrices in total, of which 11 are DSMs capturing the interdependences within a same module and 55 are DMMs capturing the interdependences between two different modules.

However, populating the entire LPDS-MDM would take a significant amount of time due to its large size. This motivates the researcher to propose the approach as follows:

- **Step 1:** At the beginning of a project, the project team identifies how the five aspects (customer, product, process, organizational, and market) of structural complexity could manifest themselves on the project.
- **Step 2:** The project team colors up the DSMs and DMMs of the LPDS-MDM framework that could be affected by each of the five aspects of structural complexity.
- **Step 3:** For each colored up LPDS-MDM framework, the project team determines which principles (ideally all) from the LPDS to implement on the project to manage the complexity captured by the colored cells.

Thus, for use at a higher level (as done previously), the LPDS-MDM framework is useful to understand, at a glance, the impact of five aspects of structural complexity on the project delivery. It also helps identify principles from the LPDS that can help mitigate such complexity.

3.7 Conclusions

In the cooling tower case, structural complexity manifested itself in five aspects: (1) customer, (2) product, (3) process, (4) organizational, and (5) market. These five aspects are relevant for any type of facility upgrade on large campuses. The types of organizations operating on large campuses share characteristics: their structure is usually mechanistic, they lack a formal decision-making system, they house a wide range of programs (and hence customers), and they highly rely on facility plants to serve their buildings on a continuous basis. On the cooling tower case, these factors have contributed significantly to the project complexity.

The cooling tower case also showed how DSM could help model the structural complexity on a project as shown through the comparison of the "planning" and work-observed DSMs. The lack of anticipation of complexity on the project led to unplanned iterations. Furthermore, the LPDS-MDM framework helped bring the analysis of structural complexity one step further: it allowed to (1) understand how complexity encountered in one module spreads across all the other modules because of the interdependences between those modules, and (2) identify strategies and principles from the LPDS that could have been implemented to manage complexity on the project.

4. SUPERCOMPUTER FACILITY CASE

The goal of this chapter is to document a second case study, that is, the Shyh Wang Hall, also known as the Computational Research and Theory Facility (CRTF) named here the "supercomputer facility case" at the Lawrence Berkeley National Laboratory (LBNL). The chapter describes how the facility failed to deliver value to occupants. The analysis of the Value Engineering (VE) process shows how the poor management of dependences contributes to FM failure.

The chapter is organized as follows. Section 4.1 presents the project background. Section 4.2 describes the research methodology followed, namely case-study research, to collect data and analyze the supercomputer facility case. Section 4.3 explains the design intent. Section 4.4 describes the problem selected for this study. Section 4.5 illustrates five aspects of structural complexity met on the project. Section 4.6 expands on one instantiation of process complexity, that is, the design process and compares it against Target Value Design (TVD), a Lean design management method. This allows to identify some shortcomings of the design process. Section 4.7 concludes this chapter.

4.1 Project Background

4.1.1 Project Overview

The scope of the case study is the VE undertook during the design of a new building, the CRTF, located near the main entry of LBNL. A need for this building was to support collaboration between the University of California (UC) Berkeley, the National Energy Research Scientific Computing Program (NERSC), and LBNL through co-location of academics, researchers, and students from the three institutions. Another motivation was the need for more space, more power and newer infrastructures, so far constrained at the Oakland Scientific Facility. A third motivation was to provide High Performance Computing (HPC) with higher energy efficiency.

The building (Figure 4-1) is approximately 150,000 gross ft^2 (13,935 gross m^2); with 83,000 usable ft^2 (7,711 usable m^2) and can accommodate approximately 300 occupants.

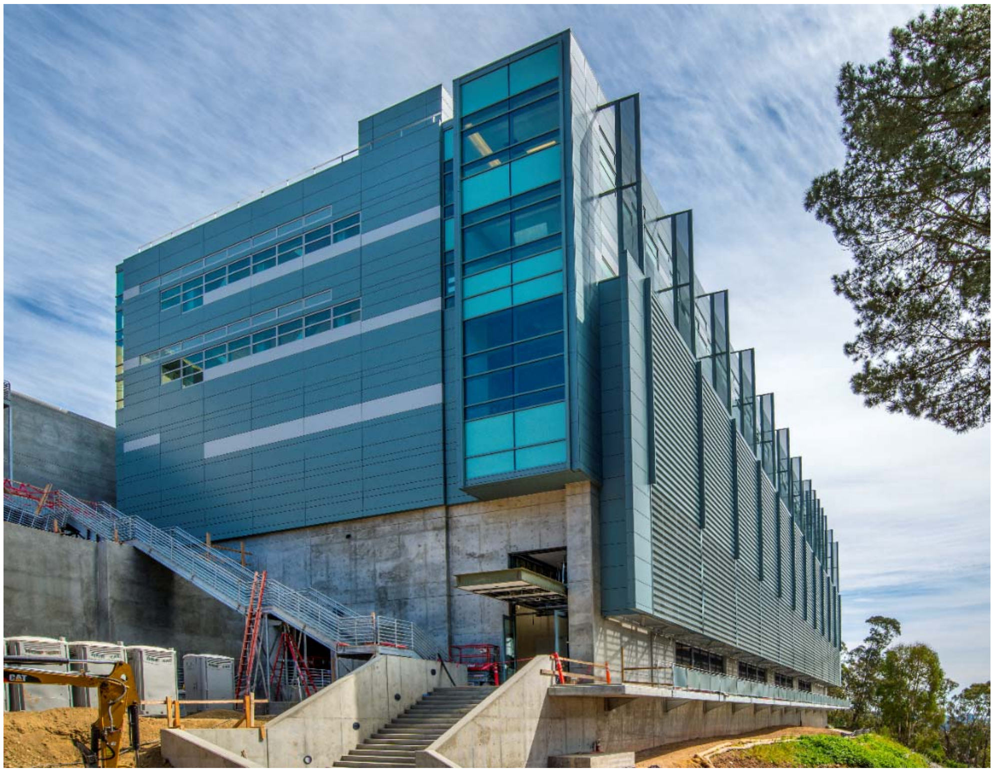


Figure 4-1: CRTF in April 2015 (LBNL 2015a)

The CRTF houses:

- A mechanical, electrical, and plumbing support space of 26,000 gross ft^2 (2,415 gross m^2) on the ground floor.
- HPC on the level above of approximately 27,500 usable ft^2 (2,555 usable m^2). HPC is "the application of supercomputers to scientific computational problems that are either too large for standard computers or would take them too long" (NERSC 2016). A supercomputer essentially consists of a very large number of desktop computers wired together.
  - The HPC floor is composed of two HPC system areas (NERSC-7 and NERSC-8), a common area in the middle which houses support systems, and an area not built out yet on the North.
- Offices on the two upper floors totaling 70,000 gross ft^2 (6,503 gross m^2).
  - These floors primarily comprise offices (partitioned and open plan), conference rooms, visualization lab, and Building Distribution Frame /Independent Distribution Frame rooms.

4.1.2 Project Structure, Team, and Project Delivery Method

The project was delivered by joint venture between the Department of Energy (DOE), LBNL and UC Berkeley. It was funded to the amount of approximately $20M by DOE and $142M by UC Berkeley. As a clarification, buildings on LBNL campus and the land are owned by UC.

LBNL is operated by UC Berkeley under a contract with DOE. This means that DOE directs UC Berkeley to accomplish the missions and programs assigned by DOE.

The delivery method was a Construction Manager/General Contractor (CM/GC). LBNL contracted with a CM/GC and with an architect/engineer.

Figure 4-2 captures the CRTF project delivery structure. Because UC Berkeley and DOE are two separate entities, it meant double reporting (to UC Berkeley and DOE) on behalf of LBNL project management team, which contributed to the organizational complexity.

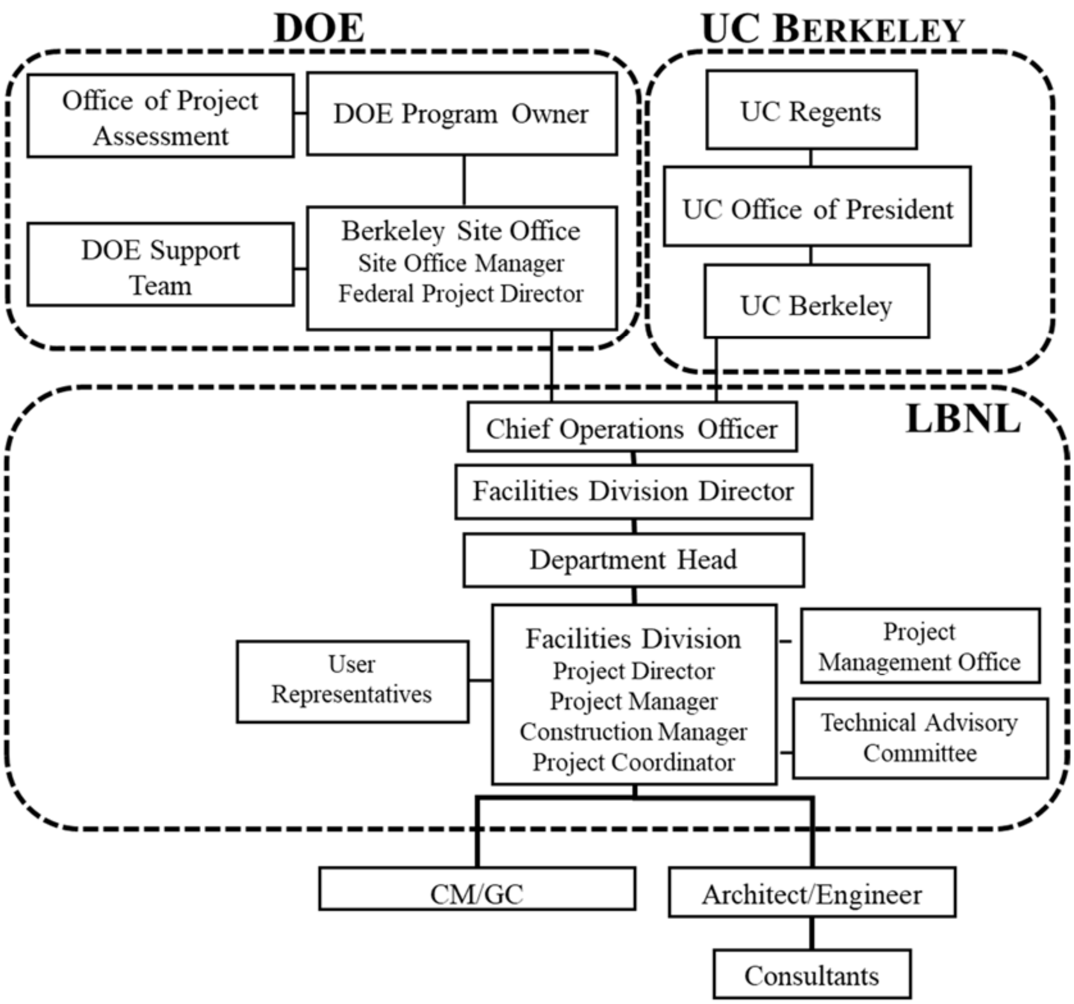


Figure 4-2: CRTF Project Delivery Structure (LBNL 2015b)

The architect/engineer was Perkins and Will (P+W). P+W hired multiple consultants such as the engineering firm ARUP for energy performance analyses and mechanical engineering design, and Degenkolb was the structural engineer for the raised floors. The CM/GC was DPR Construction. The cost estimator was Cumming Corporation. LBNL also hired multiple consultants: a civil consultant (BKF), a landscape consultant (CMG), a structural consultant (Dasse Design), an air movement and cooling consultant (ANCIS), a mechanical, engineering, plumbing and fireproofing consultant (EYP), etc.

Although not shown in the project structure, NERSC program was a critical project stakeholder and customer as described in the next section.

4.1.3 National Energy Research Scientific Computing Program (NERSC)

NERSC belongs to the US DOE Office of Science. NERSC started under a different name (Controlled Thermonuclear Research Computing Center) and a different mission in 1974 at the Lawrence Livermore National Laboratory (LLNL) when defense research made a supercomputer available for fusion energy research (NERSC 2017). From 1974 to 1996, the research program changed name and research mission multiple times. It was eventually named the National Energy Research Scientific Computing Center (NERSC) in 1996 with the mission to "accelerate scientific discovery at the DOE Office of Science through high performance computing and data analysis" (NERSC 2017). The NERSC computing system moved from LLNL to the Oakland Scientific Facility in downtown Oakland in 2000.

Over the years, NERSC has upgraded its supercomputers several times to keep up with technology breakthroughs. The Cray XE6 (NERSC-6) named Hopper after the computing scientist Grace Murray Hopper was the last system to "retire" at the Oakland Scientific Facility before NERSC was relocated. Hopper had more than 150,000 processor cores. The peak theoretical performance of the system was 1.05 petaflops (one thousand million million, or 10^{15}, of "floating point operations" per second) (NERSC 2017).

Currently, the supercomputer systems housed in the facility are:

- Edison (NERSC-7), a Cray XC30. Cray XC30 was named after Thomas Alva Edison, an American scientist and inventor. Its peak performance is of more than 2 petaflops (NERSC 2017).
- Cori (NERSC-8), a Cray XC40. Cray XC40 was named after the American biochemist Gerty Cori, the first American woman to win a Nobel Prize. Its peak performance is of about 30 petaflops (NERSC 2017).

Today, NERSC supports 6,000 users from 48 states. HPC has allowed researchers from various field to make scientific discoveries (NERSC 2017).

4.1.4 Project Timeline

The project definition started in 2004. At the time, a budget of $90M was established for the proposed scope. However, the allowable cost was deemed too low with respect to the scope (estimated at $132M) and the project team was consequently asked to re-scope the project within the allowable cost, a targeted start of construction in 2008 and a project completion in the first quarter of 2011. UC Regents approved the budget of $90.4M in May 2007. The same year, the design was revised to take into account anticipated Air Cooled technology. As a result, the building structure and systems design changed significantly. In May 2008, the Regents approved an increase of $22.5M in budget to accommodate the increase in project scope including: energy efficient cooling, additional power capacity, additional offices, revised foundation/shell, and a doubling of the computer floor loading requirement from 250 lbs/ft^2 (1220.6 kg/m^2) to 500 lbs/ft^2 (2441.3 kg/m^2).

From 2008 to 2011, the project was at a standstill because of a lawsuit initiated on the ground of infringement of the National Environment Policy Act (NEPA).

In 2011, project estimates were still over budget, which forced scope reduction, extensive VE, and staff reduction. Site work started in November 2011. In July 2014, the budget was increased by an additional $18M to adapt the scope to improvements to the electrical safety program and protocols, infrastructure changes to support programmatic changes, sustainable heating, and added costs resulting from schedule delays.

In terms of the project's construction, foundation work started in the summer 2012, along with the site preparation work for the cooling towers. These were followed by the construction of concrete walls, the structural steel, the elevated deck pours, and the exterior skin system. The interior buildout including the penthouses at the roof level, the overhead rough-ins and the interior walls started early 2014. The finishes started in the summer 2014. Start-up and commissioning started in March 2015. Construction was completed in May 2015. Occupants started to move in before the HPC systems were installed.

The next section presents the research methodology adopted to analyze project structural complexity and its impact on the value delivered to customers.

4.2 Research Methodology

When the researcher informed LBNL that she was interested in studying facility upgrades and structural complexity, LBNL upper management recommended the CRTF project as a case study.

Similar to the cooling tower case, the researcher used case-study research to create knowledge from the supercomputer facility case. As mentioned, she worked at LBNL as a Graduate Student Research Assistant from January 10, 2017 to December 15, 2017, which facilitated data collection and analysis. It also gave her the opportunity to tour the supercomputer facility twice with a LBNL project manager, who was familiar with the project.

Unlike the cooling tower case, data collection for the supercomputer case happened post-project, since the CRTF project was completed in May 2015. However, all project documentation from the owner, the GC, the Architect, and consultants was available on the shared network at LBNL, which allowed the researcher to retrace the project history with the help of LBNL project managers, who had been involved in the project.

Similar to the cooling tower case, the supercomputer facility case research took place in two phases: (1) an exploratory phase from April 2017 to June 2017 and (2) an explanatory phase from July 2017 to October 2017.

The next section explains the design intent, which will help understand the problem selected for this study.

4.3 Design Intent

The project objectives guided the design intent. The project objectives were threefold: (1) be "a model of HPC" (Wilson and Sartor 2010), (2) be flexible so as to meet increasing HPC needs in the future (ARUP 2008), (3) be a "showcase for energy efficiency" (ARUP 2008, Wilson and Sartor 2010), and (4) be cost efficient (ARUP 2008).

Designing energy efficient data centers is no easy task. Indeed, high performance computers can consume up to 1MW. Thus, "the CRT will use 50-100 times more energy than a standard office building of same size" (Page 7 in ARUP 2012). To tackle this challenge, practitioners developed metrics to assess data centers' energy efficiency (e.g., Data Center infrastructure Efficiency (DCiE), Power Usage Effectiveness (PUE)). DCiE is the ratio of the energy use of the IT equipment to the energy use of the facility. It is expressed as a percentage: the higher the percentage, the more energy efficient the data center infrastructure (Figure 9-7 in Appendix defines DCiE). For the CRTF, DCiE was set at 83%, which constitutes a relatively ambitious number in comparison with DOE existing data centers (Greenberg et al. 2009, Wilson and Sartor 2010). Being more environmental friendly is not the only driver for the design. Cost is another driver: "the US DOE supercomputer system uses an aggregate $100 million of energy annually, and that number is rising rapidly" (Wilson and Sartor 2010).

Because supercomputers cooling schemes are likely to change in the future (air cooling to liquid cooling or a combination of both), the infrastructure must be flexible to accommodate those different cooling schemes. The next paragraphs describe the design intent for HPC systems cooling and office heating.

4.3.1 HPC Systems Cooling

CRTF relies on large Air-Handling Units (AHU) for air-cooling. AHUs are located in the mechanical room on the ground floor (Figure 4-3). They suck cool Bay Area air up from the West side of the building. The ductwork channels this supply air to the HPC raised floor plenum.

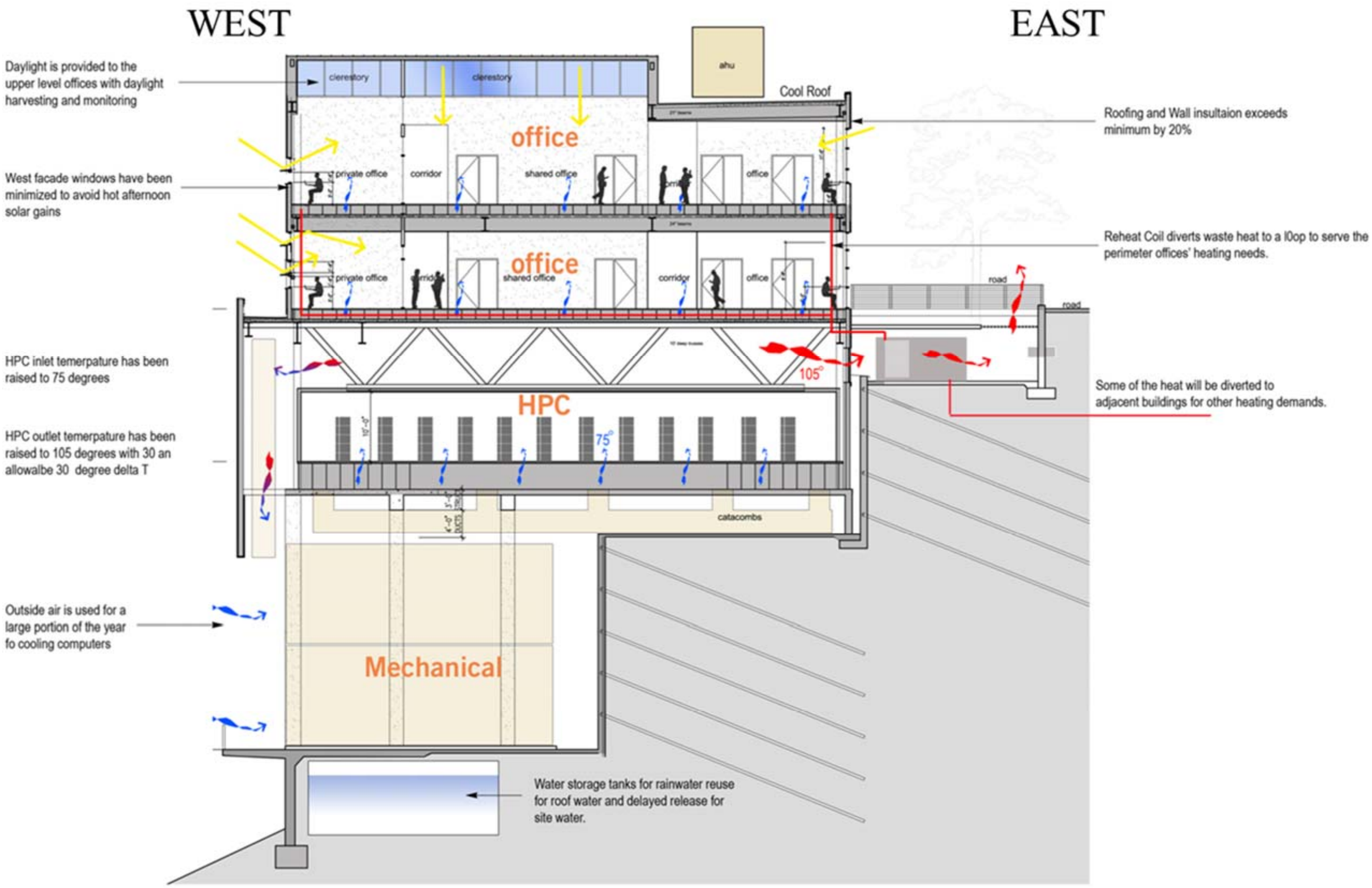


Figure 4-3: Illustration of Design Intent for Heating and Cooling System at CRTF (Page 7 in ARUP 2012)

The air is then supplied to the IT equipment to cool it (Wilson and Sartor 2010). CRTF can rely on cooling towers (closed-loop cooling water) to provide liquid cooling in the future. This approach, relying on outside air and evaporative cooling (through the cooling towers), is called "free" cooling. The advantage of using such cooling approach is that it uses only 1/3 of the energy that an equivalent system using chillers would have required. The design team assessed this design to be compatible with Bay Area weather conditions (temperature and humidity) all year long.

4.3.2 Office Heating

CRTF being a mixed-use type of building (i.e., including offices, not only supercomputers), the design must ensure occupant thermal comfort as well. The design relies on the heat generated by the HPC floor to heat the offices in the above floors. The hot exhaust air is discharged out through the East face of the HPC floor via dedicated exhaust fans (Figure 4-4). Some of it is re-used to dehumidify the inlet air of the HPC floor. The rest is used to heat the upper floors. The heat from the exhaust air is collected by heat reclaim coils placed at the end of HPC. The heat recovery coils will run at 80 ºF (26.7 ºC) (Entering Water Temperature) and 100 ºF (37.8 ºC) (Leaving Water Temperature).

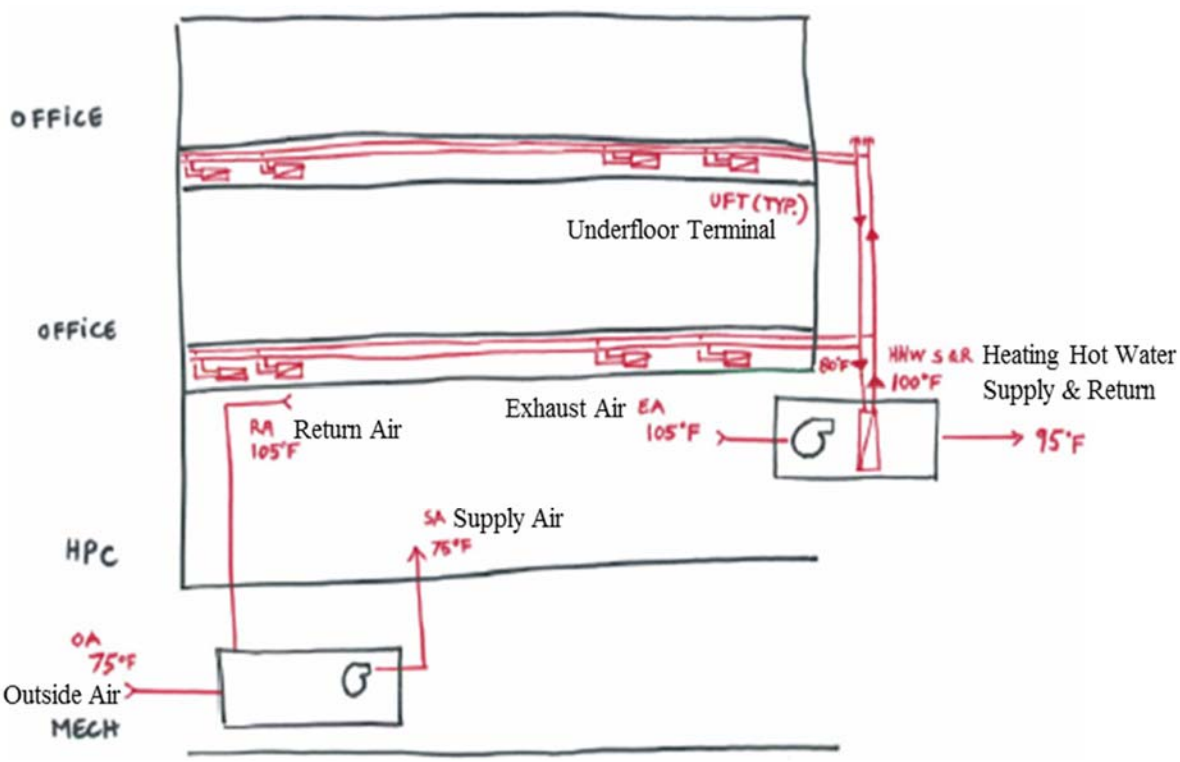


Figure 4-4: Design Intent for Heat Recovery (Page 30 in ARUP 2012)

In this respect, Wilson and Sartor (2010) write:

“Of course, given that over 80% of the 17 MW entering the CRTF will be converted to heat by the IT equipment, and with discharge air temperatures of about 100°F, there is significant opportunity to recover and use this heat.” They further add:

“There will be so much waste heat available from the CRTF that it could heat a whole cluster of nearby buildings, replacing the heat now provided by their natural gas-fired boilers.”

Thus, the design team (incl. mechanical engineering design consultants) was expecting that so much heat would be generated that it would be able to not only heat the office levels but also be used for other buildings. The next section describes how the actual performance fell short of expectations.

4.4 Selected Problem for Study

After the design was finalized, the University ordered the addition of a heat pump on the roof, because they realized that the occupants would move into the building before the complete installation of HPC systems. Following the start of occupancy, occupants at the office levels complained that the office space was cold, despite the installation of the heating system toward the end of the project.

The next section answers the question: “How did five aspects of structural complexity manifest themselves in the supercomputer case?” Answering this question reveals that (1) some project structural complexity is self-inflicted and (2) failure to meet customer requirement is caused by a lack of management of structural complexity.

4.5 Aspects of Structural Complexity on the Project

4.5.1 Customer Complexity

In the next sections, “customers” or “project stakeholders” are used interchangeably and refer to the group of individuals composed of: (1) research divisions and programs such as: NERSC, the computation research division, the scientific networking division, the Computational Science and Engineering program at UC Berkeley, (2) DOE, (3) UC and UC Berkeley, (4) research support staff, (5) maintenance staff (LBNL Facilities Division), and (6) IT and technology support staff.

In the customers listed, NERSC program was critical. Actually, the program was a central piece to the project as reflected in the design: the heating and cooling systems were all sized based on the HPC systems’ expected performance range:

“Employees in more than one office have come to blows over the Heating, Ventilating, and Air Conditioning (HVAC) settings. However, this situation is even more intense when a large number of your occupants are finicky supercomputers that will simply go on strike if the temperatures get too hot.” (Wilson and Sartor 2010).

Because of the high financial investment that such a system required, it made it difficult for the design team to consider NERSC needs and occupant needs as equally important to satisfy.

“Since the computing sciences group that will occupy the building is judged on computational output, there was strong incentive to maximize the amount of energy available for computational work and to minimize the infrastructure loading.” (Greenberg et al. 2009).

What was therefore particularly complex on this project for the design team was to deliver a design that would meet both supercomputers’ (uncertain, due to changes in technology) and occupants’ needs, although the project objectives (as formalized in the project documentation reviewed) emphasized meeting supercomputers’ needs. Additionally, needs vary with time: they are dynamic. On the CRTF project, needs expressed in 2004 when the project was initiated were likely very different from needs in 2015 when construction was completed.

Customer complexity is recurrent on projects. Aspects can be decomposed into: (1) needs prioritization, (2) conflict resolution, and (3) finding the ‘right’ representative of each users group. Although these aspects are commonly encountered on relatively large construction projects, they had a compounding effect with other aspects of complexity surrounding the design process.

4.5.2 Organizational Complexity

Non-symmetrical team structures and people turnover contributed to the project organizational complexity.

It is common on construction projects that each team develops its own internal structure. Each member of the team agrees to a specific project scope (structure, envelope, finishes, etc.) or a process to handle (change orders, RFI, etc.). The structure of a given team (such as LBNL’s) does not necessarily match one on one with the structure of the other team (such as GC’s), hence the terms “non-symmetrical” team structures. This can have advantages (e.g., people on each team have different skill sets: while one person may be good at doing A and B on one team, another person may be good at doing B and C on the other team) and disadvantages.

On the CRTF project, LBNL’s team was composed of seven people (names encoded from A to G), who shared responsibilities in cost control, schedule control, quality control, and “miscellaneous” (Table 9-29 in Appendix). Some scopes were overlapping. For example, both A and B were responsible for the monthly budget and contingency updates in cost control. In quality control, both C and D were responsible for submittals. On the GC side, the scope was divided between 12 team members (names encoded from 1 to 12). Team member 8 was responsible for some of the scope of A, B, C, F and G in LBNL’s team. Similarly, team member 9 was responsible for some of the scope of A, B and C.

On the project, flows of information were thus complicated and could quickly become complex (cf. Cynefin).

People turnover is frequent on projects that span many years, and even more so on projects that are interrupted. Both were the case on the CRTF project. When the CRTF project resumed, new people joined the team since former team members had been demobilized and assigned to other projects. This impacted information flows. People who are new to the project may be unaware of critical discussions that happened earlier, etc., which makes team members unequal in terms of project knowledge and understanding.

4.5.3 Product Complexity

Product complexity on the project was induced by the numerous interdependences between the mechanical, plumbing, HVAC systems (the interdependence between the system serving HPC and the office levels), and HPC systems.

Supercomputers are complicated pieces of equipment. Researchers, manufacturers, engineers are continuously improving their performance (e.g., through increased chip density). Faster supercomputer models have been released almost every year for two decades**.** Consequently, an accurate anticipation of energy/power demand at the time of the design (the CRTF design started in 2007 and the first of the two supercomputers was installed in 2015) was almost impossible.

Since better performance is accompanied with an increase in heat dissipated, supercomputers require that a lot of energy is used to make them remain within an operating temperature range. Significant research effort in HPC designs is geared toward exploring heat mitigation strategies. To this date, a handful of strategies exist to dissipate heat. They can be air cooling-based, liquid cooling-based, or a mix between the two.

Practitioners have looked at allowing HPC systems to operate at higher temperatures to save energy and costs on the cooling. In fact, "choosing the environmental conditions (temperature and humidity) acceptable for supercomputer operations can be tricky" (Wilson and Sartor 2010). The temperature at which a supercomputer runs optimally varies from one model to the next. This poses a challenge when designing a facility that must be able to accommodate regular supercomputer upgrades (i.e., every three to five years).

For the CRTF design, Wilson and Sartor (2010) report that LBNL invited supercomputer vendors to discuss whether the environmental conditions recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) could be used for the design of mechanical systems. The concern was that some of the supercomputers on the market required more stringent conditions. The vendors validated ASHRAE recommended ranges.

This discussion led ASHRAE data center committee to broaden the recommended ranges (Wilson and Sartor 2010) (from Figure 4-5 to Figure 4-6). The following text accompanied the figures (P+W 2014):

"To reduce the operational cooling energy of HPC, the allowable supply conditions were expanded beyond the recommended ASHRAE range but within the ASHRAE allowable range. The air systems are thus design for a CRT specific supply range 60°F - 75°F (15.6°C - 23.9°C) design-bulb, 30% - 70% relative humidity."

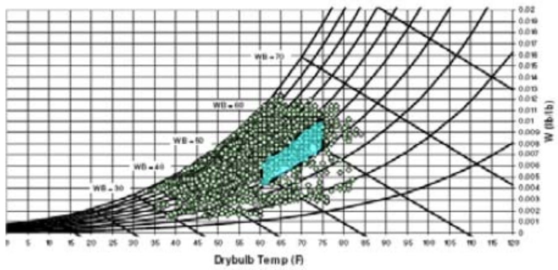


Figure 4-5: ASHRAE ‘Recommended’ and ‘Allowable’ Class 1 Operating Conditions (P+W 2014)

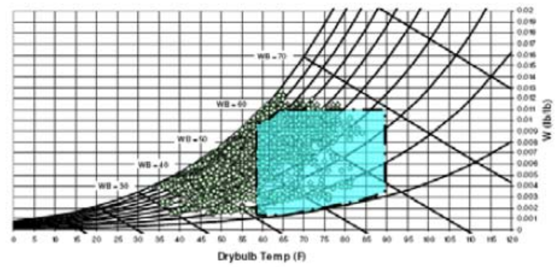


Figure 4-6: CRTF Operating Conditions (P+W 2014)

4.5.4 Process Complexity

The project design process is an instantiation of process complexity. This section describes the timeline and the challenge faced by the team to steer the design to the project allowable cost. It further explains how a project objective (i.e., making the design flexible) contributed to process complexity.

The design of the project started in 2007 with a construction budget of $76 million. VE efforts lasted from 2007 to 2012 (with an interruption during LBNL’s trials). When Cummings updated the estimate in August 2009, it was still $3-5 million above the allowable budget. In December 2009, the team considered removing two air handlers, and 4 exhaust fans for an approximate saving of $2 million. In September 2010, a heat recovery study by ARUP pushed the VE effort even further and explored different alternatives of heating system designs. The design was put out for bid in winter 2010-2011. However, the bids received by CM/GC aggregated to $88 million, which meant that more than $10 million saving in VE had to be carried out in order to bring the estimate under the allowable cost. Since the project team deemed the effort infeasible, they decided to kick off the redraw of the CRTF project in May 2011, with a rebid planned in November 2011. Due to the realization that the project scope and allowable costs were not reconcilable, some scope was removed and put in bid alternates to be funded and described in a separate DOE Project. Many of the alternates consisted of mechanical and electrical equipment removed from the CRTF Project scope and transferred to the DOE Project scope.

An additional complexity to the design process was to make the design flexible for future expansion, supercomputer systems upgrades, and changes in supercomputer cooling strategies (ARUP 2008, Wilson and Sartor 2010). The design team knew that supercomputer upgrades would be frequent: “it is our understanding that the NERSC systems are replaced every 3 years and each system can be procured from a different vendor.” (ARUP 2008). This represented a significant uncertainty for the design, since “it is impossible to know the number and type of computers that will inhabit the building over its lifespan” (Wilson and Sartor 2010). As a result, the design team developed a “modular” design for future flexibility and adaptability (Greenberg et al. 2009, Wilson and Sartor 2010)

4.5.5 Market Complexity

The stringent environmental regulations and some public opposition to the project contributed to the market complexity. In March 2009, the federal judge restrained LBNL from proceeding with the construction of the CRTF until LBNL's trial, which was scheduled to take place 6 months later. The legal action was filed by a group of local citizens called "Save Strawberry Canyon." The defendants included DOE, the Secretary of Energy, the director of LBNL and the UC Regents. The group claimed that LBNL was trying to avoid complying with the National Environmental Protection Act (NEPA) and that LBNL deemed complying with the California Environmental Quality Act (CEQA) sufficient.

From a legal perspective, if CRTF is serving federal needs (that is, a "major federal action"), it is subject to federal control and thus compliance with NEPA. Save Strawberry Canyon (plaintiffs) argued that a motivation for this project was to house DOE's high-performance computers currently located in Oakland at the National Energy Research Scientific Computing (NERSC) center and the CRTF would constitute therefore a federal project.

The Court's decision was to stop construction until DOE conducted a NEPA review. The NEPA review was completed in March 2011. However, the same group filed suit challenging the accuracy of the NEPA document. Construction was stopped again. The hearing on the subsequent NEPA challenge took place on October 20, 2011. The Court's judgment was in favor of DOE and the University on November 14, 2011. It allowed the project to resume construction.

4.6 Instantiation of Process Complexity: Value Engineering (VE)

VE is a design management practice used in construction to reduce total project cost. If the team realizes that the project cost estimate exceeds the allowable costs after detailed engineering has started, the design team along with their engineering consultants are instructed to carry out VE. VE is "applied at phase transitions" (Tuholski 2008). For simple buildings, VE might be straightforward. For the CRTF, the VE process was complex.

To cut energy costs, the design team worked on several optimization studies. Figure 4-7 captures names of optimization studies as formulated in ARUP's presentation (2012).

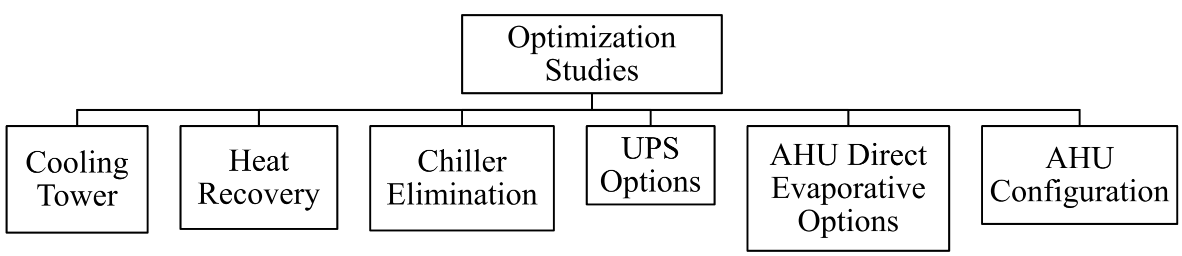


Figure 4-7: Optimization Studies to cut Energy Costs on CRTF project (after page 36 in ARUP 2012)

In their presentation, the design team explained that they chose Life Cycle Cost (LCC) as 'the evaluation criterion' for prioritizing the optimization studies. LCC enables to compare the cost of ownership of alternatives:
"Decisions and selections were based on energy and/or life cycle cost performance of select individual systems as well as whole building."
In other words, the design team prioritized their VE efforts. They displayed the optimization studies in an 'LCCA decision matrix.' The horizontal axis indicates the level of complexity (or simplicity) of a study. The vertical axis indicates the potential cost impact of a study to the project. This analysis led the team to first conduct studies in quadrant I, then the ones in quadrant II, etc.

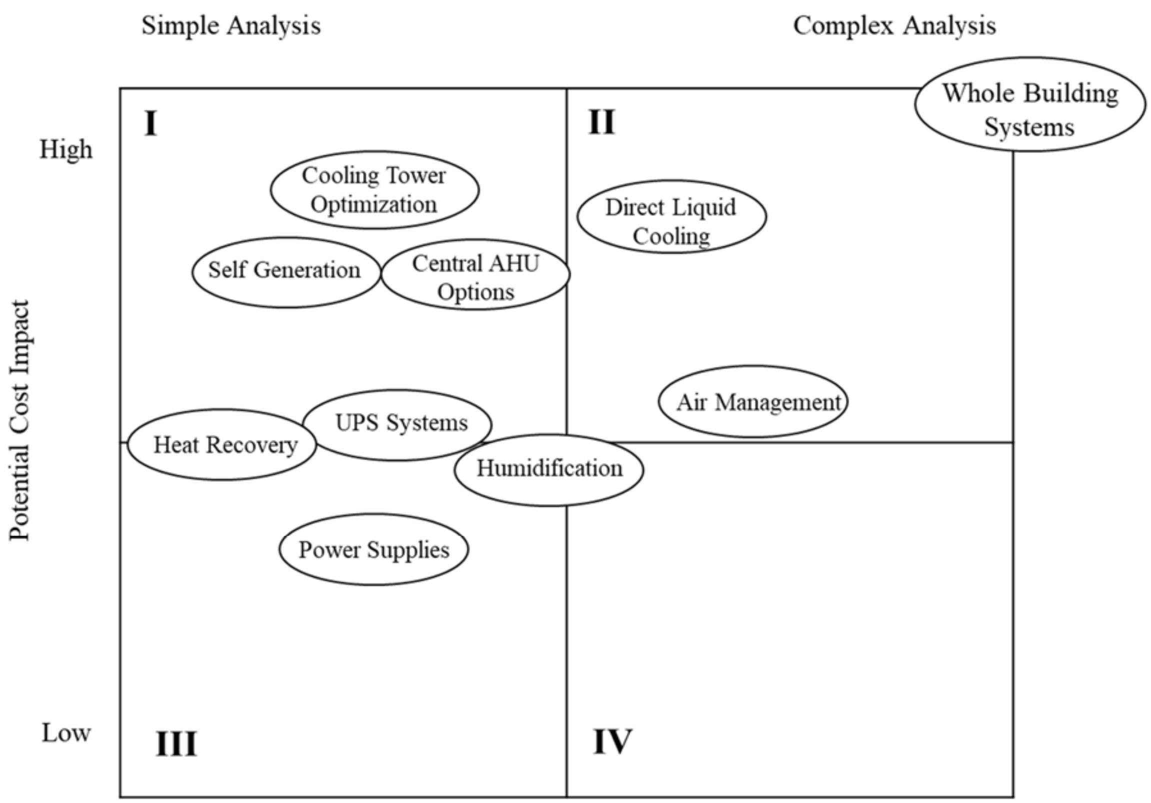


Figure 4-8: LCC Analysis Decision Matrix for Prioritizing Optimization Studies (Page 18 in ARUP 2012)

Interestingly, the 'heat recovery' analysis is on the 'simple' side of the matrix. If the analysis was simple, why did the heat recovery not meet customer requirements on the project? Could it be that the heat recovery analysis was more complex than the design team thought? Could it be that the design team did not see some dependences between the heat recovery analysis and other project aspects (e.g., customer, product, process, organization, market)? Could it be that the team did not assess the uncertainty surrounding the assumptions made for the analysis?

The next paragraphs describe how the decision was made to discard the installation of a boiler that could have complemented the heat-recovery system.

4.6.1 Boiler Elimination Decision

Concerning the VE effort targeting the heating system, a basis of design dated from 2007 read:

"A natural gas fired boiler plant shall be provided to meet peak heating system loads should heat reclaim systems be unavailable. Two high efficiency boilers will be provided 'Day One' with each boiler capable of carrying 50% of the load. In the 'Day Two' installation a third boiler will be provided to provide an N+1 arrangement (3 boilers at 50%)."

Yet, in 2010, the mechanical consultants started to consider eliminating the boiler: "The study explored multiple options for heating systems design at CRT including possible elimination of boiler and potential for inter-connecting with building 70 for exchange of heating hot water." More specifically, "Return air is mixed with cold outside air to provide desired supply air conditions for the HPC floor during winter months. No other heat source is needed for the HPC floors." In 2013, the team was reconsidering the addition of a boiler.

The presentation materials by ARUP (2012) included a matrix showing the alternatives ('potential system scenarios,' terms used by the design team) considered for the heating system (Table 4-1). They were:

- *"Basecase*: On-site boiler only (no heat recovery from HPC)
- *Option 1*: Heat recovery from HPC and no on-site boiler
- *Option 2*: Heat recovery from HPC and on-site boiler for back-up
- *Option 3*: Heat recovery; no on-site boiler and interconnection to Building 70 heating plant for back up."

Table 4-1: Decision on Boiler Elimination based on Payback Period (Page 41 in ARUP 2012)

Description	Basecase	Option 1	Option 2	Option 3
Description	- On-site Boiler - **No** heat recovery from HPC	- **No** on-site Boiler - Heat recovery from HPC	- On-site Boiler - Heat recovery from HPC	- **No** on-site Boiler - Heat recovery from HPC - HHW S&R piping to Bdg 70 for heat rejection - same piping to be used for back-up HHW from Boiler
design intent	traditional design with efficient condensing boilers	heat recovery from HPC results in significant operational energy & cost savings	heat recovery from HPC conditions Office floors in normal mode, boiler is installed for back-up	- bdg 70 heating plant has extra capacity and will act as back-up to CRT, - per current CRT design, low-grade captured heat from HPC does not suit existing systems (AHU coils, VAV coils) at bdg 70
Total Capital Cost Premium	-	$334	$124,100	$240,734
Annual Energy Cost Savings	-	$2,278	$2,278	$2278 +
Simple payback		< 1 yr	54 yrs	-
Operational Concerns/ Risks	- disruption of natural gas supply (not likely) - two boilers sized at 60% provide redundancy - two pumps sized at 100% provide redundancy	- current assumptions are based on 105 F exhaust air from racks. Actual heat released from IT equipment may be different depending on final selection, - minimum 160,000 CFM of continuos exhaust at 105F at HPC is required - HPC should be operational at the time of office occupancy to capture heat, - disruption to HPC operation will leave the office perimter zones without any heating	boiler will pick up heating load in absense of HPC heat recovery	bdg 70 heating plant will pick up heating load in absense of HPC heat recovery

The presentation also mentioned the two assumptions made when considering the alternatives. They were:

- “Capital Cost: Cost numbers are referenced from cost estimate prepared by Cummings Corporation at 90% CD stage.
- CRT Basis of Design: Per client brief, it is assumed that the exhaust air from the racks is 105ºF (40.6°C).”

From Table 4-1, it seems that the decision was based on minimizing the payback period and maximizing energy efficiency. As a result, ‘Option 1’ was selected, despite presenting more ‘operational concerns/risks’ than any other option. Among them:

- “Current assumptions are based on 105°F (40.6°C) exhaust air from racks. Actual heat released from IT equipment may be different depending on final selection.
- HPC should be operational at the time of occupancy to capture heat
- Disruption to HPC operation will leave the office perimeter zones without any heating.”

It also seems that the design team was aware of two key elements: (1) the uncertainty surrounding the type of IT equipment used and corresponding operating conditions and (2) the strong dependence of office heating on running HPC systems. Questions arise: “Knowing these elements, why did the team proceed with this design?” “How could the boiler have been eliminated in the first place to be added back later?” “Could it be that the VE process is not the most appropriate approach for handling complexity?”

The next paragraphs identify other potential shortcomings of the VE process on this project.

4.6.2 Magnitude of VE Effort

On CRTF, the project team had to carry out a significant VE effort over several years. The initial estimate was more than 10 million above the allowable costs. Although the purpose of VE is to bring back the design so that its cost does not exceed owner’s allowable costs, is there a point from which the project estimate is so high that VE is doomed to fail by negatively undermining value delivery?

Knowing the significant gap between the project cost estimate and the allowable cost in 2008, the instruction received by ARUP at the time to “include no safety factor in any mechanical system sizing calculations” does not come as a surprise. While there was a necessity to make the project be within budget, the magnitude of the VE effort encouraged risky decisions.

Could a different design approach have avoided the team to be in such situation (i.e., take high risk to ensure that the design can be brought back within budget)?

4.6.3 Compounding Effect of Complexity

Table 4-2 describes how VE fails to manage five aspects of structural complexity and how this impacted the decision to eliminate the boiler in the heat recovery study.

Table 4-2: Failure of VE to Manage Aspects of Complexity and Impact on Boiler Elimination Decision

	In VE, …	**Impact on boiler elimination decision**
Customer	Success of VE effort is measured in amount of money saved by the proposed alternative.	For the boiler elimination study, the amount of money saved overshadowed the risks associated with the selected alternative.
Organizational	Usually, external or insulated group of people conduct the VE effort (e.g., mechanical consultants). Solution are then presented to the owner. As a result, project team considers VE as a detached function in the design. Project team (incl. owner, its FM, GC) participation is poor. Poor participation creates misalignment and lack of shared understanding on problem to solve.	Since VE effort was executed as a detached function, FM did not participate in the decision. However, FM was aware of the risks associated with the decision.
Product	VE being carried out by an insulated group of people (excl. FM), people may not have the technical knowledge required to understand the specificity of the project and its challenges.	The supercomputer facility is a high-end facility that accommodates complex HPC systems. The uncertainty surrounding the type of system installed (operating conditions, quantity of heat generated, etc.) could have been better assessed through the early and strategic involvement of HPC systems vendors. Additionally, the reviewed VE documents lack clarity on which systems actually generate heat. It is a system in the common area that generates most heat (as opposed to the supercomputers NERSC-7 and NERSC-8).
Process	VE happens late in the design development process and is local (i.e., targets specific systems). This is likely to cause negative design iteration.	The decision on whether or not to include a boiler in the design changed multiple times during design. These changes may temporally match with VE sessions.

Market	Because VE is executed by a detached function that does not regularly involve the customer, the VE team may prioritize customer requirements differently than the customer does.	Increasingly stringent environmental regulations (at least, in California) influenced the decision (cf. design intent in Table 4-1)

Considering the above, is there a different way to manage design that can avoid these shortcomings? The conclusion highlights the fitness of Target Value Design (TVD) to manage the design of complex, uncertain, and quick projects.

4.7 Conclusions

VE caused significant waste in the design of the heating system: it was decided very late that a boiler was actually needed. The design team then proposed the installation of a heat pump on the roof, which did not fully solve the problem. Indeed, the piece of equipment breaks down frequently, due to its inappropriate installation (in an enclosed space, instead of outside) and being undersized. Overall, the facility fails to deliver thermal comfort to its occupants.

The analysis revealed that the project was structurally complexity in five aspects (section 4.5). The failure of the heat recovery system design substantiates the argument that the design process was not fit to manage this complexity (section 4.6). With respect to VE, Tuholski 2008 writes:

"VE tends to have little to do with owner needs. Instead, the process tends to focus on reducing costs with 'comparable' design alternatives. VE is often ineffective because it is discrete and completed by a review team that is separate from the project, and traditionally ends up being more of a cost-cutting workshop than a value-generating process. This traditional form of VE, similar to the Transformation view of management, tends to myopically focus on individual component savings rather than system-wide delivery efficiencies/savings."

Instead, Target Value Design (TVD), defined as "the practice of defining scope, performance goals, and target cost in advance of starting design, and then steering the design and construction process so as to meet all" (P2SL 2017b), seems to be fitter for dealing with complexity. TVD relies on the following principles (Macomber and Barberio 2007):

- "Rather than estimate based on a detailed design, design based on a detailed estimate.
- Rather than evaluate the constructability of a design, design for what is constructable.
- Rather than design alone and then come together for group reviews and decisions, work together to define the issues and produce decisions then design to those decisions.
- Rather than narrow choices to proceed with design, carry solution sets far into the design process. [in other words, practice set based design]
- Rather than work alone in separate rooms, work in pairs or a larger group face-to-face."

Figure 4-9 (respectively Figure 4-10) is an activity-based DSM representing the main phases involved in a traditional design process (respectively TVD). Marks above the diagonal indicate a feed-forward relationship. Marks below the diagonal indicate an iteration.

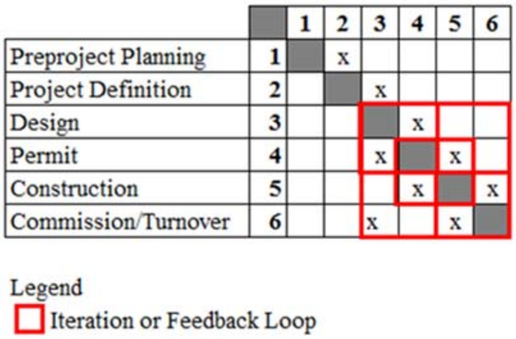


Figure 4-9: Project Phases and Traditional VE Approach

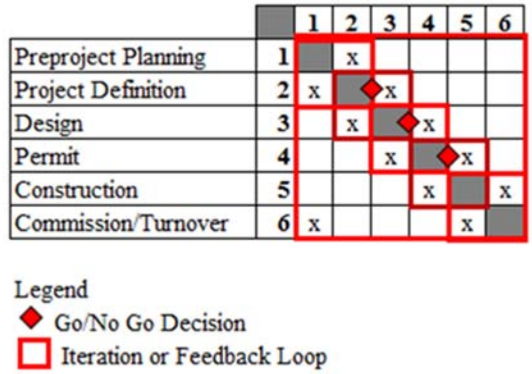


Figure 4-10: Project Phases and TVD (after Ballard 2008, Figure 9-8 in Appendix)

A traditional design process is one where the project team sequentially plans the project, then defines it, and last designs it. Iteration may occur if the permit is rejected. In that case, the team re-designs the building. Once the permit is approved, construction starts and is then followed by the commissioning/turnover. The iteration shown in Figure 4-9 between construction and permit (mark below the diagonal) happens when a building is inspected (by the GC, regulatory agencies, etc.). Post-Occupancy Evaluations are captured in the feedback loop between commission/turnover and permit. Thus, the traditional VE approach overlooks interdependences between pre-project planning and project definition, project definition and design, and the commissioning turnover and the preproject planning. On the CRTF project, the negligence of those interdependences led to: an initial budget that was significantly below the market value (VE is a consequence of the design process), and a design that proceeded without understanding HPC requirements. Furthermore, the fact that the feedback loop from commissioning/turnover was overlooked led to a misalignment of the design concept with the project turnover, that is, occupants moving in before the installation of HPC.

Unlike a traditional design process, TVD presents more, earlier, and shorter iteration loops between project phases (e.g., mark in row 2 and column 1, mark in row 3 and column 2 in Figure 4-10). Unlike a traditional design process, TVD allows a project team to stop the process at any time through Go/No Go decisions. TVD involves additional elements that support the management of project structural complexity:

- The fact that "the customer is an active and permanent member of the project delivery team" helps the design team better understand the prioritization of customer requirements (cf. customer complexity, Table 4-2).
- Cross-functional teams facilitate the understanding of dependences between systems (cf. product complexity, Table 4-2).
- The fact that "cost estimating and budgeting is done continuously through intimate collaboration between members of the project team 'over the shoulder estimating'" avoids cost-cutting operations that undermine value delivery. It helps avoid negative design iteration (cf. process complexity, Table 4-2).

5. CROSS-CASE ANALYSIS

Chapter 5 presents the cross-case analysis of the cooling tower case and the supercomputer facility case using the Lean Project Delivery System (LPDS)-Multi-Domain Matrix (MDM) framework introduced in section 2.11.2. The goal of this chapter is to identify how project delivery teams could have managed project structural complexity by the use of Lean principles and methods.

The chapter is organized as follows. Section 5.1 summarizes the instantiation of process complexity encountered in the cooling tower case. It concerns the steel structure re-design. Section 5.2 summarizes the instantiation of product complexity encountered in the cooling tower case. It concerns the sizing of the cooling tower. Section 5.3 summarizes the instantiation of process complexity encountered in the supercomputer facility case. It concerns Value Engineering (VE). Section 5.4 uses the LPDS-MDM framework to highlight how Lean Construction could have helped manage structural complexity in these two cases. Section 5.5 extends the recommendations made for each case study by listing a set of Lean principles and methods that a project team may use to manage complexity on projects.

5.1 Cooling Tower Case: Steel Structure Re-Design

The cooling tower case takes place at the Lawrence Berkeley National Laboratory (LBNL). The objective for this project is to improve the operational stability and reliability of the Advanced Light Source's (ALS) operations. Specifically, it concerns the replacement of two wooden cooling towers that feed ALS and 13 other buildings with Low Conductivity Water (LCW) and Treated Water (TW).

In terms of planning the work, an objective was to minimize disruptions to ALS operations and therefore align the construction schedule with ALS planned maintenance windows. The facility is running 24/7/365 except for maintenance shutdowns. The main and longest planned shutdown occurs in the winter and is followed by two-day shutdowns every other week.

Regarding commercial terms, LBNL contracted with the engineer and the commissioning agent under a fixed price contract, and with the General Contractor (GC) under a separate CM/GC best value contract. LBNL's intent was to involve the GC early so that it could provide insights on the engineer's design and phasing of the project. However, the GC was hired later than anticipated on the project. The engineer phased the work so that most of the project would be accomplished during the long winter shutdown and minor work would take place afterwards. However, the proposed phasing matrix demonstrated the feasibility of the design, not necessarily the reasonability of the plan. As a consequence, when the GC got onboard, it developed its own schedule from the design drawings issued for bid.

The problem selected to illustrate process complexity concerns the unplanned design iteration, which increased the duration of Phase 1 and delayed the start of Phase 2. Phase 1 involved the replacement of one of the two cooling towers. Phase 2 was initially planned (by the Engineer and the GC) to start shortly after Phase 1. The motivation for this was to minimize the time during which ALS would have to run on a single cooling tower (instead of two). Due to the delay of Phase 1, ALS ran on one cooling tower for longer than expected, and hence during hotter days than anticipated (Spring). A major unplanned design iteration that delayed Phase 1 was the steel structure re-design.

The analysis conducted in Chapter 3 highlighted some dependences missed in the design, for example, the dependence between "checking the existing conditions" and the feasibility (and reasonability) of the designed steel structure anchoring. Indeed, the initial design showed the steel structure anchored in 64 locations in the existing roof. This was deemed unsafe (by LBNL and the GC) to execute, because the roof structural slab comprised two layers of rebar, embedded 220V electrical conduit, and a topping slab reinforced with welded wire fabric. It appeared that the engineer did not take into account the feedback loop linking the results of the scanning to the feasibility of the detailed design.

From the analysis of the case study, the researcher recommends the following:

- **Work as an integrated project team**. Had the GC been involved earlier in the project, it would have been able to provide feedback on the feasibility of the anchoring the steel structure into the existing roof. An integrated project team would have allowed to:
- Gather information on existing field conditions earlier through FM early involvement.
- Develop collaboratively an activity-based Design Structure Matrix (DSM) to: (1) plan the work and assess risks and opportunities with relevant project stakeholders and (2) reveal dependences and eliminate iteration-masking language.
- **Implement set-based design and design charrettes.** Parrish (2009) summarizes set-based design as "postponing commitment to a specific design, and instead generating and evaluating sets of design alternatives." For the steel structure design, the engineer presented only one design to the stakeholders. In the industry, engineers are seldom tasked with and compensated for communicating design alternatives with project teams.

5.2 Cooling Tower Case: Cooling Tower Selection

The objective of the cooling tower selection was to choose the new cooling tower model (replacing the two existing ones).

To do so, the engineer received design criteria from LBNL's Subject Matter Experts (SME). The engineer proposed a first selection of models and then shortlisted some. The final cooling tower model was selected following a meeting gathering various groups at LBNL in addition to the engineer.

During the commissioning of the first cooling tower, the lack of cooling capacity raised concerns among the project participants. The team spent the three following months diagnosing the problem, which contributed to delaying the start of the second phase of the project.

In terms of dependences neglected in the cooling tower selection, the project Ends apparently had not been discussed sufficiently in depth to reveal: (1) the relative importance of customer requirements, (2) the assumptions underlying the design criteria serving as input for the cooling tower selection, and (3) the dependences between those design criteria and external factors (such as the mean coincident wet-bulb temperature). Furthermore, product complexity (of cooling towers) contributed to the apparent lack of shared understanding among team members on which factors to use for the selection and which cooling tower model to select. Last, the cooling tower selection happened earlier than when needed on the project.

From the analysis of the case study, the researcher recommends the following:

- **Develop the DSM of customer requirements**. The project team could have mapped the customers' requirements in a DSM. A benefit of this could have been to identify the reliability of LCW flow and temperature during the transition phase as critical.
- **Develop the DSM of assumptions**. Assumptions such as: specific needs in LCW flow during the transition period and how many hours per year the new cooling towers would (or not) be able to meet ALS's and other buildings' demand could have been made explicit.
- **Develop the Multi-Domain Matrix (MDM) of assumptions and design criteria**. The design criteria used for the selection of the cooling tower such as tonnage were not clear with respect to meeting or not the customer requirements (e.g., how does tonnage translate in terms of flow during 'regular' ALS operating conditions?).
- **Implement Choosing-By-Advantages (CBA) to make decisions**. The project team could have used CBA as a sound decision-making system to create a shared understanding about the problem to solve, have a shared language, base decisions on the importance of advantages, and anchor decisions to the relevant facts (Suhr 2008).
- **Make decisions at the Last Responsible Moment.** The selection of the cooling tower happened before the finalization of the Current Facility Requirements (CFR) document and the understanding of how to execute the transition. Making a decision at the Last Responsible Moment could have given the team the opportunity to reveal additional factors for the selection of the cooling tower.

5.3 Supercomputer Facility Case: Value Engineering (VE)

The supercomputer case concerns the Computational Research and Theory Facility (CRTF) at LBNL.

The problem selected for this study was the VE conducted over several years due to a project cost estimate exceeding the allowable costs. The VE effort was interrupted from 2008 to 2011.

From the documents reviewed, it appears that the MEP consultant made optimization studies on different elements (e.g., "heat recovery study," "cooling tower study," "chiller elimination study," "AHU direct evaporative options study"), but did not have the opportunity to test the detailed design holistically and check the reasonability of the underlying design assumptions (and thus, dependences).

An optimization study ("heat recovery") led to the boiler elimination, so that heating at the office floors would only rely on the heat generated by the High-Performance Computing (HPC) floor. The MEP consultants selected this alternative among three others. The evaluation criterion used for the decision was the reduction of life cycle costs.

Following the start of occupancy, occupants at the office floors reported that the office space was cold, despite the recent addition of a heating system toward the end of the project. The University ordered this addition, because they realized that occupants would move into the building before the complete installation of the HPC systems. This meant that the heat generated by the HPC floor could not be used to heat the two office floors, as intended.

The analysis of the design process (incl. VE) on the project showed that the design process was not fit to manage the project complexity from different aspects. This led the researcher to recommend the following:

- **Develop the DSM of assumptions / DSM of design criteria.** The assumptions underlying some design criteria were not made sufficiently explicit to the project team. For example, the risk incurred from the tight coupling between the construction schedule (start of occupancy, installation of HPC) and indoor temperature was not sufficiently communicated or understood.
- **Implement Target Value Design (TVD).** Designers and consultants were allowed to proceed with detailed design, although the project cost estimate exceeded the allowable cost. This creates waste (rework) in the design process. Conversely, TVD is a "method that makes customer constraints (on cost, time, location, and others) drivers for design in pursuit of value delivery," "rather than treating cost as an outcome of wasteful design-estimate-rework cycles" (P2SL 2017b). TVD requires early involvement of trade partners and stakeholders (i.e., FM). The first step in TVD is to set the target cost (Ballard 2008). The target cost must be lower than the expected cost, which must be lower than the allowable cost. If the team cannot set a target cost meeting those conditions, they must iterate through the preproject planning. The second step in TVD is to design to the target cost. During design, the team members update their cost estimates on a monthly basis. This helps reduce negative design iteration as a design cluster does not pursue an alternative if it significantly exceeds the budget allocated for the cluster. Money can move across clusters though. The third step in TVD is to build to the target cost.

- **Use a set-based design approach.** Set-based design could have prevented the negative design iteration resulting from the early elimination of the boiler and the subsequent reconsideration. Set-based design relies on exploring multiple alternatives simultaneously and eliminating alternatives at the Last Responsible Moment.

The next section uses the LPDS-MDM framework to highlight opportunities for managing complexity regarding the cooling tower selection.

5.4 Application of the LPDS-MDM Framework to Explore Opportunities for Managing Complexity

In this section, the LPDS-MDM framework is used as follows:

- Figures 5-1 to 5-4 illustrate the timeline from the cooling tower selection to its installation during Phase 1. Section 3.1.5 (chapter 3) describes the timeline. The figure captures the sequence of the project deliverables and their corresponding activities.
- Figure 5-5 illustrates the interpretation of the problem encountered when operating the new cooling tower. To read more about it, section 3.5.8 presents the 5-Whys on the problem.
- Figures 5-6 to 5-9 highlight how the use of Lean principles and methods could have helped manage structural complexity regarding the cooling tower selection. A comparison between Figure 5-5 and 5-9 illustrates how the observed cooling tower selection process neglected the consideration of some interdependences.

Section 2.11.2 (chapter 2) describes the LPDS-MDM framework in details and presents its Transformation-Flow-Value (TFV) interpretation. In the TFV interpretation of the framework, DSMs in the diagonal translate the Transformation view of production, which is the focus of traditional project management. Traditional project management is activity-centered and focuses on contractual deliverables, which was the case for the cooling tower selection (Figures 5-1 to 5-4).

LBNL, the Engineer, and the commissioning agent jointly developed a document called "Current Facility Requirements" (CFR) (purposes). The CFR identified project purposes and some project constraints (Figure 5-1). The project team selected the cooling tower (detailed engineering), before finalizing the CFR mid-April 2016 (Figure 5-1). From the documents reviewed and confirmation with project team members, the project team did not use a formal decision-making system or a methodology used for the cooling tower selection.

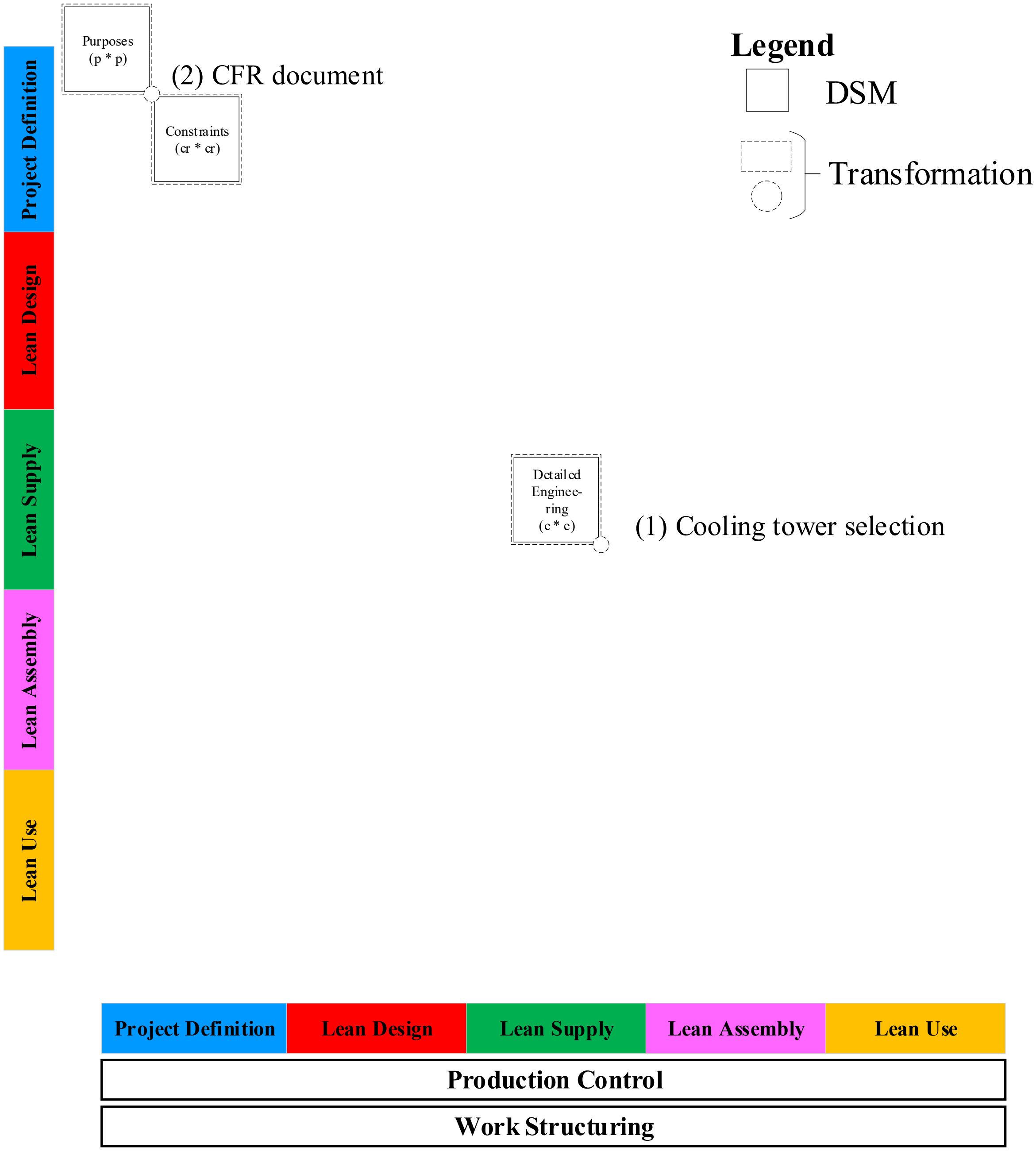


Figure 5-1: Observed Cooling Tower Selection Sequence shown in LPDS-MDM Framework (1/4)

The engineer then developed the design drawings (product design). During this time, LBNL contracted with a GC. Once the engineer finalized the design drawings, LBNL gave the GC the approval to release the shop drawings (Figure 5-7).

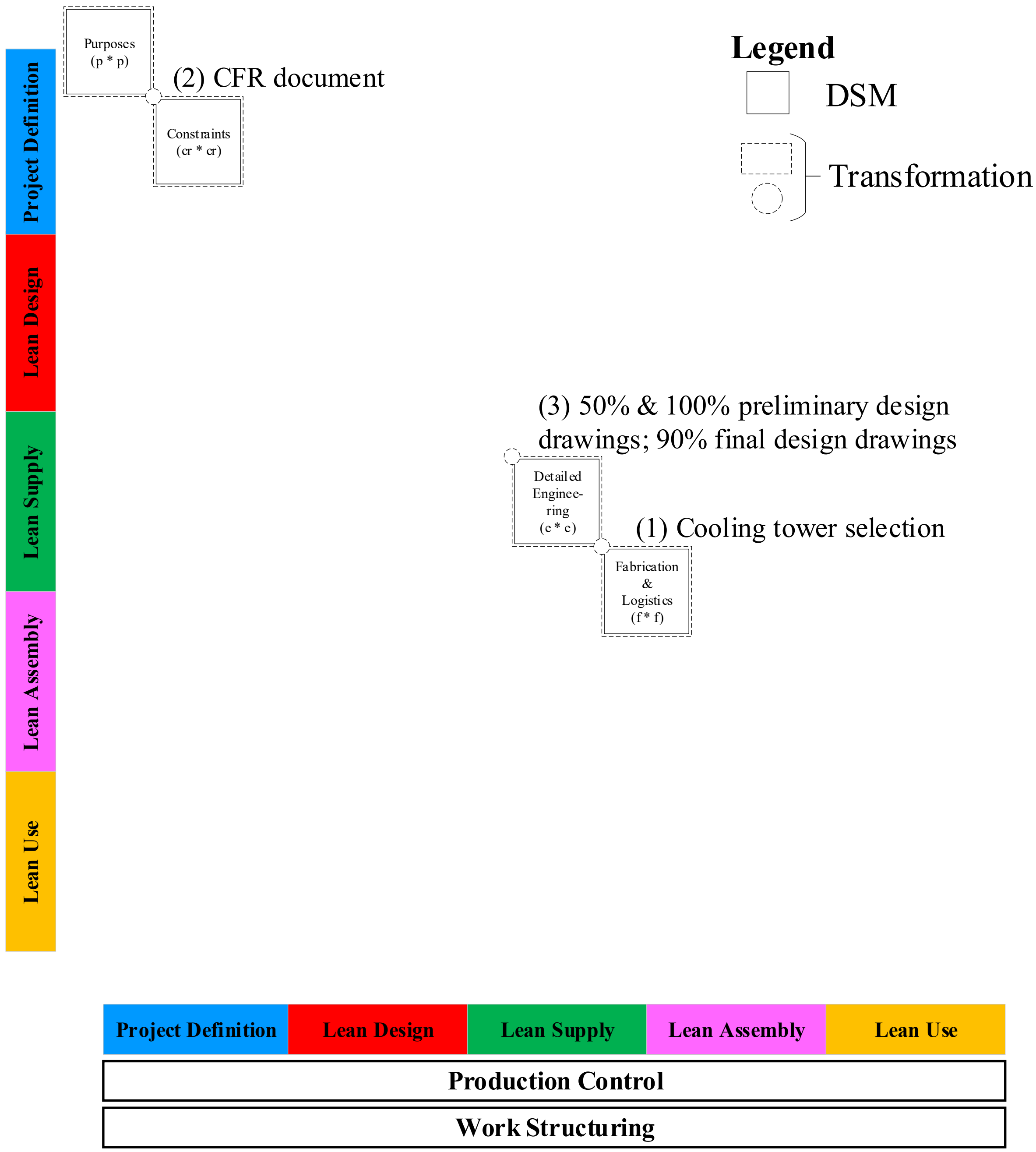


Figure 5-2: Observed Cooling Tower Selection Sequence shown in LPDS-MDM Framework (2/4)

During this time, the engineer created the phasing matrix to demonstrate the feasibility of the design (Figure 5-3).

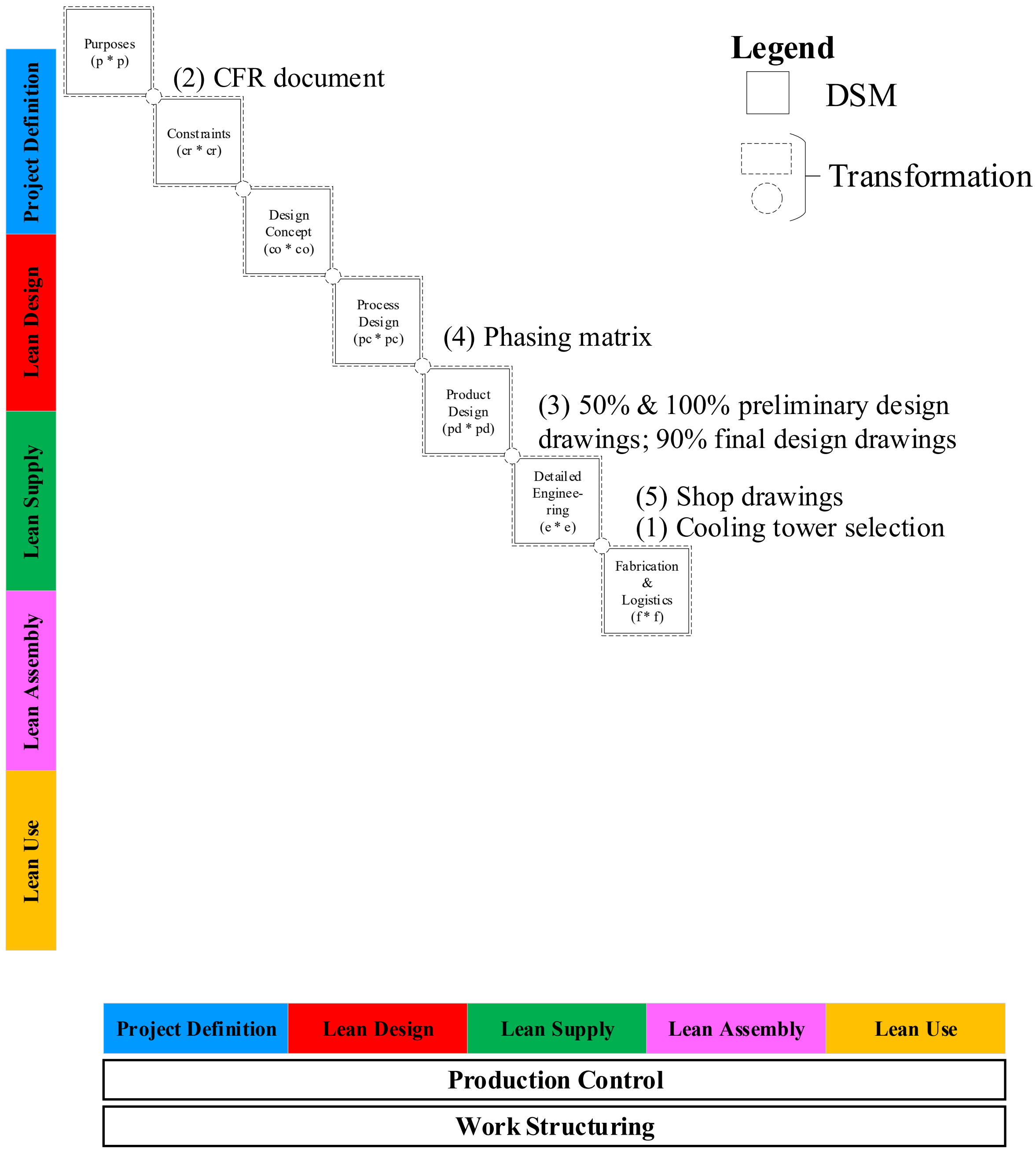


Figure 5-3: Observed Cooling Tower Selection Sequence shown in LPDS-MDM Framework (3/4)

The GC installed the cooling tower (Figure 5-4).

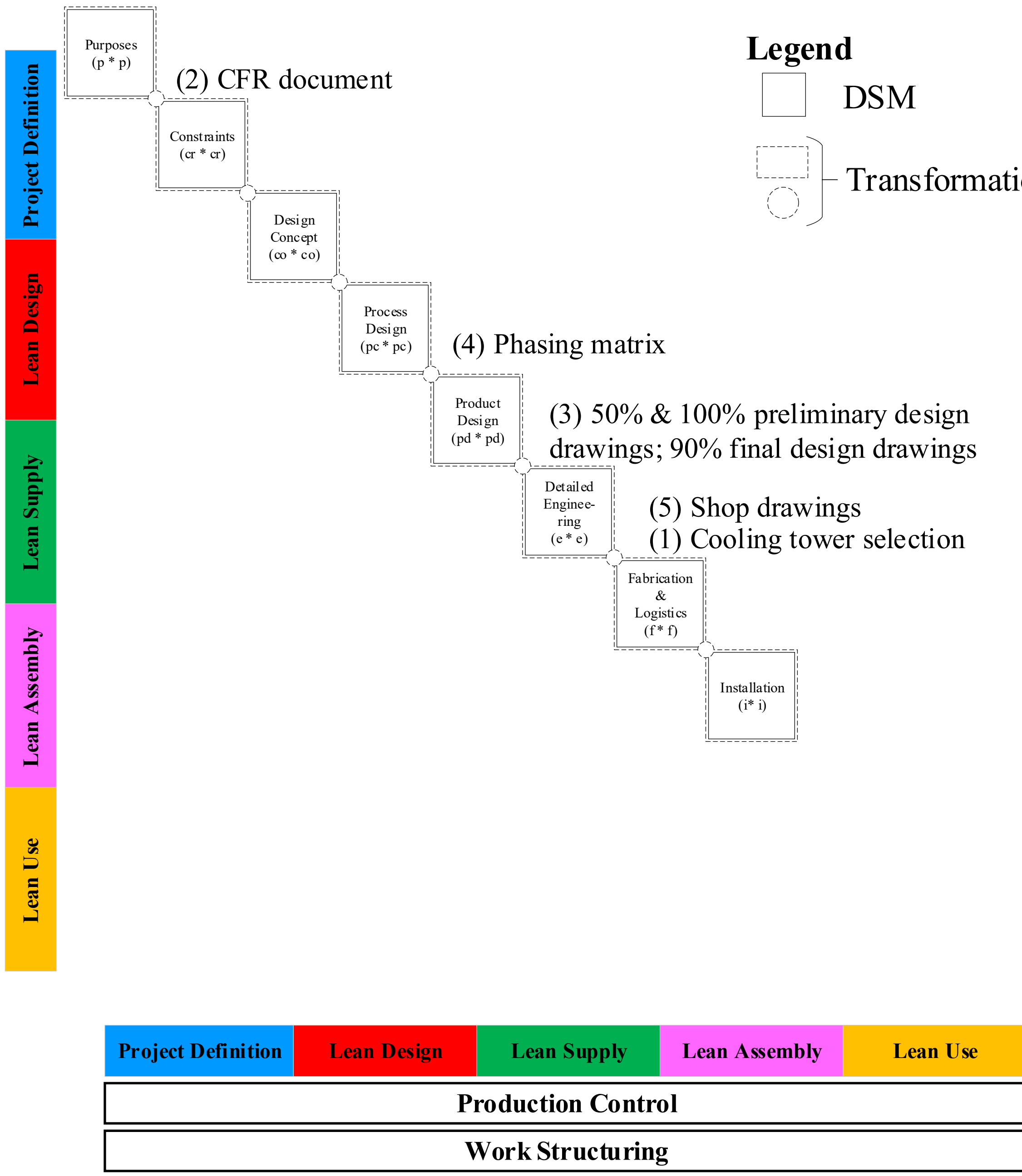


Figure 5-4: Observed Cooling Tower Selection Sequence shown in LPDS-MDM Framework (4/4)

Following the installation of the first cooling tower, the commissioning agent identified a lack of cooling capacity through testing. The project team spent three months diagnosing the problem. This contributed to delaying the start of the second phase of the project. Figure 5-5 proposes an interpretation of the cooling tower selection problem. It identifies dependences missed in the observed selection process.

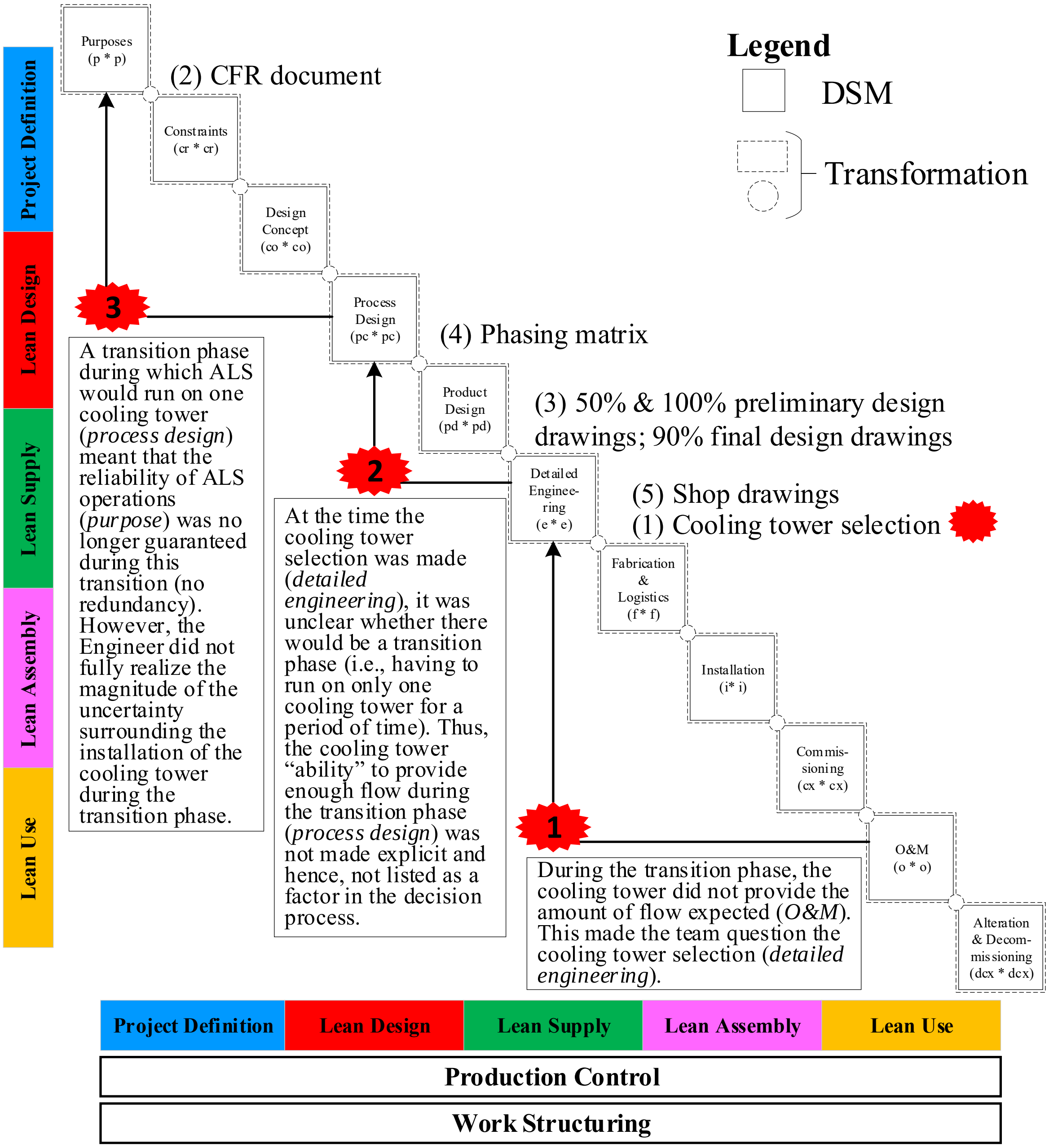


Figure 5-5: Proposed Analysis of the Cooling Tower Selection Problem

Considering the above, what recommendations can be made to reveal dependences earlier in the cooling tower selection? The researcher answers this question by using the LPDS-MDM framework and its TFV interpretation (section 2.11.2).

In the LPDS-MDM framework, the arrows pointing down across the MDMs represent work-, information, and material- flows, in other words the Flow view of production. The arrows pointing up are feedback loops representing the Value view of production.

In Figures 5-6 to 5-9 highlight how the use of Lean principles and methods could have helped manage structural complexity regarding the cooling tower selection.

First, early FM involvement could have helped the engineer better understand the existing cooling towers configuration and their performance during the project definition phase. FM (incl. building controls engineers) could have helped refine project purposes by informing the project team about the current state (MDM purposes * O&M) (Figure 5-6). O&M informs project purposes, which are in turn compared against project constraints (MDM purposes * constraints). This step helps create alignment within the project team. This is vital for project success, since engineer and FM may have different project objectives (proposing a feasible plan vs. ensuring highly reliable operations) (MDM constraints * O&M) (Figure 5-7).

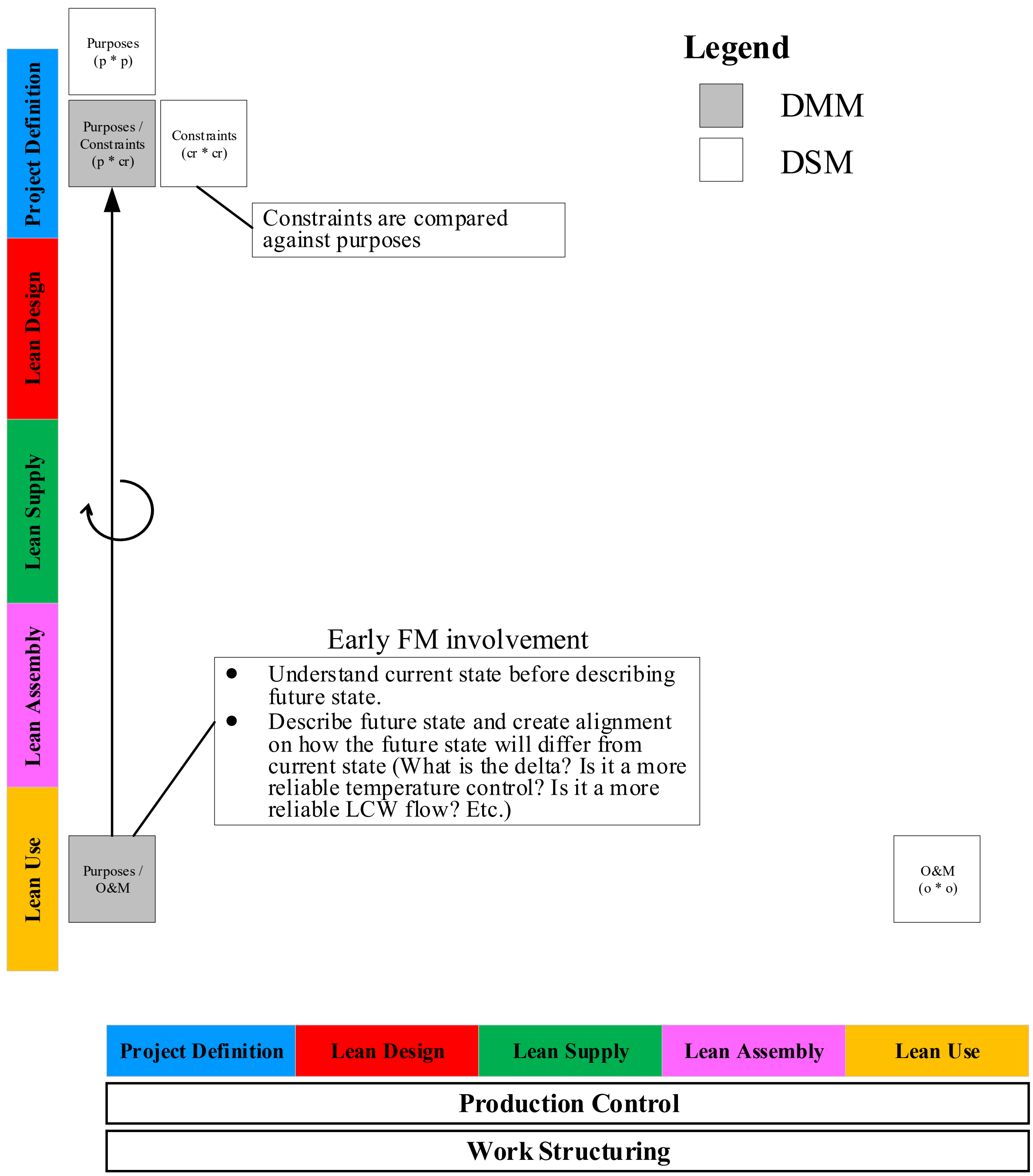


Figure 5-6: Proposed Approach to Manage Structural Complexity in Cooling Tower Selection (1/4)

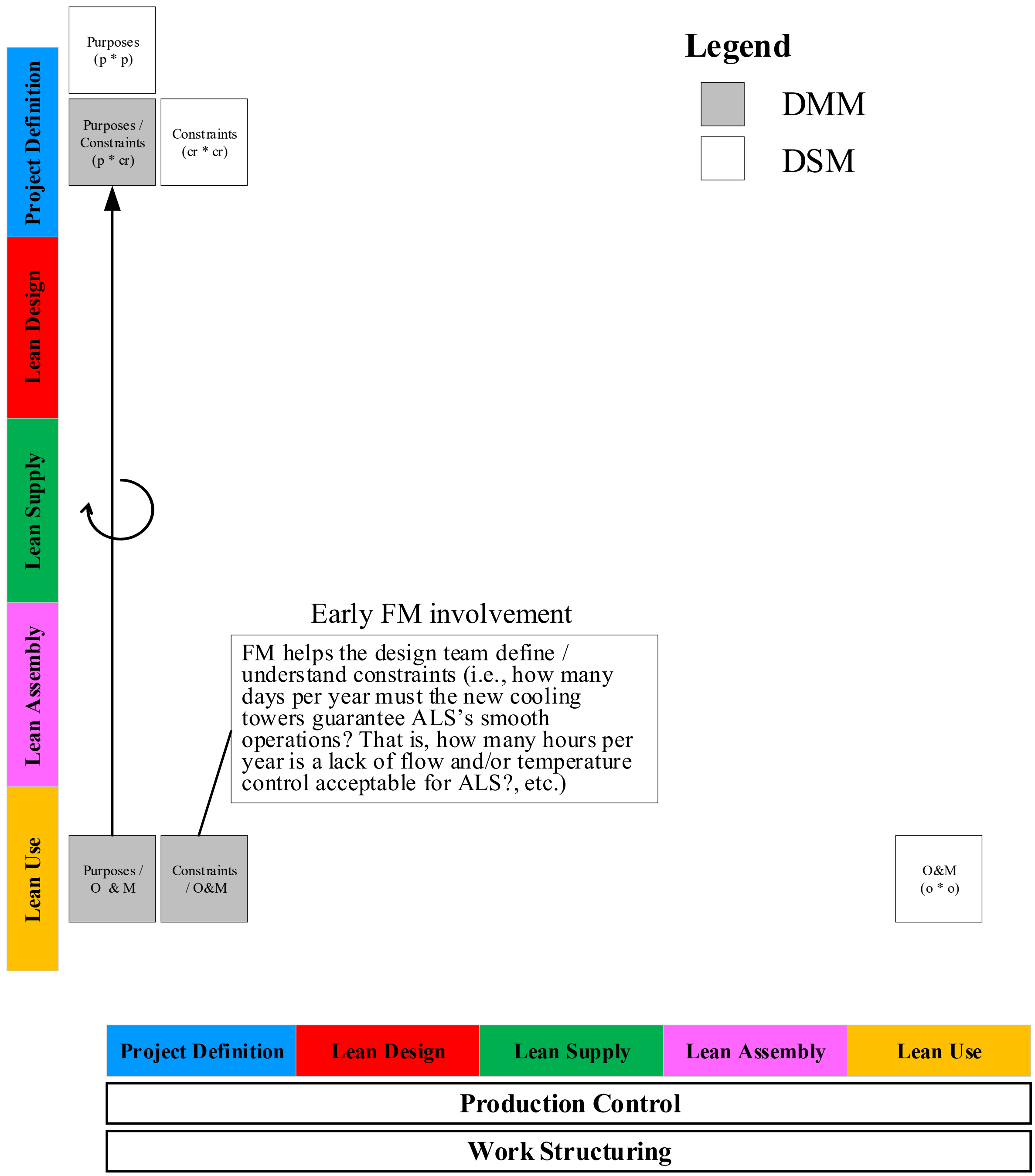


Figure 5-7: Proposed Approach to Manage Structural Complexity in Cooling Tower Selection (2/4)

The refinement of project purposes is iterative. Once purposes are collaboratively defined, the integrated project team (incl. the GC and main subcontractors) concurrently develop product and process designs. Since the team fully understands project purposes and constraints, the proposed process and design mitigate risk threatening project success (MDM purposes * process design). Since FM is strategically involved in project delivery, they can give feedback on the uncertainty surrounding proposed approaches to the cooling tower replacement (e.g., phased or not) (MDM process design * installation, MDM product design * installation) (Figure 5-8). For example, strategically involving FM could have revealed the challenge of a phased cooling tower installation, since the existing cooling towers ‘acted as two lungs’ (MDM constrain * constraints) (Figure 5-6).

The project team does not select the cooling tower yet (Figure 5-8).

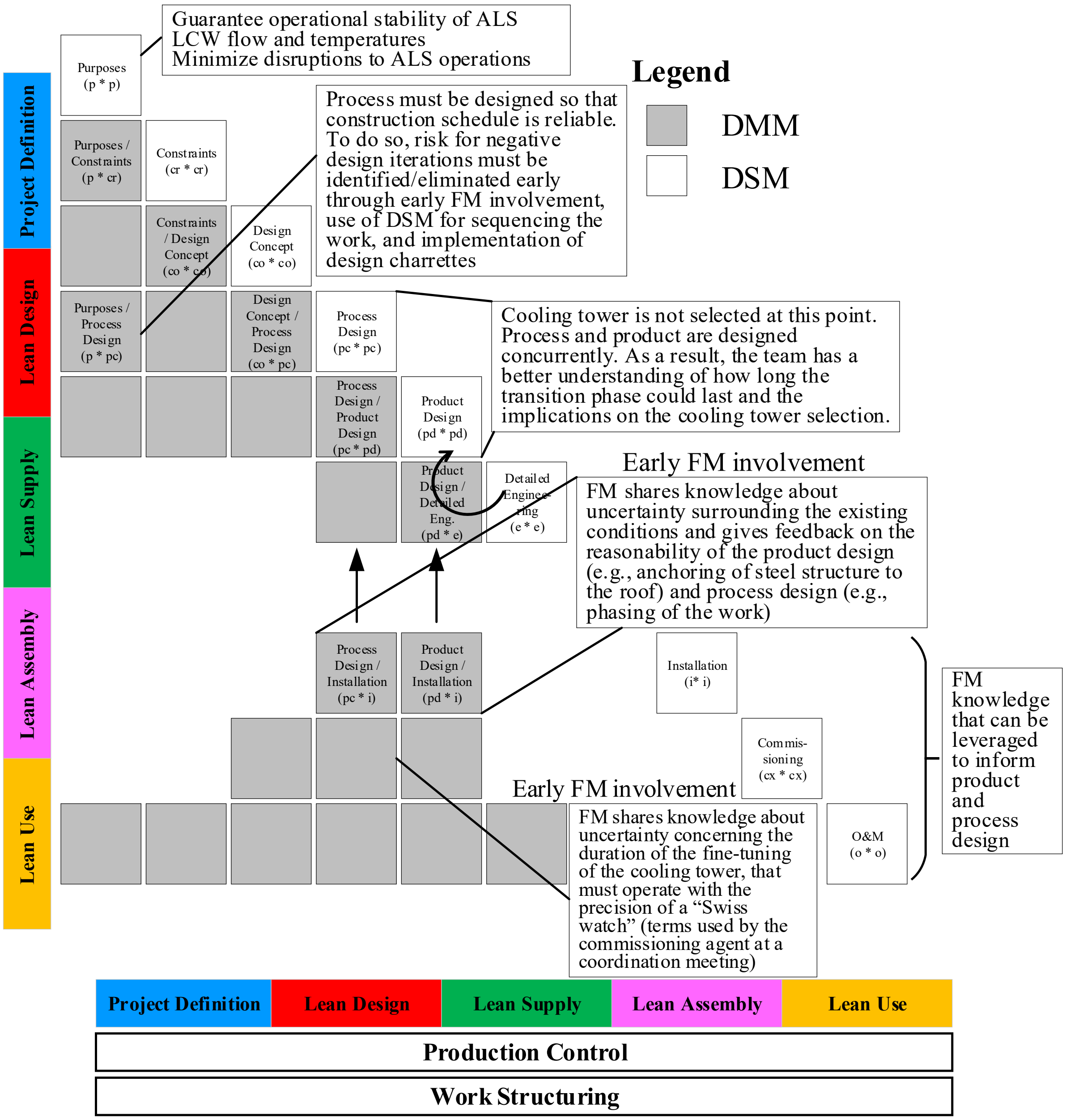


Figure 5-8: Proposed Approach to Manage Structural Complexity in Cooling Tower Selection (3/4)

Process and product designs have been concurrently developed. The integrated project team selects the cooling tower model at the Last Responsible Moment using CBA (MDM process design * detailed engineering) (Figure 5-9).

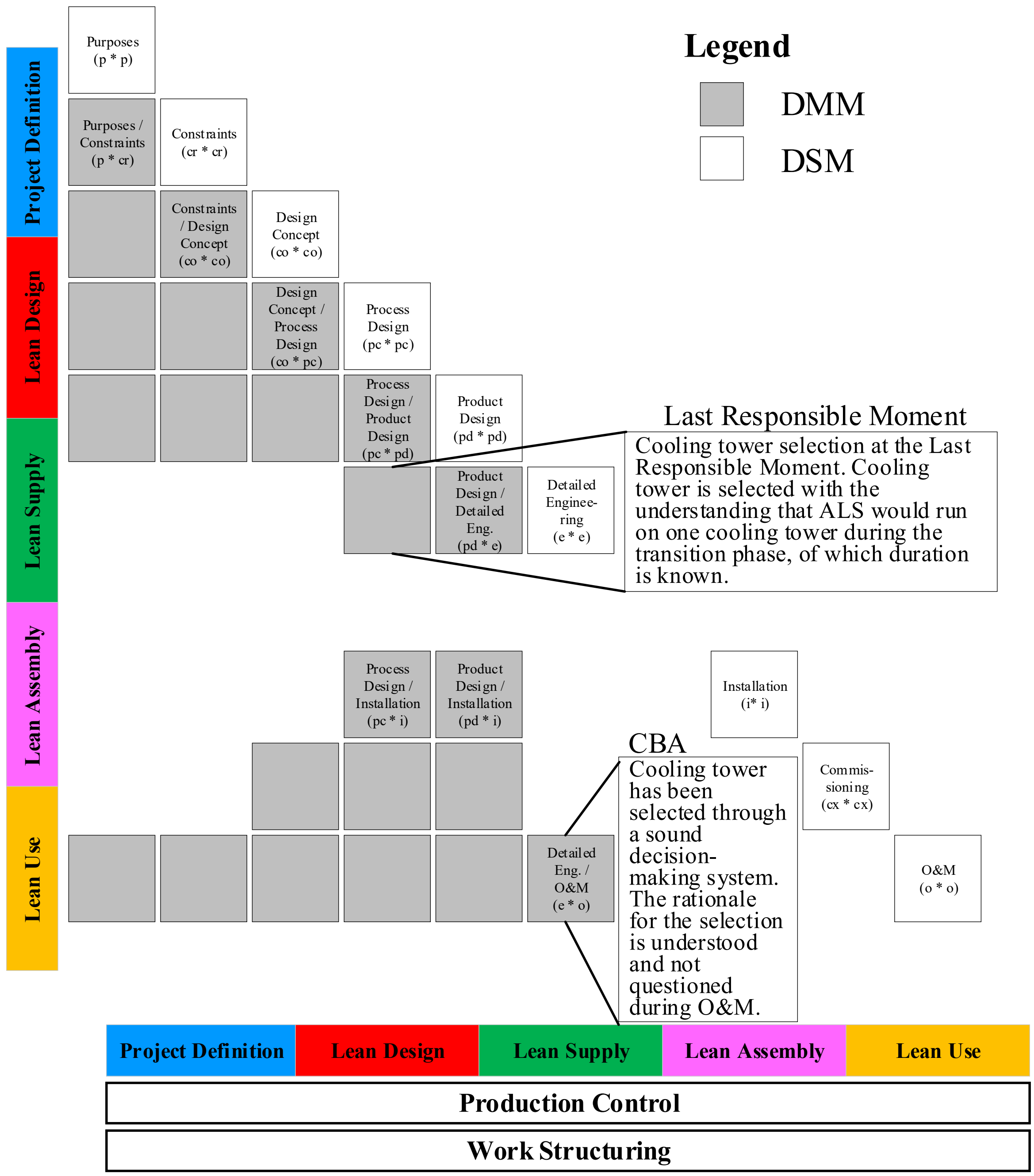


Figure 5-9: Proposed Approach to Manage Structural Complexity in Cooling Tower Selection (4/4)

5.5 Fitness of Lean Construction to Manage Project Structural Complexity

Lean principles and methods have been developed for complex, uncertain and quick projects (Howell 1999, Ballard and Tommelein 2012). However, how each principle or method relates specifically to the management of complexity is sometimes unclear in the literature and/or explanations are scattered across the published work.

Table 5-1 intends to fill this gap. The Lean principles listed in Column 2 are from Koskela (2000). For each of them, the researcher assessed whether the main intent was to reduce variation (Column 3) or manage complexity (Column 4). In the light of the reviewed literature, she differentiated the structural complexity framework from the edge of chaos/Cynefin framework. The corresponding methods are listed in Column 5.

Noting that the traditional PM literature pertains to the Transformation (T) model of production, a multitude of Lean methods were designed with the intent of supporting the principles of the Flow (F) model of production. The researcher found very few methods supporting the Value (V) generation model.

Table 5-1: Overview of Lean Methods to Manage Project Complexity

Production view (1)	**Principle (2)**	**Reducing variation (3)**	**Managing complexity (4)**		**Selected Methods (5)**
			Structural framework	Chaos/ Cynefin framework	
T	Decomposition				WBS
T	Cost minimization				
T	Buffering	x		x	
T	Value				CBA, Set-Based Design, TVD
F	Reduce lead time				Prefabrication, off-site assembly, modular construction
F	Reduce variability	x			Standardization
F	Simplify		x		DSM, standardization
F	Increase flexibility	x	x		Management-as-organizing (Bertelsen 2003)
F	Increase transparency		x	x	Last Planner® System, CBA, A3, DSM, TVD
V	Requirements capture		x		CBA, TVD
V	Requirements flow-down		x		LPDS-MDM framework, Hoshin Kanri

Production view (1)	Principle (2)	Reducing variation (3)	Managing complexity (4)		Selected Methods (5)
			Structural framework	Chaos/ Cynefin framework	
V	Comprehensive requirements		x		LPDS-MDM framework
V	Ensuring the capability of the production system	x		x	First-run studies, mock-ups, analysis using discrete-event simulation
V	Measurement of value			x	(See recommendations for future research in section 7.6)

5.6 Conclusions

In this chapter, the researcher implemented the LPDS-MDM framework, adapted from Tuholski (2008), to visualize how unmanaged structural complexity propagates across the different modules of the project delivery system. Managing project complexity means that project team members continuously reveal dependences across project delivery modules and take action to mitigate the impact of those dependences on project performance. The application of the LPDS-MDM framework to the cooling tower selection revealed how the timely implementation of Lean methods could have helped reveal dependences across modules that appeared to be either neglected or revealed too late using a traditional project management approach.

Additionally, the LPDS-MDM framework could serve as a differentiator between competing teams during the team selection process on Integrated Project Delivery (IPD) projects. When Lean owners select IPD teams, they expect teams to demonstrate their understanding of Lean principles and methods and how the implementation thereof will ensure reliably high project performance. During the team selection process, owners could ask teams to explain, using the LPDS-MDM framework, which processes the team will put in place to manage structural complexity on the project.

Finally, the case studies showed that some project complexity is self-inflicted, because some complexity results from the project production system design. The LPDS-MDM framework showed how project teams will benefit from Lean thinking to manage this complexity.

6. HOSHIN-FOR-FACILITIES TO ENGAGE FACILITY MANAGEMENT (FM) IN PROJECT DELIVERY

The goal of chapter 6 is to propose a model to support and enable FM integration with project delivery teams, building upon Lean Construction principles and methods, while acknowledging the complex nature of FM. It builds upon the research findings from chapters 2, 3, 4 and 5.

This chapter is organized as follows: section 6.1 examines the current state of Facility Management (FM) at two large public organizations: the Lawrence Berkeley National Laboratory (LBNL) and the University of California San Francisco (UCSF). It then explores the use of Hoshin Kanri to support and enable FM integration through an academic application of the tool. It gives recommendations for best practice after validation with practitioners and researchers. Specifically, recommendations are presented to decision makers at LBNL and UCSF and their feedback is incorporated in this research.

6.1 Research Methodology

The researcher followed a design science research approach. Chapter 2 identifies the problem to solve. It describes FM context, how FM fails, and what tools have been proposed in the literature to address how FM fails. The analysis of these solutions allows the researcher to identify their limitations. Limitations can be linked to a failure to address all dimensions of FM, as revealed by the Transformation-Flow-Value (TFV) interpretation of FM.

The Transformation interpretation of FM is to transition from a state A in which building systems do not perform as expected to a state B in which building systems perform as expected. The Flow interpretation of FM is to collect and channel data on the performance of a building or group of buildings to feed decision making or support maintenance operations (see Transformation interpretation). The Value interpretation of FM is to ensure that the building achieves customer satisfaction and best value. Furthermore, the TFV interpretation of FM can be enriched by analyzing the context in which FM operates. First, at the organizational level, the Cynefin framework helps characterize FM environment as complex. It helps understand the nature of the challenges faced by FM with respect to decision-making and planning. Second, at the project level, the structural complexity prism gives insights on how projects may fail due to a lack of awareness and management of dependences.

At the project level, chapters 3 and 4 documented the cooling tower case and the supercomputer facility case, and how project delivery can fail due to a lack of understanding of structural complexity. Chapter 5 tests the revised version of the LPDS-MDM framework on the cases. It shows why and how Lean Construction is specifically fit for structurally complex projects such as high-end facility upgrades.

At the organizational level, FM is the learning loop that can inform project delivery from past breakdowns and successes. Solutions presented in chapter 2 do not leverage this knowledge. This tacit knowledge can help reveal dependences early, before dependences impact project performance during design and construction. Informing project delivery being part of strategic planning, the researcher looked into Lean planning methods used for strategic planning in organizations. The researcher used the CBA decision-making system to select a planning method, upon which the proposed model would build. The researcher then validated it with practitioners at LBNL and UCSF and shares the feedback received in this chapter.

6.2 Description of FM at two Large Public Organizations

The two next paragraphs describe how LBNL and UCSF have (1) organized FM and (2) integrated FM with other departments in their respective organizations.

6.2.1 FM at the Lawrence Berkeley National Laboratory (LBNL)

The Facilities Division encompasses four "business units": (1) business center, (2) the Projects and Construction Office (PCO), (3) facilities services, and (4) facilities Building Control Officer (BCO)/Engineering (Figure 6-1).

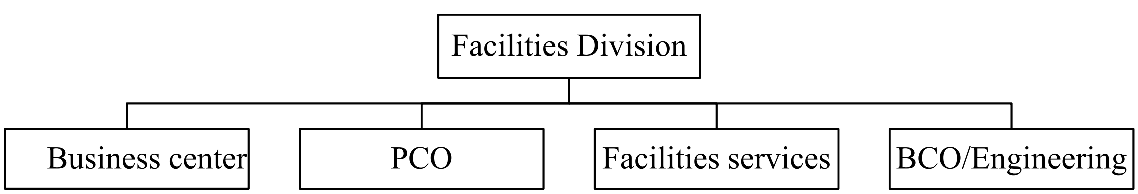


Figure 6-1: LBNL Organizational Chart for the Facilities Division

The **business center** is responsible for space planning, quality assurance, zone managing and conditioning assessment, National Environmental Protection Act (NEPA)/California Environmental Quality Act (CEQA), and work planning. **PCO** is responsible for maintenance projects, General Plant Projects (GPP) and Institutional General Plant Projects (IGPP), decommissioning and demolition, and capital projects such as the Integrative Genomics Buildings and NERSC 9 (the Facilities Division created the PCO during the researcher's internship). The **facilities services** include maintenance and repair, electrical work, receiving and shipping, and custodians. Last, **BCO/Engineering** encompasses: structural/civil engineering, drawings/document management, plan check inspection, mechanical engineering, electrical engineering, high voltage engineering, and energy management.

6.2.2 FM at the University of California, San Francisco (UCSF)

UCSF can be divided into two sub-organizations: UCSF "health" and UCSF 'campus," which have different operating models. This chapter concerns UCSF 'campus.' UCSF campus undertook many construction projects in 2016, such as: the Weill Institute for Neurosciences, Center for Vision Neuroscience, renovation of the Clinical Sciences building, Minnesota Housing.

Figure 6-2 shows the structure of 'Finance and Administration.' Capital programs is separated from Campus Life Services.

Figure 6-3 shows the services encompassed under "Facilities Services" at UCSF, which fall under "Campus Life Services."

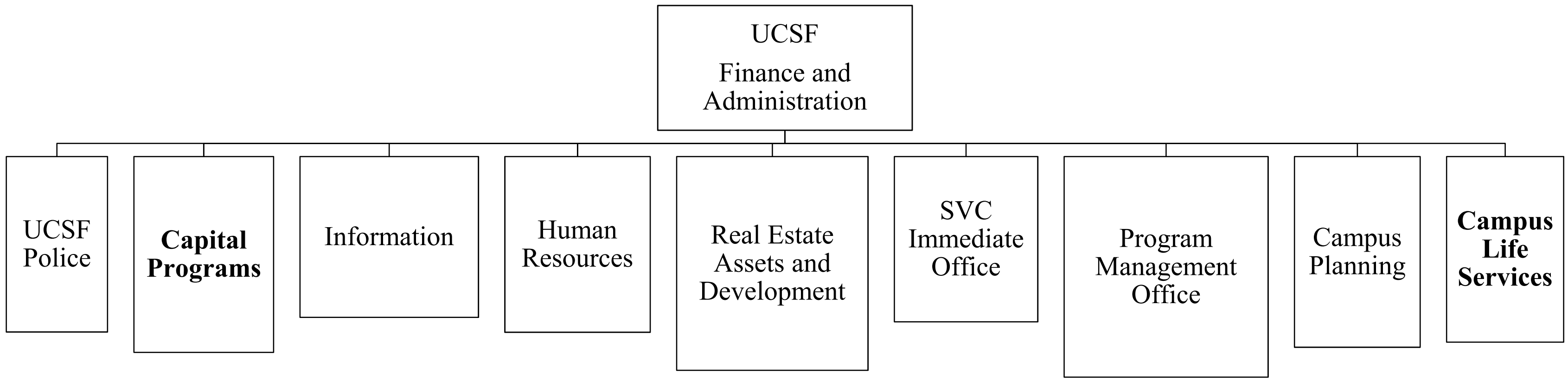


Figure 6-2: UCSF Organizational Chart Showing that Capital Programs is Separated from Campus Life Services (UCSF 2017a)

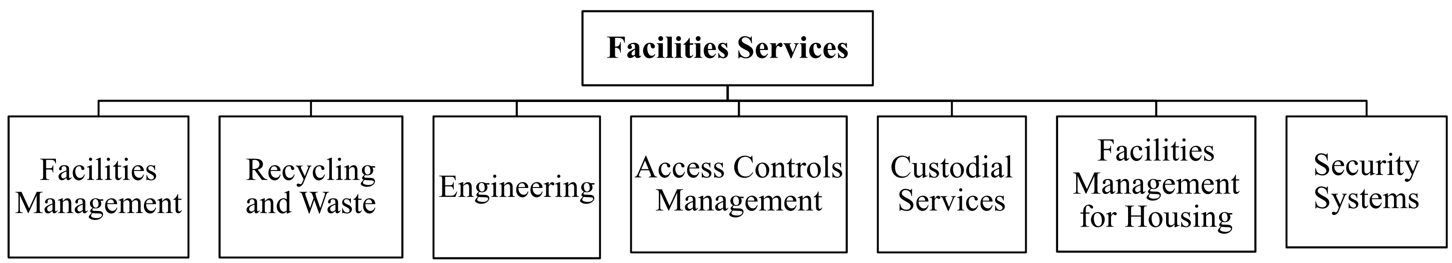


Figure 6-3: Facilities Services Organization for UCSF East Campus as of September 20, 2017 (UCSF 2017b)

Because UCSF's campus is scattered across San Francisco, Facilities Services was organized accordingly (i.e., separation of Mission Bay Operations from Parnassus Operations).

One major difference between LBNL and UCSF is the size. While UCSF is scattered across multiple campuses in San Francisco, LBNL's buildings are mostly concentrated in one campus (to some exceptions such as the Joint BioEnergy Institute in Emeryville). Another major difference between the two organizations is in the adoption of Lean: UCSF started its Lean journey more than ten years ago, while LBNL has recently started it. The next paragraph gives an overview of UCSF's Lean journey.

6.3 Overview of UCSF's Lean journey

UCSF has been using Lean for delivering projects since 2007 (Bade and Haas 2015) and has been successful at it on complex projects exceeding $2 billion and many others.

When UCSF began developing Mission Bay in the late 1990s, it used design-bid-build contracts and Construction Management (CM) at risk delivery methods. A few years later, UCSF became involved in multiple litigations resulting from the unfitness of the selected project delivery methods for its complex and uncertain projects (i.e., Bayer's Hall in Schöttle 2017).

Michael Bade initiated UCSF's Lean journey with the conviction that conflicting relationships could be avoided on construction projects. He had seen Lean being implemented in Japan, where he had lived for several years (LCI 2017c). At the time, UCSF also connected with Glenn Ballard from P2SL at UC Berkeley. Michael Bade became involved in organizations developing the Lean theory such as LCI. During those years, successes of Lean Construction implementation at another healthcare services provider, Sutter Health, were getting noticed (ENR 2007).

Thus, UCSF started its Lean journey by addressing the root cause of poor project performance: the misalignment between the operating system, the organization and the commercial terms (contract). Therefore, UCSF developed a Construction Management (CM) at risk with design-build subcontractors and an incentives contract for the $254 million Smith Cardiovascular Research Building. Then, it developed a design-build contract for the $123 million for the Dolby regeneration medicine building with "lean elements." It then expanded upon these for the $1.5 billion Mission Bay Medical Center.

A critical component of Lean project delivery is the early involvement of key project team members. Yet, UCSF being a large organization, projects can have many stakeholders. The difficulty that emerges then is answering the questions: "Who to involve in project delivery?" and "When to involve them?" In that respect, UCSF has been integrating FM in project delivery increasingly earlier.

Figure 6-4 depicts the evolution of FM integration in project delivery at UCSF. On the upper half of the timeline, the shaded triangles of the LPDS schematic (cf. Figure 2-15 in section 2.11.2) indicate when FM integration in project delivery starts. On the lower half of the timeline, the evolution of FM integration is illustrated using five UCSF projects: (1) Genentech Hall, (2) Helen Diller Family Cancer Research Building, (3) Smith Cardiovascular Research Building, (4) Mission Hall, and (5) Block 33. The dates indicated below the horizontal bars indicate the start and end of construction. However, the dates for the start of project definition would have been a better indicator of UCSF's evolution with FM integration. This would have allowed readers to compare these dates with UCSF's changes in contracting practices and team selection processes.

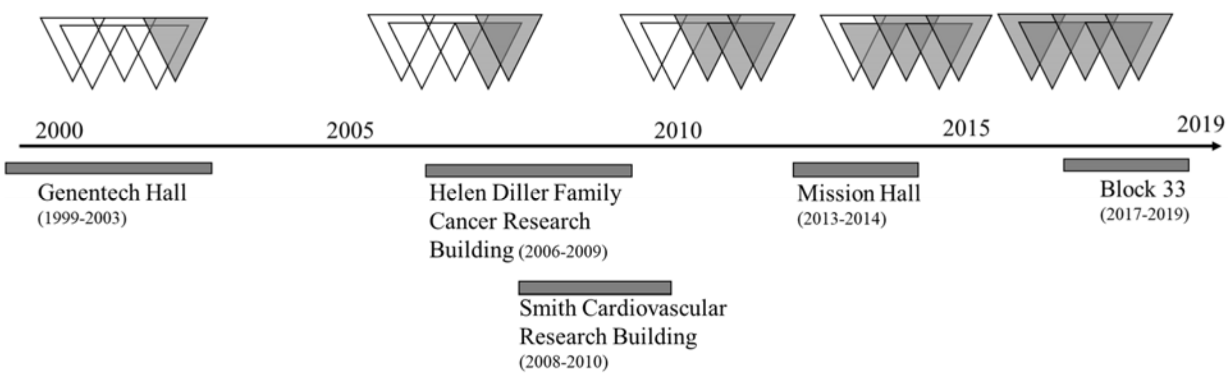


Figure 6-4: Evolution of FM Integration in Project Delivery at UCSF

Construction of **Genentech Hall** UCSF's first building on Mission Bay started in 1999 and was completed in 2003. The $161 million five-story building houses programs in structural and chemical biology as well as molecular, cellular and developmental biology. It also houses the Molecular Design Institute, Nikon Imaging Center and the Center for Advanced Technology.

At the time, UCSF had not started its Lean journey and FM was involved in the project use phase only. FM at UCSF gave the researcher examples of input that the project team could have requested from them but did not, due to use of a traditional delivery method. These include: needs in space (e.g., janitors, shops, storage rooms, etc.) or the type of water system to use. Concerning the latter, FM indicated they would have recommended the use of a Reverse Osmosis/Deionized water system as opposed to a deionized water system as delivered. Following this project, FM started to be brought in earlier in project delivery as UCSF started its Lean journey.

Construction of the **Helen Diller Family Cancer Research Building** started in 2006. Occupancy started in 2009. This five-story building houses researchers investigating into basic biological mechanisms causing cancer, including brain tumors, urologic oncology, pediatric oncology, cancer population sciences, and computational biology. Although UCSF had already initiated the development of new contracts for integrated project delivery teams, FM at UCSF reported that their involvement remained limited on this project. For example, they mentioned that the building was delivered before being fully commissioned, which FM would have recommended against had they been consulted.

Construction of the **Smith Cardiovascular Research Building** started in 2008 and was completed in 2010. The building houses nearly 500 research scientists and clinicians who focus work on the development of new treatments for cardiovascular disease. This project is a landmark in UCSF's Lean journey: project team members met in the "big room" and were collocated in one large trailer. FM became more involved in the design phase and started to be recognized as important project stakeholders to consult when making design decisions.

Construction of **Mission Hall** started in 2013. The seven-story building was completed in September 2014. In terms of contractual relationships, UCSF had a Design-Build contract with the architect and the GC, which the owner selected on best value. All project team members were involved early on the project, which supported the implementation of the Last Planner System in the design phase. Furthermore, UCSF provided the design-build competing teams with the Technical Performance Criteria book "version 1.0." In version 1.0, FM weighed in, but it was involved only after the project was awarded to discuss specific FM-related issues. In the first year of building occupancy, the energy profile of the building differed from customer expectations. In fact, FM was not familiar with the underfloor mechanical system. FM had therefore to learn how to operate it. This breakdown motivated UCSF to integrate FM in project delivery earlier (cf. Block 33). Mission Hall was the first building at UCSF to be delivered with a two-year warranty.

Construction of the building on **Block 33** started in 2017. The project will provide new space split between two main programs. The building will house academic and administrative office space (including desktop research, dry core and computational laboratories), ophthalmology clinical space also called "Center for Vision Neuroscience."

Contractually, the project is delivered under a Design-Build Agreement which is UCSF's new Integrated Project Delivery (IPD)-like contract, binding the Architect to UCSF, and the GC to UCSF. The contract is qualified as "IPD-like," because it is not a multi-party agreement despite this being a fundamental requirement for IPD projects. However, the use of such contracts is legally impossible for UCSF due to its public status and the applicable contracting regulations for public entities.

For this project, UCSF created the Technical Performance Criteria book version 2.0 as part of its project definition process. The Technical Performance Criteria book documents UCSF's expectations about the building from a performance perspective. It is meant to capture what UCSF's project stakeholders value, and to translate what they value into design criteria. The Technical Performance Criteria book is the result of close collaboration between FM and a design consultant, and active engagement of relevant project stakeholders to unveil operational and physical criteria, understand space requirements, define room layouts that promote efficiency and well-being, and understand past failures and successes by visiting existing spaces and learning from precedents. The Technical Performance Criteria book is also being used for the Weill Institute for Neurosciences, Center for Vision Neuroscience, and Minnesota Housing.

The researcher was interning at UCSF during the team selection process for this project. Three prequalified teams participated in a Design/Build competition involving interviews and stress tests during which teams presented their concepts to relevant project stakeholders.

The next section summarizes the differences between LBNL and UCSF.

6.4 Comparison between LBNL and UCSF

Table 6-1 provides elements of comparison between LBNL and UCSF. The two organizations differ in many aspects: field, mission, and size (campus area, number of buildings, number of employees). Their budgets are also drastically different. Furthermore, UCSF started its Lean journey 10 years before LBNL.

Despite the major differences between the organizations, the researcher will present the same framework to UCSF and LBNL. A purpose of this validation with practitioners is to ensure that the framework is applicable to organizations operating high-end facilities but that can also be very different. The researcher gathered LBNL's and UCSF's feedback in 6.14.

Table 6-1: Elements of Comparison between LBNL and UCSF

	LBNL	**UCSF**
Field	Sciences, research	Healthcare, education, research
Organization's mission	"Solving the world's most challenging problems and answering its most elusive questions through great science and technological discovery." (LBNL 2017)	"Advancing health worldwide through preeminent biomedical research, graduate-level education in the life sciences and health professions, and excellence in patient care." (UCSF 2017c)
Number of employees	3,300	43,000
Campus size (area)	200 acres	255 acres
Number of buildings	Around 90 buildings	Around 100 buildings
Capital improvement and new construction budget	Between 70 and 90 million dollars (2017 annual budget).	More than a billion dollars for ongoing projects on UCSF campus in 2017 (2017 annual budget was not available).
Likelihood of changes in business objectives and customer requirements on the short term	High due to: • product complexity (e.g., innovations in equipment used to do research in sciences) • market complexity • organizational complexity (e.g., public institution with mechanistic structure)	High due to: • product complexity (e.g., innovation in healthcare equipment, and advances in research) • market complexity (e.g., competition with other healthcare services providers) • organizational complexity e.g., (public institution with mechanistic structure)
FM in-house vs. outsourced	In-house	In-house
Relationship between FM and Design and Construction (D&C)	Facilities and D&C are separated in two departments.	Facilities and D&C are separated in two departments.

Start of Lean journey	2017	2007

6.5 Opportunities for Improvement

At the project level, the LPDS-MDM framework highlights how Lean Construction principles help manage structural complexity on projects. However, the LPDS-MDM framework is not a solution to ensure FM involvement in project delivery hence, the need for a process and a tool. Kalantari et al. (2017) write:

"Incorporating FMs' knowledge into the design process has been of increasing interest over the past two decades; however, this interest has seldom led to specific organizational recommendations."

In their model, Kalantari et al. (2017) identified how and when FM could participate in the development of the programming and the design of a project. They developed the model with the intent of addressing specifically the barriers to FM involvement in project delivery that they previously identified in their research. They did not consider other aspects in which FM could fail, as developed in Chapter 2, section 2.4. FM failures were classified under: (1) building systems, (2) people, (3) tools and data, (4) processes, and (5) changes.

The researcher's conditions of satisfaction for the proposed process and supporting tool are described next. The process and tool must:

- Propose a way to manage some (it not all) aspects of structural complexity: customer, organizational, process, product, and market.
- Proof FM against some (if not all) common failures classified under (1) building systems, (2) people, (3) tools and data, (4) processes, and (5) changes.
- Take into account all TFV views of FM.
- Capitalize on FM knowledge by positioning FM in a role that supports learning from past facilities failures and continuous improvement, following a Plan-Do-Check-Act cycle.

6.6 Choosing-By-Advantages (CBA)

Among the diversity of FM tasks, facility upgrades fall within strategic planning. As described in Chapter 2, the strategic level was only added recently to FM scope relatively to the operational and tactical levels of planning. The value of FM for contributing to strategic planning being critical, the researcher looked into planning methods used for strategic planning in corporations. Various strategic planning methods exist, but distinguishing them can be difficult. Thus, only four methods are compared in this section due to the available elements of comparison presented in Mulligan et al. (1996). One is selected through the decision-making system "CBA" described in Chapter 2, section 2.11.1. In that respect, Mulligan et al. (1996) emphasize the fact that "the ultimate cause of the problem is that managers fail to match their planning methods to the specific challenges they are confronting," hence the need for selecting the appropriate method.

The researcher extracted the methods and their attributes from Mulligan et al. (1996) (Figure 9-9 in Appendix). She developed the factors in alignment with the four conditions of satisfaction listed previously (section 6.5) and the Lean Construction philosophy. The next paragraphs describe the four methods.

Hoshin Kanri is a planning process that links strategic objectives, with tactical and operational objectives. Through the involvement of every level of the organization from senior management to shop floor, Hoshin Kanri ensures that the strategy set will be implemented by the entire organization (Mulligan et al. 1996).

Issue-based planning is defined as "issue-centered, personal planning, by an individual executive who believes he has seen some early sign of threat or opportunity which may warrant transforming his organization." (Mulligan et al. 1996). This process usually begins when a senior manager an external threat or a source of uncertainty that could harm the business success (Mulligan et al. 1996).

Formal strategic planning (FSP) is a process driven by senior management. From a vision, philosophy and mission, it flows down to strategic business units. Functional managers are responsible for enforcing it. It is a structured process, usually hierarchical and top-down. Typically, the information that informs planning is quantitative and analytical (Mulligan et al. 1996).

Strategic assumption analysis (SAA) and **dialectic inquiry** are treated together, because SAA only proposes a procedure to implement the dialectic (Mulligan et al. 1996). Unlike FSP which is informed by a lot of quantitative data and analysis, SAA performs well in uncertain environments with limited knowledge on past, present and future. The ultimate goal is not about creating a strategic plan but rather question the validity of the strategic plan and its underlying assumptions. In the dialectic approach, the assumptions are tested by playing the devil's advocate. The process is usually initiated by senior management, but it requires a moderator. Eventually, if the process reveals that the assumptions were not valid, it can lead to (1) revealing the need for better strategy, (2) the discovery of other strategies through the debates (Mulligan et al. 1996).

Table 6-2 and Table 6-3 are the results of the CBA comparing the four planning methods described above. The tables describe the factors and criteria used for the decision. Hoshin Kanri scored 60 points, issue-based planning scored 5 points, formal strategic planning scored 1 point, and SAA and dialectic inquiry scored 6 points. Thus, the CBA led to the selection of Hoshin Kanri as a starting point for the prototyping of the solution.

Table 6-2: CBA of Planning Methods (1/2)

		Hoshin	IOA	Issue-based	IOA
Factor 1: Fitness for continuous improvement Criterion: Continuous improvement is fitter for FM integration in project delivery than change-driven methods for example, because this founding principle of the Lean philosophy prevents the acceptation of the status quo and is motivated by the tenet that the "ideal state" can always be pushed further once reached (Principle 14 of the TPS).	Attribute	High		Low	
	Advantage	Fitter for continuous improvement.	10		0
Factor 2: Embedded in the organization's routine Criterion: The more frequent "planning/policy deployment" is done, the better, because ensuring that the building delivers end-user satisfaction and best value is a continuous effort.	Attribute	On-going.		Sporadic, as needed.	
	Advantage	Most embedded in routine.	10		0
Factor 3: Planning process is driven by the entire organization Criterion: This is a want criteria, because the entire organization is a consumer of the building and the entire organization produces value from using the building. However, how the building is used to create value depends on the specific business objective(s) to which the building user is contributing.	Attribute	"Hierarchically stratified participation of entire organization." (Mulligan et al. 1996)		Planning process is driven by individual questioning current plan.	
	Advantage	Planning driven by everyone	10		0
Factor 4: Planning process is based on a PDCA cycle Criterion: a PDCA cycle is better, because it involves a feedback loop to compare outcomes against expectations, so that one can take action to eliminate deviations from the plan.	Attribute	Yes, PDCA is called "catchball."		No	
	Advantage	Process has a PDCA cycle.	10		0
Factor 5: Visibility and transparency of plan, at every level of the organization Criterion: visibility ensures that every level of the organization is aware of the process, and gets involved. Transparency enables process buy-in.	Attribute	"Pervasive through organization at the shop floor level" (Mulligan et al. 1996)		Planning is conducted by an individual, later joined by others, but remains isolated. Visibility incrementally grows.	
	Advantage	Is transparent	10		0
Factor 6: The planning content is driven by communication Criterion: communication is important, because it ensures that the planning reflects the organization's needs (at every level) and incorporates the lessons learned from the past. Communication allows a holistic approach to planning.	Attribute	Communication across all levels of the organization is a key component in the planning process.		Planning process is motivated by the issue encountered, or an individual's willingness to make a case for a change in the plan.	
	Advantage	Process mostly based on communication.	10	Some communication is involved.	5
			60		5

Table 6-3: CBA of Planning Methods (2/2)

		Formal strategic	IOA	SAA and dialectic inquiry	IOA
Factor 1: Fitness for continuous improvement Criterion: Continuous improvement is fitter for FM integration in project delivery than change-driven methods for example, because this founding principle of the Lean philosophy prevents the acceptation of the status quo and is motivated by the tenet that the "ideal state" can always be pushed further once reached (Principle 14 of the TPS).	Attribute	Low		Low	
	Advantage		0		0
Factor 2: Embedded in the organization's routine Criterion: The more frequent "planning/policy deployment" is done, the better, because ensuring that the building delivers end-user satisfaction and best value is a continuous effort.	Attribute	Annual or bi-annual.		Planned, as needed.	
	Advantage		0		0
Factor 3: Planning process is driven by the entire organization Criterion: This is a want criteria, because the entire organization is a consumer of the building and the entire organization produces value from using the building. However, how the building is used to create value depends on the specific business objective(s) to which the building user is contributing.	Attribute	Usually, a planning group is involved and it presents the plan to senior management. If accepted by senior management, the plan is deployed.		Planning process is driven by senior management.	
	Advantage	Planning driven by small group.	1	Planning driven by small group.	1
Factor 4: Planning process is based on a PDCA cycle Criterion: a PDCA cycle is better, because it involves a feedback loop to compare outcomes against expectations, so that one can take action to eliminate deviations from the plan.	Attribute	No		No	
	Advantage		0		0
Factor 5: Visibility and transparency of plan, at every level of the organization Criterion: visibility ensures that every level of the organization is aware of the process, and gets involved. Transparency enables process buy-in.	Attribute	The plan is not visible to the entire organization, since it is developed by a dedicated group.		The plan is not visible to the entire organization, since it is first developed by senior management.	
	Advantage		0		0
Factor 6: The planning content is driven by communication Criterion: communication is important, because it ensures that the planning reflects the organization's needs (at every level) and incorporates the lessons learned from the past. Communication allows a holistic approach to planning.	Attribute	Planning process is driven by costs and quantitative data.		Planning is questioned and changed (if needed) by playing the devil's advocate.	
	Advantage		0	Some communication is involved.	5
			1		6

6.7 Hoshin Kanri Implementation Steps from Literature

Different variations and representations of Hoshin Kanri exist (Bititci et al. 1997, Goal/QPC 1996 cited in Lee and Dale 1998, Meier et al. 2010, Boisvert 2012). Figure 6-5 and Figure 6-6 are two complementary examples. While Figure 6-5 emphasizes the catchball effect, Figure 6-6 breaks down Hoshin Kanri steps in further details and overlays them with the PDCA cycle.

Figure 6-5: Closed Loop Deployment and Feedback System for the Performance Management Process (Figure 2 in Bititci et al. 1997)

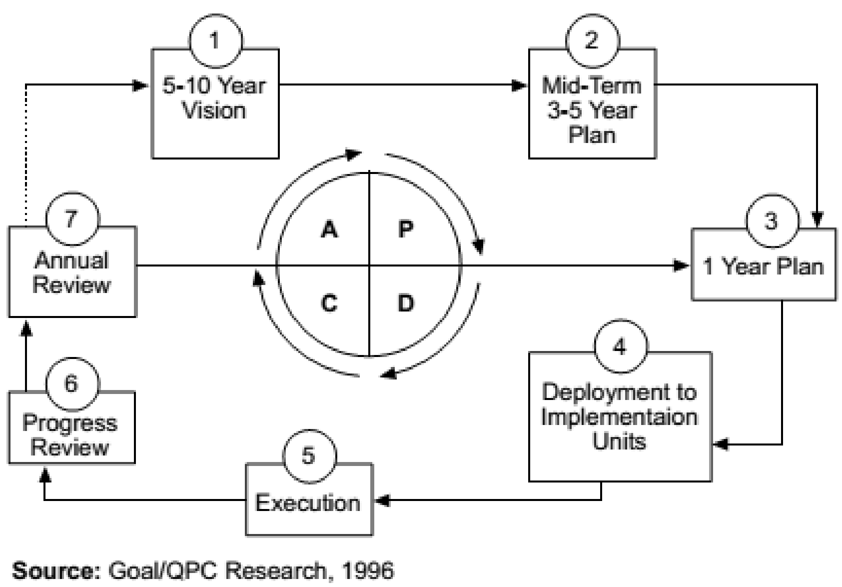


Figure 6-6: Hoshin Kanri Representation (Figure 4 in Lee and Dale 1998)

Hoshin Kanri implementation steps are as follows (Nicholas 2016):

1. "Analyze organizational and environmental data for strategic planning.

2. Develop mission/purpose relating the company to its customers.
3. Develop a philosophy addressing what the organization cares about.
4. Develop a vision that defines the organization's direction and aspirations.
5. Develop long- and medium-term objectives and strategies to achieve the vision. Senior and division managers use catchball to develop objectives.
6. Develop annual plans to achieve long- and medium-term objectives. Senior and division managers use catchball to create plans that include:
    - A 'vital few' objectives that will bring 'breakthrough' improvements.
    - Annual strategies/means to achieve the objectives.
    - Targets for expected results.
    - Means/actions to be taken to achieve the desired results.
    - Measures to monitor progress and check whether strategies were appropriate.
7. Deploy policies: engage entire organization to align plans with the organization's strategic direction; cascade plans to every level using catchball.
8. Implement plans and daily management: deploy annual plans to achieve breakthrough objectives while controlling and improving business fundamentals (daily management).
9. Review progress: identify problems, take corrective action, prepare revisions to plans.
10. Standardize processes and work tasks: retain gains resulting from breakthrough and routine improvements."

The next section proposes a model, named "Hoshin-for-Facilities," which builds upon Hoshin Kanri to enable FM integration in project delivery.

6.8 Proposed Model: Hoshin-for-Facilities

Figure 6-7 represents the House of Quality. The terms "House of Quality" were coined by Hauser and Clausing (1988). The House of Quality is identifiable by the triangular DSM that constitutes the roof of the house. The DSM captures dependences between technical requirements. In addition, the House of Quality includes 3 DMMs. The first captures dependences between customer requirements and technical requirements. The second captures dependences between customer requirements and criteria. The third captures dependences between technical evaluation and technical requirements.

The House of Quality builds upon the method of the Quality Function Deployment (QFD), which was invented by the Japanese in the mid-1960s (Bahill and Chapman 1993, Prasad 1998). Sullivan (1986) defines QFD as:

"An overall concept that provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production (i.e., marketing strategies, planning, product design and engineering, prototype evaluation, production process development, production, sales)."

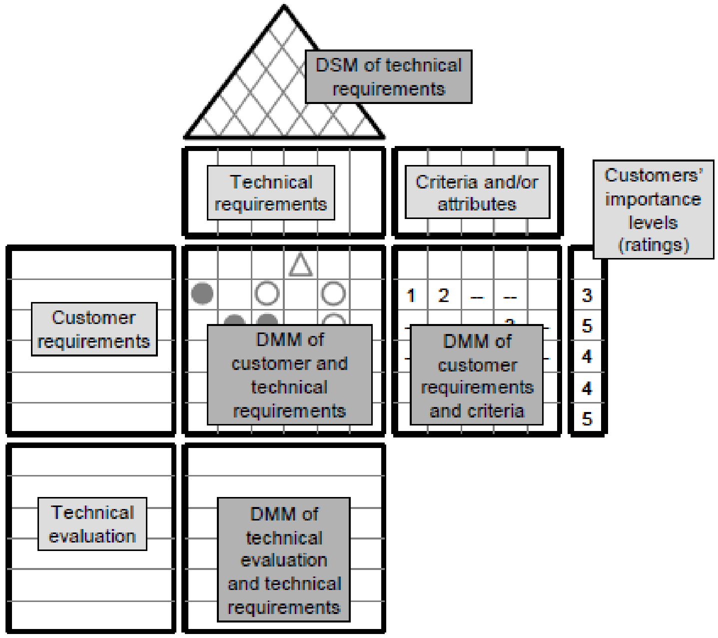


Figure 6-7:The House of Quality and Implied DMM Structures (Figure 2-10 in Maurer 2007)

Figure 6-8 shows the adapted Hoshin Kanri to integrate FM in project delivery. This prototype results from iterations. The Hoshin-for-Facilities MDM draws from the House of Quality, involving a DSM and MDMs. It includes 3 DSMs, 5 MDMs, and a table.

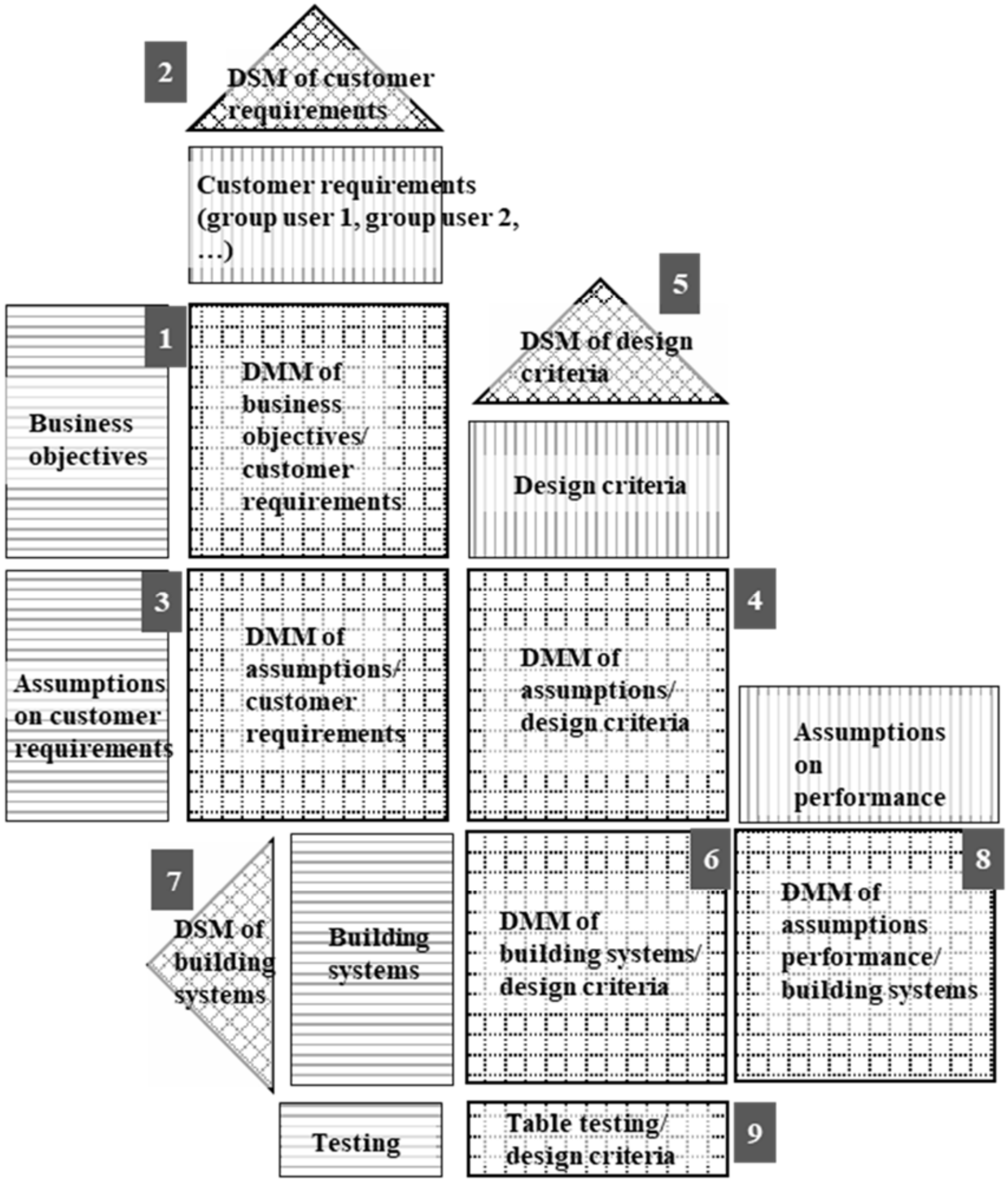


Figure 6-8: Hoshin-for-Facilities MDM for FM Integration in Project Delivery

The project teams should read the Hoshin-for-Facilities MDM in the following sequence:

1. The DMM captures the dependences between the business objectives and the customer requirements.
2. The DSM captures the dependences (including potential conflicts) between customer requirements.
3. The DMM captures the dependences between the design assumptions and the customer requirements.

4. The DMM captures the dependences between the assumptions and the design criteria.
5. The DSM captures the dependences between the design criteria.
6. The DMM captures the dependences between the building systems and the design criteria.
7. The DSM captures the dependences between building systems.
8. The DMM captures the dependences between assumptions on building systems' performance and building systems.
9. A table captures the testing protocols for each design criterion.

Table 6-4 captures the intent underlying each element of the Hoshin-for-Facilities MDM.

Table 6-4: Intent underlying Elements of Hoshin-for-Facilities MDM

Element Number in Figure 6-8	**Element Description**	**Intent**
1	DMM of business objectives/ customer requirements	• Check that customer requirements are tied to the business objectives • Identify redundancy in customer requirements: redundant customer requirements can take precedence over others • Ensure transparency of expressed requirements across user groups, departments, or business units
2	DSM of customer requirements	• Reveal conflicts in customer requirements (customer complexity)
3	DMM of assumptions/ customer requirements	• Differentiate assumptions from customer requirements • Create transparency and shared understanding in project team about what the "known unknowns" are on the project • Later assess uncertainty on assumptions and map its impact on design criteria
4	DMM of assumptions/ design criteria	• Differentiate assumptions from design criteria

Element Number in Figure 6-8	**Element Description**	**Intent**
		• Understand how changes in assumptions will impact design criteria
5	DSM of design criteria	• Reveal dependences or conflicts between design criteria
6	DMM of building systems/ design criteria	• Increase transparency on selection of building systems • Ensure that building systems selected are pulled from the customer requirements (as opposed to a selection based on the design team's experience with them)
7	DSM of building systems	• Reveal dependences between building systems (product structural complexity) • Point out where needs for "integration" between building systems will be critical to achieve desired performance
8	DMM of assumptions on expected performance/ building systems	• Increase transparency on customer's side in expected performance • Ensure alignment between customer's and project team's expectations
9	Table of performance testing protocols / design criteria	• Ensure that "expected performance" expressed by project team can be and will be tested • Ensure that the "Check" part of the PDCA cycle is embedded in the process • Ensure that systems are selected with the intent to test them • Increase reliability of "promises" on expected performance ranges

The Hoshin-for-Facilities MDM being composed of 9 elements, populating it can be daunting especially for people who are unfamiliar with the DSM methodology. The goal of the next section is to guide users on how they can populate the Hoshin-for-Facilities MDM. It provides the suggested sequence and identifies potential process iterations.

6.9 Proposed Process to Populate the Hoshin-for-Facilities MDM

The proposed process steps to populate the DSMs and DMMs in the Hoshin-for-Facilities MDM (Figure 6-8) are as follows:

- Determine the business objectives.
- Identify the customer requirements.
- Identify dependences between business objectives and customer requirements. Can all customer requirements be tied to a business objective?
    - No. Reconsider: (1) the exhaustiveness of the business objectives and (2) the validity of the customer requirement.
    - Yes. Proceed to next step.
- Map dependences between customer requirements. Distinguish two types of dependences: compatibility of customer requirements vs. incompatibility of customer requirements using two different symbols. Are some customer requirements incompatible?
    - Yes. Initiate discussion on incompatibility of customer requirements with customers. Determine whether some group users have precedence over others.
    - No. Proceed to next step.
- Translate customer requirements into assumptions for the design. Check validity of assumptions. Include any other assumption that is formulated in the design phase.
- Map dependences between assumptions and customer requirements.
- Infer design criteria from customer requirements.
- Map dependences between design criteria and assumptions. Are all design criteria mapped to one or more assumptions?
    - No. Reconsider the exhaustiveness of assumptions.
    - Yes. Proceed to next step.
- Map dependences between design criteria.
- List building systems.
- Identify dependences between building systems and design criteria.
- Identify dependences between building systems.
- List assumptions on the expected performance of the building systems.
- Map dependences between asumptions on performance and building systems.
- Identify protocols (if any) to test whether building systems meet the design criteria during design, construction, commissioning, and the use phase.

To illustrate the proposed process, the next section covers an academic application.

6.10 Academic Application of Hoshin-for-Facilities

This section presents an academic application of Hoshin-for-Facilities. A sustainable high school will serve as example.

6.10.1 Business Objectives

The primary objectives of this high school are to be a center of learning and efficient transmission of knowledge through the accommodation of different leaning styles. Secondary objectives include: provide a safe, caring, and stimulating environment for all students in order to help them grow their self-confidence; foster team work and collaboration between students; attract the best teachers; and be affordable to families.

6.10.2 Customer Requirements

Customers of a high school building include, to name a few: students, teachers, assistants, counselling, administration, facility management, and authorities acting at the school district or state level. For brevity, only three user groups are captured in this example: students, teachers, and FM.

Figure 6-9 captures the DMM of business objectives and customer requirements.

			CUSTOMER REQUIREMENTS									
			STUDENTS					TEACHERS		FM		
			Feel comfortable	Feel less stressed and anxious than in regular school environments	Make going to school enjoyable	Make friends	Be prepared for college: learn how to learn	Support different teaching styles	Focus on teaching over enforcing discipline	Deliver best value	Ensure end-user satisfaction	Spend less time on operational maintenance
			B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
BUSINESS OBJECTIVES	Be a center of learning	A1	x				x					
	Accommodate different learning styles	A2		x								
	Provide a safe, caring, and stimulating environment	A3	x	x	x							
	Foster team work and collaboration	A4				x						
	Attract the best teachers	A5						x	x	x	x	
	Be affordable to families	A6								x		x

Figure 6-9: DMM of business objectives and customer requirements

6.10.3 Assumptions

The design team and the customer make assumptions during the design. Examples of assumptions include, to name a few: the number of students that the high school will accommodate, what temperature range qualifies as “comfortable temperature,” and the impact of furniture arrangement on students’ capacity to learn and teachers’ capacity to teach. Figure 6-10 captures the DMM of assumptions and customer requirements.

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			CUSTOMER REQUIREMENTS									
			STUDENTS					TEACHERS		FM		
			Feel comfortable	Feel less stressed and anxious than in regular school environments	Make going to school enjoyable	Make friends	Be prepared for college: learn how to learn	Support different teaching styles	Focus on teaching over enforcing discipline	Deliver best value	Ensure end-user satisfaction	Spend less time on operational maintenance
			B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
ASSUMPTIONS	The high school will accommodate 1,500 students	C1									x	
	A temperature comprised between 68F and 75F is comfortable for most people	C2	x									
	Variation in colors and textures can reduce occupants' stress level	C3		x	x							x
	Good acoustical insulation can reduce occupants' stress level	C4		x								
	Good acoustical insulation can increase occupants' capacity to focus	C5							x			
	Indoor green plants can reduce occupants' stress level	C6		x	x							
	Open spaces support collaboration and team work	C7					x					
	Pieces of furniture such as sofas invite students to relax and spend more time at school	C8										
	The arrangement of the classroom furniture is an integral part of a teaching style	C9						x				
	Sustainable buildings have lower operating costs	C10								x		

Figure 6-10: DMM Assumptions / Customer Requirements

6.10.4 Design Criteria

Examples of design criteria are, to name a few: provide an indoor temperature between 69°F (20.5°C) and 74°F (23.3°C); provide an open space that can accommodate 20% of the students' population at a time; use different types of finishes in the classroom to provide diversity in colors and textures; and use materials that provide acoustical insulation. Figure 6-11 captures the DMM of assumptions and design criteria.

ASSUMPTIONS		D1 Provide an indoor temperature 69F - 74F	D2 Provide an open space that can accommodate 20% of the students'	D3 Use different types of finishes in the classroom to provide diversity in colors and textures	D4 Use materials that have a high acoustical insulation property	D5 Landscaping must be colorful and aesthetically pleasant	D6 Provide indoor plants	D7 In open space, provide sofas	D8 Provide movable furniture to allow students and teachers to arrange the space to their liking	D9 Provide 16 classrooms	D10 Be compact in shape	D11 Have windows oriented south	D12 Increase thermal mass	D13 Provide windows great insulating power	D14 Eliminate thermal bridges	D15 Make the building air-leak proof	D16 Re-use waste heat	D17 Use low-energy heating
The high school will accommodate 1,500 students	C1		X							X								
A temperature comprised between 68F and 75F is comfortable for most people	C2	X																
Variation in colors and textures can reduce occupants' stress level	C3			X		X												
Good acoustical insulation can reduce occupants' stress level	C4				X													
Good acoustical insulation can increase occupants' capacity to focus	C5				X													
Indoor green plants can reduce occupants' stress level	C6						X											
Open spaces support collaboration and team work	C7		X															
Pieces of furniture such as sofas (which are not common in schools) invite students to relax and spend more time at school	C8							X										
The arrangement of the classroom furniture is an integral part of a teaching style	C9								X									
Sustainable buildings have lower operating costs	C10										X	X	X	X	X	X	X	X

Figure 6-11: DMM Assumptions / Design Criteria

6.10.5 Building Systems

Building systems may include: site and landscape, shell and finish, interiors, utilities, heating system, cooling system, ventilation system, water system, lighting system, control system, and fire protection system. Figure 6-12 captures the DMM of building systems and design criteria. Figure 6-13 captures the DSM of building systems (the researcher only populated the upper triangle, the lower triangle is symmetric). The intent underlying the DSM of building systems (Figure 6-13) is to reveal interdependences between systems from a design perspective. Here, two building systems are interdependent if they help fulfill at least one same design criterion.

The researcher followed the following process to create Figure 6-13:

- The diagonal of the DSM is composed of the design criteria that each system contributes to fulfill. Thus, a diagonal cell E indexed "i" in Figure 6-13 should list all the design criteria checked in row E indexed "i" in Figure 6-12. For example, the building system "E6: Cooling" helps fulfill the design criteria "D1," "D13," and "D14" Figure 6-12. As a result, in the DSM of building systems (Figure 6-13), the diagonal cell "E6: Cooling" lists "D1," "D13," and "D14."
- From the populated diagonal (Figure 6-13), the researcher computed the upper triangle of the matrix. For a given row E indexed "i:"
    - If the design criterion D indexed "j" is shared with other building systems such as E indexed "k," a dependence is added between E indexed "i" and E indexed "k." For example, the design criterion "D4" is listed in the diagonal cells "E2" and "E3" (that means that both E2 and E3 help meet the design criterion "D4"). Thus, the researcher added a dependence "D4" in the cell at the intersection of row E2 and column E3.
- The researcher took an additional pass to capture emerging dependences, not captured in the previous step.

In the Hoshin-for-Facilities MDM (Figure 6-15), the researcher summarized the results from Figure 6-13 by summing the number of design criteria in each cell and representing this sum by a dot of proportional size.

BUILDING SYSTEMS		DESIGN CRITERIA: Provide an indoor temperature between 69F - 74F	Provide an open space that can accommodate 20% of the students' population at a time	Use different types of finishes in the classroom to provide diversity in colors and textures	Use materials that have a high acoustical insulation property	Landscaping must be colorful and aesthetically pleasant	Provide indoor plants	In open space, provide sofas	Provide movable furniture to allow students and teachers to arrange the space to their liking	Provide 16 classrooms	Be compact in shape	Have windows oriented south	Increase thermal mass	Provide windows great insulating power	Eliminate thermal bridges	Make the building air-leak proof	Re-use waste heat	Use low-energy heating
		D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17
Site and landscape	E1					X												
Shell and finish	E2	X			X						X	X	X		X	X		
Interiors	E3		X	X	X		X	X	X	X							X	X
Utilities	E4	X																
Heating	E5	X									X	X	X	X	X		X	X
Cooling	E6	X												X	X			
Ventilation	E7													X		X		
Water	E8																	
Lighting	E9													X			X	
Control	E10	X																X

Figure 6-12: DMM of Building Systems and Design Criteria

			BUILDING SYSTEMS									
			Site and landscape	Shell and finish	Interiors	Utilities	Heating	Cooling	Ventilation	Water	Lighting	Control
			E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
BUILDING SYSTEMS	Site and landscape	E1	D5									
	Shell and finish	E2		D1, D4, D10, D11, D12, D14, D15	D1, D4, D14	D1	D1, D10, D11, D12, D13, D14	D1, D12, D13, D14	D1, D13, D15			D1
	Interiors	E3			D2, D3, D4, D6, D7, D8, D9, D16, D17		D16, D17				D16	D17
	Utilities	E4				D1	D1	D1				
	Heating	E5					D1, D10, D11, D12, D13, D14, D16, D17	D1, D14	D11, D13, D16		D16	D1, D17
	Cooling	E6						D1, D13, D14	D11, D13			D1
	Ventilation	E7							D1, D13, D15			D1
	Water	E8										
	Lighting	E9									D16	
	Control	E10										D1, D17

Figure 6-13: DSM of Building Systems

6.10.6 Assumptions on Expected Performance

This step ensures that prerequisites for the testing of the building systems are revealed. For example, the controls engineer may require that the Testing, Adjust, and Balancing is done prior to the fine-tuning of the controls. Since building systems are increasingly more integrated, the pass/fail of a test on a system may be dependent on the pass/fail of other tests. Design should strive for making building systems "testable" independently as much as possible.

6.10.7 Testing Protocols

Design criteria can be tested at different stages of the building life cycle. For example, simulation tools exist to model indoor temperature. Using them could be a first step in testing the building with respect to its ability to meet design criterion D1. D1 can also be tested during the commissioning and the use phase. Some tests may involve just a visual check.

				TESTING PROTOCOLS					
				DESIGN	CONSTRUCTION	COMMISSIONING	USE (1 yr)	USE (3 yrs)	USE (N yrs)
				G1	G2	G3	G4	G5	G6
DESIGN CRITERIA	D1	Provide an indoor temperature between 69F and 74F	F1	x		x	x	x	x
	D2	Provide an open space that can accommodate 20% of the students' population at a time	F2	x			x	x	x
	D3	Use different types of finishes in the classroom to provide diversity in colors and textures	F3	x			x	x	x
	D4	Use materials that have a high acoustical insulation property	F4	x		x	x	x	x
	D5	Provide colorful and aesthetically pleasant landscaping	F5	x			x	x	x
	D6	Provide indoor plants	F6	x			x	x	x
	D7	In open space, provide sofas	F7	x			x	x	x
	D8	Provide movable furniture to allow students and teachers to arrange the space to their liking	F8	x			x	x	x
	D9	Provide 16 classrooms	F9	x					
	D10	Be compact in shape	F10	x					
	D11	Have windows oriented south	F11		x				
	D12	Increase thermal mass	F12	x					
	D13	Provide windows great insulating power	F13	x			x	x	x
	D14	Eliminate thermal bridges	F14	x					
	D15	Make the building air-leak proof	F15			x	x	x	x
	D16	Re-use waste heat	F16				x	x	x
	D17	Use low-energy heating	F17				x	x	x

Figure 6-14: Table of Testing Protocols and Design Criteria

6.10.8 Summary

Figure 6-15 gathers the previously presented DSMs and DMMs in the Hoshin-for-Facilities MDM, introduced in section 6.8.

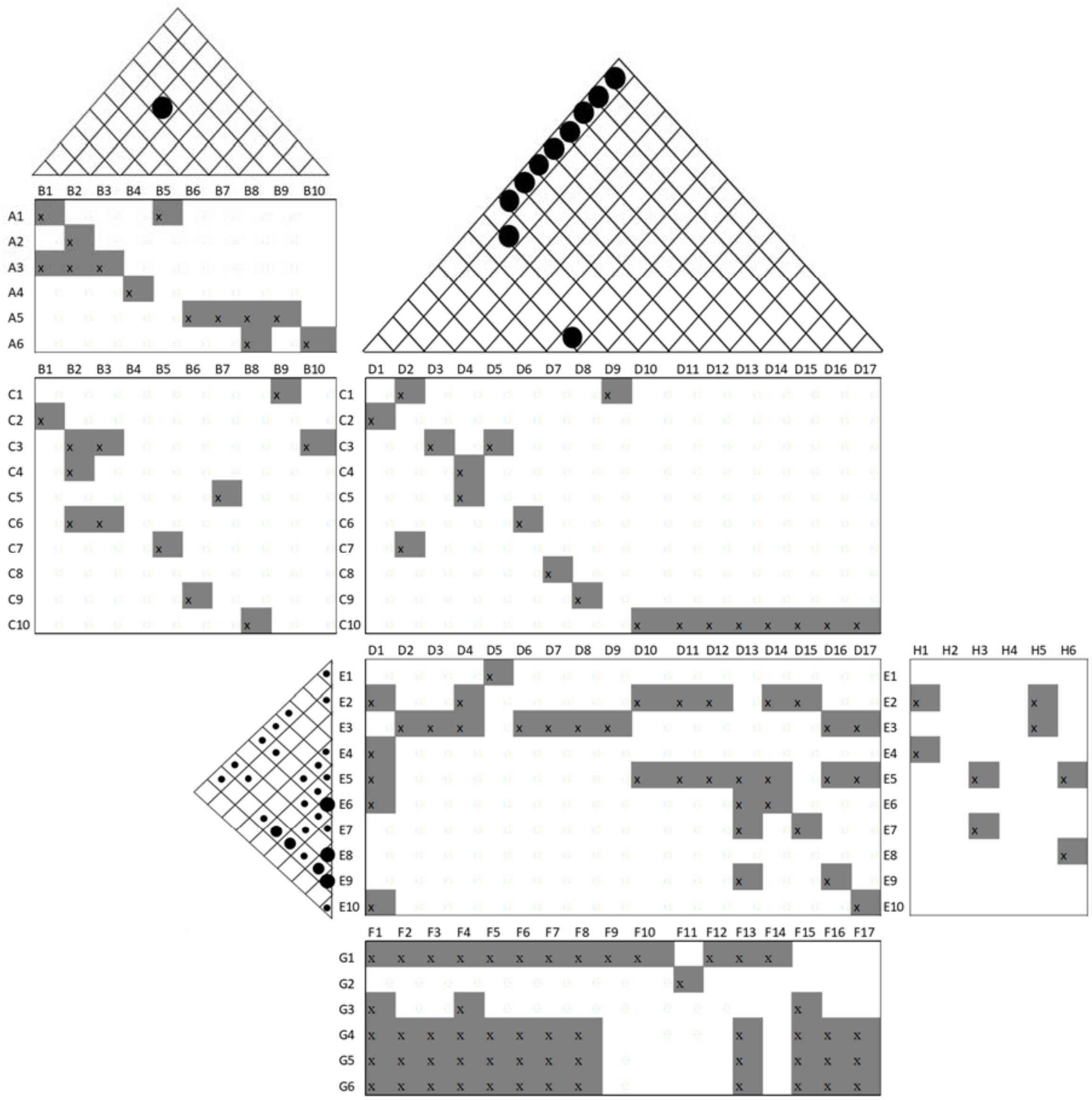

Figure 6-15: Results of Academic Application of Hoshin-for-Facilities

The DSM of the customer requirements shows one potential conflict between requirements B3 and B7. The DSM raises the designers' awareness on requirements that may be more challenging to meet due to conflicts.

The assumptions underlying the design criteria are made explicit. The project delivery team could ensure that either they are valid or the magnitude of uncertainty surrounding the assumption. Customer requirements B2 and B3 rely on multiple assumptions. How certain are these assumptions? Can they be validated by customers, data, or else?

The DSM of the design criteria shows that D1 relies on multiple other design criteria. Thus, if further design development considers the elimination or modification of these other design criteria, the design's ability to meet D1 may be affected.

The MDM of the design criteria and assumptions shows that many rely on the validity of the assumption C10. Could the delivery team ensure that C10 is valid? Or can the team identify the certainty/uncertainty surrounding this assumption and generate alternatives to reduce the uncertainty?

The MDM of the building systems and design criteria shows that building systems E2, E3, and E5 must be compatible, integrated, and tested together to ensure that they meet the design criteria that depend on them.

The DSM of building systems shows that the systems E6, E8, and E9 deserve particular attention in the design, since they help meet a significant number of design criteria. The integrations of E9 with E5, E9 with E6, and E9 with E8 are critical to ensure that the design meets customer requirements.

6.11 Assumptions and Recommendations for Practice

Multiple DSM/MDM software applications are commercially available, including: ADePT Design Software suite (ADePT 2017), Boxarr (Boxarr 2017), Lattix (Lattix 2017), Loomeo (Loomeo 2017), or made accessible for free by academic institutions, including: Cambridge Advanced Modeler (CAM 2014), and Excel macros developed by Professor Eppinger's students at MIT shared in Lindemann (2016). More software applications can be found on dsmweb.org, a website created by Professor Lindemann from the Technical University of Munich. The benefit of using such applications is in part the ease of use of different algorithms for both static and dynamic DSMs. However, for the implementation of Hoshin-for-Facilities, Excel is sufficient to reap the intended benefits of this process as listed in Table 6-4.

Assumptions for practice are as follows:

- **Be familiar with the DSM methodology**. If the project team is not familiar with DSM, a DSM consultant can be brought in to introduce the methodology.
- **Be familiar with the TFV model of production.** The owner must understand the Lean philosophy and must be value-oriented (not only cost-oriented).
- **Create a psychologically safe environment.** A psychologically safe environment will encourage project stakeholders, including FM to actively engage in project definition and design conversations (Edmondson 1999).
- **Work with an integrated project team.** Information required to populate the Hoshin-for-Facilities MDM requires some expertise. The early involvement of domain experts is therefore critical for its success.

- **Have in-house FM.** In-house FM will be more familiar with the facilities and past experiences than outsourced FM.

Recommendations for practice are as follows:

- **Make the process transparent**. Each time the team adds some additional information to the tool, the new version should be printed and displayed so that everyone in the organization can see it.
- **Make incremental progress and validate often.**
- **Iterate.** Iterate the process several times and keep a database of previous versions.
- **Learn**. Capture the lessons learned from the process and augment the proposed MDM with additional DSMs and MDMs when appropriate.

The opportunities for improvement listed in Section 6.5 guided the overall development of Hoshin-for-Facilities. At a finer level of granularity, Table 6-4 lists the intent underlying each element of the MDM (that is, the intended benefits). Section 6.12 identifies additional benefits in using Hoshin-for-Facilities.

6.12 Additional Benefits

6.12.1 Discussion on "Design Intent" and "Basis of Design"

The design intent defines "the benchmark by which the success of a project is judged" (Stum 2002), while the basis of design is "the narrative description of what the designer will or has developed to respond to and meet the owner's project requirements, including the assumptions and criteria used" (Stum 2002). Although Hoshin-for-Facilities (Figure 6-8) does not use the terms "design intent" and "basis of design," it still captures the design intent in the "customer requirements" DSM and the dependences between the design intent and the basis of design in the "assumptions/customer requirements" MDM, and "design criteria."

In a traditional process, the design team develops the basis of design after being handed over the design intent (and sometimes these two happen concurrently) by the owner. Since the design intent usually continues to change after the basis of design is initiated, it requires that the hand-off between the owner and the design team takes place multiple times or is continuous. This involves risks that could undermine the project success. A first risk is that a change in the design intent could be missed by the design team. A second risk is that the assumptions made by the design team are not validated by the owner, and could thus be incorrect. This risk stems from the fact that the traditional process does not involve a formal feedback loop between the development of design criteria and the refinement of project requirements. A third risk is that a dependence between design criteria and design intent is missed due to the lack of screening of assumptions (missed assumption).

Therefore, from a "basis of design" perspective, the benefit of using the proposed MDM is twofold: (1) make changes "easier to see" and (2) ensure transparency in the information exchanged and its underlying assumptions. Thus, this process could help avoid negative design iteration.

6.12.2 Delaying the Act of Drawing

Be it in traditional or lean project delivery, architects/designers like to draw (or model): they like transforming concepts into shapes, lines, volumes, colors, and textures. When the researcher attended meetings during the team selection process for Block 33 at UCSF, she observed that some architects talked passionately about a design; it is not uncommon to hear that architects "fall in love" with their design. Yet, since architects are tempted to start to draw early on in the project definition phase, the risk is that they favor a specific design rather than explore a set of alternatives using a set-based design strategy.

Thus, a potential benefit in using Hoshin-for-Facilities is to delay the "act of drawing" by focusing on the information flow, dependences, what the owner values, and thus understand the sources of uncertainty.

6.12.3 Reduce Project Documents Production

Another benefit of Hoshin-for-Facilities is increased transparency in the project definition and design development phases. Traditionally, project teams produce multiple sets of project documents during those phases. On top of that, the production of these documents requires multiple iterations. As a result, multiple versions of a same document exist. The burden is on project team members to always keep up with the most up-to-date version of the document. A "single version of truth" becomes difficult to identify, which makes the design process more prone to errors. Instead, Hoshin-for-Facilities can be used as the "single version of truth," and thus allow the elimination of unnecessary documents.

Furthermore, handover documents often lack information on the design intent (Dahl et al. 2005, Sunnam et al. 2015), which poses difficulties to operate and maintain the building. The historical versions of the Hoshin-Kanri based model that were developed by the team could become part of the handover documents.

6.13 Going Further with Hoshin-for-Facilities

6.13.1 Structural Complexity: Going a Level Further in the Hierarchy

A structurally complex system may be broken down hierarchically (Simon 1962) into sub-systems, which can further be broken down into sub-systems, and so, recursively. This choice of decomposition is subjective: it is in the "eyes of the beholder" as well as the tools and means used to look at it (Espejo and Reyes 2011).

Hoshin-for-Facilities can be adapted to accommodate the hierarchical structure of complex systems and the subjectivity underlying the understanding of complexity. Examples of "adaptations" are listed as follows:

- Customer requirements can be broken down to a finer level of granularity than traditional "user groups." For example, FM itself encompasses many sub-groups, which could be captured under the "customer requirements" DSM and MDMs.

- Hoshin-for-Facilities shows "building systems." These could be broken down into assemblies and components. Related, among the critical concerns for maintainability in design, Dahl et al. (2005) list the standardization of components. Thus, listing the specific assemblies and components composing each system could help FM reduce variety in components.
- The previous item would allow the introduction of "design parameters," which could be mapped against design criteria in an MDM, and against building assemblies and components in another MDM. Furthermore, a DSM of "design parameters" could be used along with a sequencing algorithm to find the optimal design sequence.

6.13.2 Modeling of Change Impact

Clarkson et al. (2001, 2004) outlined a change prediction method to predict change propagation in redesign projects. The change prediction method involves the use of multiple DSMs and risk management techniques. The method could be implemented on the building components DSM to predict the risk of change propagation between building components. This could be valuable in the design phase when a system is redesigned: the project team would be able to instantly visualize which components are likely to be impacted by the change.

The visualization of "likely" change impacts would also encourage project teams to adopt design practices that help avoid negative design iteration (e.g., set-based design over point-based design). The method could also be used after the building is constructed and when new customer requirements emerge. It could help answer questions such as: "Which systems are likely to be impacted by the addition of this new piece of equipment?" "Is the performance of the existing equipment likely to change?" and "Which design criteria may no longer be met after this addition?"

6.14 Feedback from UCSF and LBNL on Hoshin-for-Facilities

The next paragraphs present feedback received from UCSF and LBNL Hoshin-for-Facilities introduced in sections 6.8 and 6.9.

UCSF sees value in strategically integrating FM in project delivery, since they have themselves experienced building breakdowns due to a lack of FM. UCSF has realized that FM has tacit knowledge about buildings and systems that must be taken into account in the design. For example, when FM at UCSF is asked their preference for building systems, their answer is straightforward. FM at UCSF wants systems that have proven to be reliable (in other buildings), simple to use, or that FM is familiar with. Using Hoshin-for-Facilities, FM at UCSF specifies systems to reduce complexity at the building systems level, represented in the DSM of building systems.

However, UCSF noticed that FM does not fully understand the complexity of the programs housed by a facility when specifying systems that they (FM) want. It is worth mentioning that UCSF facilities commonly house multiple programs. Yet, installed systems must serve those programs. This requires that FM understands interdependences between programs and systems, that is, how building systems can serve those programs. In this respect, UCSF agreed that Hoshin-for-Facilities allowed to fill this gap, specifically by populating the DMM of business objectives and customer requirements. Integrating FM in project delivery allows FM to understand the complexity of the business objectives (Element 1 in Figure 6-8) and how they translate into customer requirements (Element 2 in Figure 6-8). This allows FM to make better recommendations for building systems (Element 6 in Figure 6-8). FM does so by leveraging their tacit knowledge on past performance of building systems (Element 8 in Figure 6-8).

Section 6.11 recommended that delivery teams use Hoshin-for-Facilities to learn. In this respect, UCSF currently learns from projects through two processes. First, project teams create A3s to document both decisions made during the design and construction and their outcomes. This allows teams to understand the rationale for a decision, keep a record of it, and learn from it. Second, UCSF's Lean senior manager organizes monthly meetings during the project design and construction phases to collect lessons learned. UCSF agreed that Hoshin-for-Facilities could make the learning feedback loop from projects more systematic and make data easier to retrieve to inform future projects.

LBNL being less advanced than UCSF on its Lean journey, it is more conservative when assessing the applicability of Hoshin-for-Facilities in projects. While LBNL sees the benefits of this process, it pointed out that success in implementing it requires all project team members' (not only FM's) buy-in. LBNL could obtain this buy-in if project team members see value in it. Conveying the value of the process seems easier if project team members are familiar with the Lean philosophy. Thus, LBNL conveyed the idea that a Lean culture could be listed in the assumptions for the implementation of Hoshin-for-Facilities (section 6.11).

6.15 Conclusions

Chapter 6 explores the use of Hoshin Kanri to support and enable FM integration in project delivery. First, it depicts the current state of FM integration at two large public organizations, LBNL and UCSF. While both organizations have similarities (public, research-oriented, operating high-end facilities, based in California), they have different approaches to FM. Unlike LBNL, UCSF has been involving FM increasingly early in project delivery. Considering that UCSF started its Lean journey ten years before LBNL, are could FM early integration in project delivery be correlated with Lean adoption? Answering this question is out of the scope of this chapter. However, the chapter proposes that project delivery teams use Hoshin-for-Facilities to strategically integrate FM in project delivery. The researcher tested Hoshin-for-Facilities with an academic example (a sustainable high school). This helped identify assumptions and recommendations for implementation. It also revealed some limitations. The researcher gathered feedback on Hoshin-for-Facilities from UCSF and LBNL. Further research should test the model on a real-life case study such as a high-end facility.

Chapter 7 summarizes the research findings.

7. CONCLUSIONS

Chapter 7 summarizes the findings of this research. It is organized as follows. Section 7.1 answers the research questions underlying the research objective. Section 7.2 summarizes recommendations for best practice to model complexity at the project level, and then gives recommendations for best practice to engage Facility Management (FM) in project delivery. Section 7.3 identifies contributions to knowledge. Section 7.4 discusses possible limitations. Section 7.5 lists knowledge disseminations. Section 7.6 suggests directions for future research in Design and Construction (D&C) and FM. Section 7.7 concludes this research with final remarks.

7.1 Research Questions and Answers

This section answers the research questions introduced in section 1.6. Research questions are grouped as follows: questions 1 to 5 focus on FM, questions 6 to 10 focus on project structural complexity, questions 11 to 12 focus on the proposed Hoshin Kanri process.

1. **What is the case for FM integration in project delivery?**

The question was addressed by reviewing the existing literature (section 2.3) and by analyzing four examples extracted from the cooling tower case (sections 3.4 and 3.5) and the supercomputer case (section 0). Findings from the case studies are summarized next.

With respect to the steel structure re-design in the cooling tower case, FM had knowledge on the existing conditions of the roof and could have informed designers early on the infeasibility of the proposed installation. FM integration could have avoided a negative iteration. The re-design of the structural steel prolonged the transition phase during which the new cooling tower was not able to meet customer requirements. Furthermore, FM knew which existing equipment and installations were needed for the maintenance of the existing cooling towers. Involving them in design could have avoided another cycle of negative design iteration regarding the re-design of the 20” pipe. The pipe had to be relocated due to the its location conflict with the existing screen wash sink needed for the maintenance of the existing cooling towers, because the Engineer did not plan for a fallback in case the first cooling tower could not be fine-tuned as expected.

With respect to the planning of the work on the cooling tower case, FM had a better understanding of the uncertainty concerning the fine-tuning of the cooling towers and could have recommended time buffers for uncertain activities in the schedule. Schedule reliability was important to the Advanced Light Source (ALS), a project customer, since it had to coordinate with researchers and inform them about when they could reliably use the beamlines booked months in advance.

With respect to cooling tower selection, design criteria for the expected flow were not made explicit for the transition phase: "Would the first new cooling tower be able to provide 'enough' ('enough' should have been defined) flow and control over the temperature to guarantee the continuous operations of ALS?" "In what circumstances could ALS lack water or control over the temperatures?" FM could have asked the Engineer to be more explicit about the expected performance during the transition phase. In addition, FM would have helped the project team better understand the performance and limitations of the existing cooling towers. FM would have asked the Engineer how the performance of the new cooling towers compared against the existing ones.

With respect to Value Engineering (VE) in the supercomputer facility case, FM would have been able to inform the design on the feasibility of- and the risk associated with the free cooling approach. FM would have asked questions so as to reveal the numerous dependences and assumptions underlying the proposed design. They would have shared experiences on recurrent difficulties encountered in buildings to maintain thermal comfort and accordingly, their concerns about the proposed design.

In conclusion, the case studies suggest that early FM integration in project delivery can help avoid waste and generate value. FM's tacit knowledge about buildings, existing conditions, occupants, past project failures and successes, helps identify dependences, regularly overlooked by- or unknown to architects/designers and contractors. Once revealed, dependences can be managed.

2. **What is the case for FM integration in project delivery?**

This research captures the current state of FM engagement in project delivery by examining how FM is integrated in project delivery at two large public organizations (section 2.1.2 and section 6.2).

At the Lawrence Berkeley National Laboratory (LBNL), FM is collocated with Engineering and Project Management. However, FM does not appear to be strategically engaged in the planning, design, and execution of construction projects. Although FM provides input, it is not empowered to "stop the assembly line."

At the University of California San Francisco (UCSF), FM has been involved increasingly early in project delivery. Before 2006, FM was not involved in project delivery. Today, they directly contribute to the writing of the Technical Performance Criteria in the preproject definition phase. UCSF realized the importance of integrating FM in project delivery: FM knows customers and how buildings actually perform. Thus, FM can commit to steering the building so that it meets customer requirements and ultimately delivers value to building occupants.

In conclusion, practitioners and academics have acknowledged the importance of early and strategic FM engagement in project delivery. However, FM engagement is not systematic in practice. From one organization to the next and even across projects within an organization, FM engagement in project delivery may greatly vary.

Impediments to FM engagement in project delivery exist (section 2.3.7). Examples of impediments include: difficult collaboration between architects/engineers and FM due to ingrained practices, variety in FM practices (e.g., work scope, scope division, department structure), and short-term cost reduction strategies.

3. **How does FM fail?**

FM fails when it is unable to steer the building so that it meets customer requirements. This can be qualified as waste.

From the literature reviewed, the researcher classified FM failure in five categories: (1) building systems, (2) people, (3) tools and data, (4) processes, and (5) changes (section 2.4). The category “building systems” captures the increasing complexity of building systems. The category “people” encompasses failure related to FM education and training, and lack of resources. The category “tools and data” refers to the lack of structured and actionable data, and tools to access valuable information that feeds FM decisions or actions. The category “processes” captures process inefficiencies in commissioning and building turnover. The category “changes” conveys the idea that facilities must operate in an environment in constant flux, and hence, customer requirements also vary, they are dynamic. The analysis of the two case studies enabled the researcher to augment findings from the literature.

In the cooling tower case, the building failed to meet customer requirements when it was unable to guarantee the reliability of ALS’s operations during the transition phase.

In the supercomputer facility case, the building failed to meet customer requirements when it was unable to guarantee occupants’ thermal comfort.

Finally, the cross-case analysis substantiates the argument that the late or lack of involvement of FM in project delivery the building’s ability to meet customer requirements (sections 5.1, 5.2, and 5.3).

4. **May the late (or lack of) FM involvement in project delivery impact (or not) project performance? If so, how?**

The researcher applied the DSM methodology to analyze the impact of late (or lack of) FM involvement in project delivery on performance thereof. DSM served to compare the planned sequences of work by the engineer and the GC against the observed sequence of work. Section 3.4.3 presents the analysis of the iterations shown as blocks along the diagonal of DSM capturing the observed sequence of work. The impact of the steel structure re-design on project performance is further explained in section 3.4.4.

In conclusion, late FM involvement results in assumptions not made explicit and dependences missed. FM involvement can bridge the gap between the (design) intent and the actual realization of that intent by guiding conversations during the planning, design, and execution of projects, to unveil dependences and assumptions.

5. **How does integrating FM in project delivery transform organizations into learning organizations?**

The researcher was able to connect FM integration in project delivery with learning thanks to conversations with her research advisor and through consultation of the literature. The Plan-Do-Check-Act (PDCA) cycle provided a starting point to answer this question.

The PDCA cycle describes how to learn from experiments (Shewhart 1939, Deming 1986). It was introduced in business management to build-in quality. Ballard and Tommelein (2014) draw on Shewhart (1939) to propose a PDCA cycle to also learn from breakdowns. They define breakdowns as "unexpected outcomes of processes" and suggest that a breakdown constitutes an opportunity to learn. Learning is a fundamental principle in Lean Construction. Thus, they combine the two cycles to propose a process for building-in quality, that is, delivering customers what they value with no waste.

The literature reviewed showed that the Japanese introduced FM as a PDCA cycle (with two steps "do") (section 2.2.3, Figure 2-7). This research augments the Japanese approach to FM by suggesting that FM integration helps organizations to learn from breakdown, and therefore build-quality in (Figure 7-1). When operating and maintaining buildings, FM accumulates knowledge about gaps between expected and actual performance, occupant behavior, etc. FM may also keep an eye on new developments in industry (e.g., technology, practices, regulations). FM engagement in project delivery enables organizations to incorporate this knowledge into project delivery. FM can also drive the PDCA cycle within organizations and be innovation leaders.

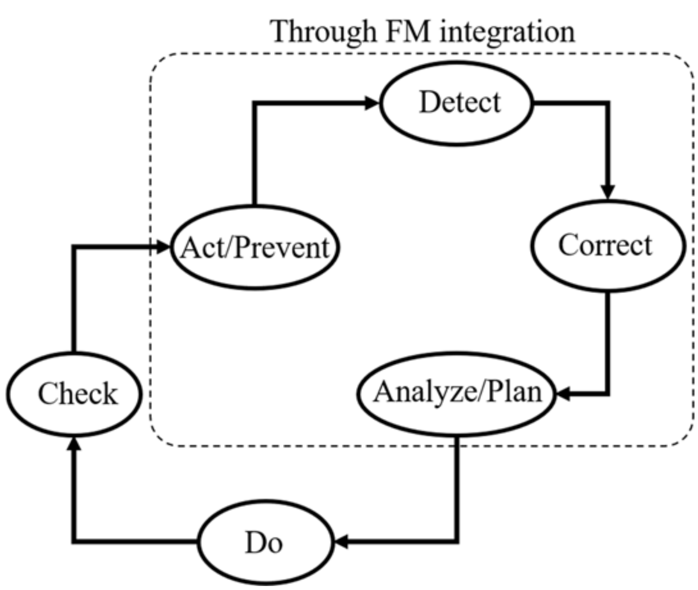

Figure 7-1: PDCA Cycle to Learn from Breakdowns through FM Integration (Adapted from Figure 3 in Ballard and Tommelein 2014)

6. **In what aspects is FM complex? How does structural complexity manifest itself in facility upgrades?**

To characterize complexity observed at the organizational level, the researcher used the Cynefin framework (section 2.6). According to Cynefin, FM responds to a complex context. Environments that are in constant flux and unpredictable are complex: FM acts at the interface between customers and the facility. Business objectives are continuously changing and the building's behavior can be drastically different from originally designed, that is, uncertain (i.e., supercomputer facility case). In complex contexts, one may see the emergence of patterns, but patterns are observable only in retrospect. FM must therefore probe, sense, and respond (cf. Cynefin) in order to make decisions and take actions so that the building meets customer requirements. Considering this, questions arise: "Could the fact that 'there is not one right way to manage facilities' (to the researcher's knowledge and observations) result from this complexity?" "Does the complexity of FM context imply that FM is complex as well?" "If so, does it mean that FM processes must be complex to respond to the complexity of FM context?" Considering structural complexity from a variational dimension, one could argue that responding to a complex context calls for complex processes.

To characterize complexity observed at the project level, the researcher built upon Maurer's dissertation (2007) on structural complexity to propose a classification of structural complexity aspects encountered in facility upgrades. The researcher added the fifth aspect, that is, customer complexity, thanks to the work of a former doctoral student at P2SL, Whelton (2004). At the project level, structural complexity manifests itself in five aspects: (1) customer complexity, (2) organizational complexity, (3) process complexity, (4) product complexity, and (5) market complexity (section 2.9).

These aspects may have a compounding effect on project performance especially when not managed.

7. **Is there a unique ('a right') classification of complexity aspects for construction projects?**

Although the researcher proposed five aspects of complexity: customer, organizational, process, product, and market, these aspects do not constitute the only possible classification. In fact, more aspects exist. The five aspects considered in this dissertation were those relevant for the analysis.

In conclusion, the classification of complexity aspects depends on its relevance for analysis.

8. **Can aspects of project structural complexity be addressed separately?**

The analysis of the case studies showed that aspects of project structural have a compounding effect on one another when not managed. In the cooling tower case, product complexity was an obvious contributor to overall project complexity. Yet, its effect on the cooling tower selection was compounded by customer, organizational, process, and market complexity as highlighted by the analysis of the decision-making process (section 3.5.9). The compounding effect of those aspects contributes to the emergence of properties or behaviors that were not expected. Related, in the cooling tower case, the cooling tower selection was questioned after LBNL experienced an unexpected performance of the new cooling tower during the transition phase.

Furthermore, the LPDS-MDM framework makes visual interdependences between delivery modules (section 2.11.2). In the cooling tower selection, the framework helps understand how complexity begets more complexity (section 5.4). It is also used to show how Lean Construction principles and methods could have helped manage project structural complexity (section 5.4).

9. **Can the Design Structure Matrix (DSM) methodology be applied to facility upgrades work?**

The successful application of the DSM methodology to the case studies confirm that DSM can be applied to facility upgrades work.

In the cooling tower case, the researcher applied the DSM methodology to model (1) the sequence of work activities as planned by the Engineer, (2) the sequence of work activities as planned by the General Contractor, and (3) the observed sequence of work (section 3.4.3). The analysis of the activity-based DSMs provided insights on the process complexity concerning planning the work and impacts of negative iterations on project duration. Two parameter-based DSMs were used to highlight product structural complexity in cooling tower sizing (section 3.5.5).

In the supercomputer facility case, DSM is used at a high level to contrast VE with Target Value Design (TVD) for the design phase and to provide insights into how VE is more inclined to create waste in project delivery than TVD (section 0).

10. **Can DSM help reduce waste in facility upgrades?**

Yes. DSM can be used to reduce waste at different levels in facility upgrades as shown in the cross-case analysis in which the researcher recommended the use of DSM to manage structural complexity.

In the cooling tower case, regarding work sequencing and the steel structure re-design, DSM captures unplanned design iteration. DSM makes waste visible. The analysis of the waste identified with the DSM led the researcher to recommend the following: (1) use DSM to create a shared understanding about project risks and opportunities, (2) use design charrettes, and (3) avoid iteration-masking language in schedules. Also in the cooling tower case, regarding the cooling tower selection, the parameter-based DSM could have helped create transparency in the decision-making process and hence, alignment on the objective to achieve and conflicts threatening this objective, between team members. Doing so would have helped eliminate the trouble-shooting of the first cooling tower installed during the transition phase.

In the supercomputer facility case, the simple comparison of the VE DSM and the TVD DSM highlights how TVD helps reduce structural complexity by decoupling activities through Go/No Go decision points (section 0). These Go/No Go decisions allow to shorten iteration loops in case of a No Go decision.

11. **How might Hoshin Kanri be applied to FM?**

Hoshin Kanri is a lean planning process used in organizations to deploy strategies and create alignment across all levels of the organization (section 2.11.3). The researcher considered other planning processes, but selected Hoshin Kanri by using the Choosing-By-Advantages (CBA) methodology (section 6.6).

Hoshin Kanri could involve FM, by ensuring the alignment of the objectives for project delivery with the business objectives, eliminating conflicts between customer requirements, and continuously learning from past projects. The proposed process is based on this planning method (sections 6.8 and 6.9).

12. What best practices can we recommend to engage FM in project delivery in order to avoid waste and generate value to owners and occupants?

The answer to this question is captured in the recommendations presented in the next section.

7.2 Recommendations

The researcher suggests best practices to: (1) model structural complexity at the project level using the DSM methodology and (2) engage FM in project delivery.

7.2.1 Model Complexity at the Project Level

Tuholski (2008) recommends that the DSM methodology is implemented with an integrated project team and the same individuals who will be working on the project. The researcher concurs with this recommendation. In addition, she suggests the following:

- **Define a clear purpose for implementing the DSM methodology**. A difficulty in implementing DSM is defining the boundary of the system under study and the relevant level of granularity for breaking down the system into elements. Thus, a first critical step is defining the purpose motivating the complexity analysis. This may be done by considering questions such as: "Is the purpose to optimize the design sequence?" "Is it to mitigate the risk for negative iteration?" "Is it to create shared understanding of the product structure to feed decision-making during product selection?" The decision on what to include (or not) in the DSM will flow from these considerations.
- **Have a DSM facilitator who guides conversations to unveil dependences**. The difficulty in mapping dependences in construction projects is that those dependences involve different fields of expertise. An expert may not necessarily know what experts from other fieladobeds do not understand in its own field and how its own field interfaces with others'. This is especially true for engineers and FMs. Thus, a DSM facilitator could help unveil those dependences by guiding the conversation between engineers, FM, and other project team members. Complexity being in the eyes of the beholder, it may be preferable that the facilitator is not be familiar with AEC to avoid bias in the discovery of dependences.

7.2.2 Engage Facility Management (FM) in Project Delivery

To engage FM in project delivery, a first recommendation is to implement the Hoshin Kanri process within organizations, because it can enable FM integration in project delivery and doing so is desirable for the following reasons:

- FM, being a super-user (Aune et al. 2009), has valuable knowledge to help fill in the DSM capturing customer requirements.

- FM can provide valuable input in solving conflicts emerging from competing or incompatible customer requirements, as they become visible when populating the DSM.
- FM can assess the reasonability of the design criteria from past experience with other facilities and help architects and designers extract the assumptions made during the definition of these design criteria. The validity of the assumptions can then be checked through data collection, conversation with building occupants, etc.
- FM knows how building systems perform in other facilities. Hoshin-for-Facilities captures the dependences between the design criteria and the building systems. FM can 'reasonably' assess whether a building system can fulfill the design criteria.

A second recommendation is to redefine FM so that the definition emphasizes FM's role in informing the project definition phase of the building life cycle. A widely accepted definition of FM is from Atkin and Brooks (2015):

"FM is creating an environment that is conducive to the organization's primary processes and activities, taking an integrated view of its services and support infrastructure, and using them to achieve end-user satisfaction and best value through support for, and enhancement of, the core business."

The definition could be improved by adding the following: "FM helps organizations to learn from past projects successes and failures by informing decisions made at each phase of building life cycle including preproject planning."

A third recommendation is to better communicate how FM is organized to the Design and Construction (D&C) team. FM organization may vary greatly from one customer to the next for two reasons: (1) there is no agreement on how to organize FM and (2) FM can encompass many tasks and responsibilities. As a consequence, the D&C team may not know whom in FM to involve in design reviews and decisions, and exclude FM from this conversations by default.

A fourth recommendation is to increase the D&C team's awareness on the value of integrating FM early in project delivery. To foster conversations between FM and the D&C team, a solution could be to collocate the two when possible.

A fifth recommendation is, for large organizations having an internal D&C department, to collocate the FM and D&C departments to enable knowledge sharing and idea pollination.

7.3 Contributions to Knowledge

Table 7-1 lists the contributions to knowledge per chapter.

Table 7-1: Contributions to Knowledge

Chapter	Contribution
2	Synthetizes the literature on definitions of FM and highlights the diversity of FM tasks through a literature review.
2	Summarizes the evolution of FM and connects increasing complexity in the workplace with the growing prominence of FM.
2	Makes the case for FM early involvement in project delivery.
2	Identifies how FM can fail and proposes a classification of FM failures.
2	Synthetizes the literature on solutions proposed for FM and identifies limitations to these solutions.
2	Proposes a Transformation-Flow-Value interpretation of FM.
2	Characterizes FM context as complex at the organizational level using the Cynefin framework, and at the project level, using the DSM methodology.
2	Identifies fives aspects of structural complexity in high-end facility upgrades.
2	Proposes a revised version of the LPDS-MDM framework.
3	Extends the body of AEC applications of DSM.
3&4	Documents two case studies illustrating how poor FM integration in project delivery leads to missing dependences. Missed dependences mean that project structural complexity is not managed. Missed dependences lead to failure in meeting customer requirements and delivering value to occupants.
5	Analyzes the value of the LPDS-MDM framework to manage project structural complexity experienced in high-end facility projects.
6	Proposes a Hoshin Kanri process to enable FM integration in project delivery.
6	Recommends best practices to enable FM integration in project delivery.

7.4 Limitations of Hoshin-for-Facilities

The researcher identified limitations to the potential generalization of the findings.

7.4.1 Time and Resource Commitment to Implement Proposed Process

The implementation of the proposed Hoshin Kanri process could be time and labor intensive. Furthermore, the process constitutes a change in work methods, which employees may not embrace. It also requires that employees are introduced to the DSM methodology. The amount of work and resources that the process entails may be daunting especially to first time DSM users.

7.4.2 Scalability of Proposed Process

Hoshin-for-Facilities allows practitioners to visualize at a glance the dependences between the business objectives, the customer requirements, the design criteria, the assumptions made, and the building systems. The researcher tested it on a simple academic example. The convenience of the tool is to show all the dependences in one page. However, one page may not suffice on a large project. Could all dependences fit in one page? Would the visualization of those dependences provide insights on the challenges induced by the project structural complexity? Are better representations available/conceivable?

7.4.3 Inapplicability of Proposed Process with Outsourced FM

The value of early FM involvement lies in part in FM knowledge and experience with building occupants, the organization's business activities. The two organizations considered (UCSF and LBNL) in this research have in-house FM. The relevance of early FM integration is valuable to organizations have in-house FM. Since outsourced FM does not interface with building users as much as in-house FM does and does not have a thorough understanding of the organization itself (business objectives, etc.), the value of their input is questioned.

7.4.4 FM Input must be Welcomed

For FM engagement in project delivery to be possible, the D&C team must understand the value FM can bring and accept FM feedback (Kalantari et al. 2017). This requires in part that the contractual terms defining the type and content of the deliverables expected from D&C team change. In addition, FM team members may disagree on problems to solve and on how to prioritize them, because of the complex context in which FM operates (cf. Cynefin).

7.4.5 Misalignment of Commercial Terms

Commercial terms binding the D&C team to the owner concern the building delivered at the time of the delivery. Usually, they do not include conditions on the building performance subsequent to its delivery and in the long term. UCSF's Mission Hall is an exception in that respect, since it was delivered with a two-year warranty. Although it is unreasonable to ask designers that they warrant a building that will consistently meet customer requirements in the long term (dynamic environment, changes in tenants, etc.), owners could put in place financial incentives to reward designers in function of the customer's continued satisfaction over time (i.e., 5 years, 10 years, or more).

7.5 Knowledge Dissemination

The researcher shared research findings with undergraduate and graduate students in Civil Engineering through academic presentations at UC Berkeley for the courses

"CE 180: Construction, Maintenance, and Design of Civil and Environmental Engineered Systems" and "CE 298: Graduate Research Seminar," as follows:

- Bascoul, A. (2017). "Built-in-Quality and Design iteration." Course CE 180, Professor Tommelein, Dr. Nguyen, and Dr. Tuholski, *University of California*, Berkeley, Apr. 26.
- Bascoul, A. (2017). "Construction Project Complexity and DSM." Course CE 298, Professor Ibbs, *University of California*, Berkeley, Oct. 5.

The researcher presented research findings to AEC practitioners and academics at industry events organized by the Project Production Systems Laboratory (P2SL), as follows:

- Bascoul, A. (2016). "Delivering Value to FM." P2SL Annual Conference, *University of California*, Berkeley, Apr. 27.
- Bascoul, A. (2017). "Engaging FM in Project Delivery." P2SL Annual Conference, *University of California*, Berkeley, May 11.

The researcher presented research findings to researchers focusing on new product development, structural complexity, and the DSM methodology at the 19th International DSM Conference in Espoo, Finland, as follows:

- Bascoul, A., Tuholski, S., and Tommelein, I. (2017). "Use of DSM to Capture Unplanned Design Iterations on a Facility Plant Upgrade Project." *19th International DSM Conference*, Espoo, Finland, Sept. 11-13.

The researcher will present two additional papers (accepted) to researchers and AEC practitioners at the ASCE 2018 Construction Research Congress, in New Orleans, LA, as follows:

- Bascoul, A., Tommelein, I., and Tuholski, S. (2018). "Construction Project Complexity as Addressed in Traditional vs. Lean Project Management Literature." *Construction Research Congress*, New Orleans, LA, USA, Apr. 2-4.
- Bascoul, A., Tuholski, S., and Tommelein, I. (2018). "Lean Construction to Manage Project Structural Complexity: The LPDS-MDM Framework." *Construction Research Congress*, New Orleans, LA, USA, Apr. 2-4.

7.6 Future Research

Through review of the literature and analysis of two case studies, the author identified areas that require further research.

7.6.1 Test and Fine-Tune Hoshin-for-Facilities

Action research could aim at implementing the proposed Hoshin Kanri process on real projects. In the long term, a rich database of applications could help understand the impact of design changes on building performance and identify (or not) patterns in how buildings fail. Are some assumptions made during design more uncertain than others? Are some systems frequently failing when both present in a building and serving the same design criterion?

7.6.2 Apply Organization Design to FM

From the reviewed literature and discussion with owners, it seems that there is no agreement on how to organize FM and how to make it interact with other functions of the organization. For example, UCSF and LBNL have structured FM differently. Further research could define an approach (if any) on how to organize FM. Related, Worren et al. (2017) developed a tool for organization design. The tool uses answers to a survey as input, displays them in a DSM, and analyzes them using a genetic algorithm to propose a better organization design. The researcher suggests that the use of this tool is explored for the design of FM and D&C departments within organizations.

7.6.3 Document how FM Generates Value and Propose Model for Assessing FM Value Generation

For many years, FM has been considered as a cost center rather than a value generator. Data is lacking to trigger a paradigm shift so that FM is considered as generating value in organizations. Future research (such as case studies) could attempt to formulate a framework that helps to assess the value generated by FM. A difficulty in this research is to assess the value generated by FM and make this data comparable across different types of organizations (i.e., healthcare, laboratories, etc.).

7.6.4 Understand the Linguistics of Complexity in Construction Projects

Flores (1982) developed the Language Action Perspective cycle to describe reliable promises. In the AEC industry, this framework has been particularly useful to describe the nature of projects as complex network of commitments and reveal opportunities for improvement in how projects are managed (i.e., Last Planner System). This raises the following questions: “Is there a linguistics of project complexity?” or in other words, “Could a similar framework be developed to support the unveiling of dependences in project delivery?”

7.7 Final Remarks

Project structural complexity is a vast and fascinating topic that has been of growing interest to researchers and practitioners. Considering FM as a key player in managing project structural complexity is novel.

This research connects poor or late FM integration in project delivery with failure to meet customer requirements. From a structural complexity perspective, it shows that poor or late FM integration in project delivery results in missed dependences between project delivery modules. Construction projects being increasingly complex, missed dependences create gaps between customer requirements, design intent, and actual realization of that intent. At the organizational level, the lack of process for engaging FM in project delivery is an impediment to early FM engagement in project delivery.

At the project level, the case studies are analysed through the prism of five aspects of project structural complexity (customer, process, product, organization, and market). The research shows how these aspects of project complexity can have a compounding effect on one another and increase overall project complexity when not managed. The researcher selects problems encountered in the two case studies and explains how Lean principles and methods could have been used to manage structural complexity using the LPDS-MDM framework. Overall, this research highlights the fitness of Lean Construction to manage project structural complexity.

At the organizational level, this research draws on Hoshin Kanri and UCSF's forward practices regarding FM engagement in project delivery to propose a process for FM engagement. The process intends to leverage FM tacit knowledge to reveal dependences early during preproject planning and design development and thus manage project structural complexity.

Similar to complexity in new product development, project complexity can be self-inflicted, some of it is value adding vs. some of it is waste. Lean thinking draws attention to production system design for managing complexity.

There is no doubt that research on project structural complexity will keep gaining momentum. Future research is encouraged to understand the linguistics of complexity in construction projects. Used in Lean to describe reliable promises, the Language-Action perspective shows the importance of language for planning and coordinating actions. This raises the question: "Could language reveal project complexity?" "Is it so that complexity arises from the language used in conversations?"

To end this dissertation on a poetic note and to hopefully inspire others to answer those research questions, the next paragraphs expand on Chapter 21 of *The Little Prince* (Saint-Exupéry 1943), in which the little prince meets the fox.

In chapter 21, the little prince wants to play with the fox. Yet, in order to play together, the little prince must first tame the fox. The fox teaches the little prince how he can be tamed. The fox gives instructions to the little prince using words. The fox asks the little prince to not speak when executing instructions (Saint-Exupéry 1943):

"You must be very patient," replied the fox. "First you will sit down at a little distance from me—like that—in the grass. I shall look at you out of the corner of my eye, and you will say nothing. Words are the source of misunderstandings. But you will sit a little closer to me, every day…"

The fox points out that language is not the best way to build trust between people, since "words are the source of misunderstandings." Language can create confusion. This suggests that other communication means could be used to create trust between people.

Could it be that complexity in construction can be avoided/mitigated by using other means of communication than language? Are construction projects complex because they rely so much on coordination through language and conversations?

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9. APPENDIX

Table 9-1: FM Tasks in Real Estate

FM Tasks in Real Estate		References
TASK	Give input to new building design and construction team.	Barrett and Finch (2013)
TASK	Advise on acquisition and disposal of sites and buildings.	Barrett and Finch (2013)
TASK	Negotiate and manage leases.	Banyani and Then (2010), Barrett and Finch (2013)
TASK	Advise on property investment.	Barrett and Finch (2013)
TASK	Control capital budget.	Barrett and Finch (2013)

Table 9-2: FM Goals and Tasks in Space Planning

FM Goals and Tasks in Space Planning		References
GOAL	Allow for future change in the provision and use of space.	Atkin and Brooks (2015)
GOAL	Plan space strategically.	Barrett and Finch (2013)
TASK	Plan best allocation and utilization of space and resources for new buildings, or re-organize current premises.	Levitt (2013)

FM Goals and Tasks in Space Planning		References
TASK	Identify user needs with respect to space.	Barrett and Finch (2013), Becerik-Gerber et al. (2012)
TASK	Monitor space use.	Barrett and Finch (2013), Becerik-Gerber et al. (2012)
TASK	Plan furniture layouts.	Barrett and Finch (2013)
TASK	Select and control use of furniture.	Barrett and Finch (2013)

Table 9-3: FM Goals in Culture and Image

FM Goals in Culture and Image		References
GOAL	Enhance the organization's culture and image.	Atkin and Brooks (2015)

Table 9-4: FM Goals and Tasks in Liaison

FM Goals and Tasks in Liaison		References
GOAL	Act as liaison with tenants of commercial properties.	Levitt (2013)
TASK	Be the coordinator of functional units in the facilities department. Functions include: maintenance, interior planning, architecture and engineering services, etc.	Atkin and Brooks (2015)
TASK	Work directly with Operations Manager, Maintenance Supervisor, and Landscape/Grounds Manager to ensure all areas of concern across the campus are being addressed.	Levitt (2013)
TASK	Formulate and communicate a facilities policy	Alexander (1994)

Table 9-5: FM Goals and Tasks in Business Operations

FM Goals and Tasks in Business Operations		References
GOAL	Enhance individual well-being.	Atkin and Brooks (2015)

FM Goals and Tasks in Business Operations		References
GOAL	Enhance performance by contributing towards the provision of the optimal working environment.	Atkin and Brooks (2015)
GOAL	Support people in their work and in other activities	Atkin and Brooks (2015)
GOAL	Improve workplace environment and productivity	Chanter and Swallow (1996)
GOAL	Enable the organization to deliver effective and responsive services.	Atkin and Brooks (2015)
TASK	Interact on a regular basis with the core business to identify current facilities management requirements.	Atkin and Brooks (2015)

Table 9-6: FM Goals and Tasks in Benchmark and Regulations

FM Goals and Tasks in Benchmark and Regulations		References
GOAL	Supporting the drive towards a sustainable campus	Lawrence and Mrozowski (2002)
GOAL	Provide competitive advantage to the core business, Strategic Facilities Management: interacts with the core to ascertain what future changes may occur to the business, as a response to external influences, such as competitors' plans.	Atkin and Brooks (2015)
TASK	Benchmark existing internal facilities services against other facilities management organizations, so that possible areas for improvement can again be identified.	Atkin and Brooks (2015)
TASK	Develop, implement, document, and maintain the energy management program for electrical consumption, water and sewer usage, and natural gas consumption within the facility.	Levitt (2013)
TASK	Inspect, monitor, implement, and direct compliance for all governmental requirements within the facility operations functions.	Levitt (2013)

Table 9-7: FM Goals in Anticipating Future Needs

FM Goals in Anticipating Future Needs		References
GOAL	Plan for future development in line with strategic business objectives.	Levitt (2013)
GOAL	Manage and lead changes to ensure minimum disruption to core activities.	Levitt (2013)
GOAL	Synergistically balance current operations with the needs of the future.	Atkin and Brooks (2015)
GOAL	Continuously develop new ways to efficiently run this campus mechanically and add direct input to Director of Operations for energy efficiency.	Levitt (2013)
GOAL	Scan for possible developments within the facilities management arena.	Atkin and Brooks (2015)
GOAL	Anticipate changes in demand and act swiftly while considering adding value to the core business	Banyani and Then (2010)
GOAL	Continually seek workable engineering solutions to maintenance problems.	Magee (1988) after Arditi and Narwakowarit (1999)

Table 9-8: FM Tasks in Obsolescence

FM Tasks in Obsolescence		References
TASK	Replace obsolete items.	Becerik-Gerber (2012)

Table 9-9: FM Goals and Tasks in Life-Cycle Costs

FM Goals and Tasks in Life-Cycle Costs		References
GOAL	Sweat the physical assets; that is, make them highly cost-effective.	Atkin and Brooks (2015)
GOAL	Reduce overhead.	Vanier (2001)
GOAL	Cost effective asset management and maintenance.	Chanter and Swallow (1996), Banyani and Then (2010)

FM Goals and Tasks in Life-Cycle Costs		References
TASK	Weigh cost of maintenance/repair/renewal vs technical/functional benefits of implementing solutions	Vanier (2001)
TASK	Identify design and complete improvement projects to reduce and minimize total operating and maintenance costs.	Magee (1988) after Arditi and Narwakowarit (1999)
TASK	Monitor and control the affected budget areas relation to staffing costs, normal purchases, payroll issues, repairs, equipment replacements, renovations, and new materials.	Levitt (2013)
TASK	Calculate and compare costs for required goods or services to achieve maximum value for money.	Levitt (2013)
TASK	Investigate availability and suitability of options for new purchases.	Levitt (2013)
TASK	Operate the facility utilities in the most economical manner while providing necessary reliability.	Magee (1988) after Arditi and Narwakowarit (1999)
TASK	Complete major repairs based on lowest life-cycle cost.	Magee (1988) after Arditi and Narwakowarit (1999)
TASK	Perform accurate cost estimating to ensure lowest cost solutions to maintenance problems.	Magee (1988) after Arditi and Narwakowarit (1999)

Table 9-10: FM Tasks in Project Management

FM Tasks in Project Management		References
TASK	Monitor the progress of all maintenance work.	Magee (1988) after Arditi and Narwakowarit (1999)
TASK	Coordinate schedule maintenance of all mechanical equipment either through maintenance contract or in-house work.	Levitt (2013)
TASK	Project management; supervise and coordinate work of contractors.	Levitt (2013)
TASK	Check that agreed work by staff or contractors has been completed satisfactorily; follow up on any deficiencies.	Levitt (2013)

FM Tasks in Project Management		References
TASK	Use performance management techniques to monitor and demonstrate achievement of agreed service levels and to lead on improvement.	Levitt (2013)

Table 9-11: FM Tasks in Data Tracking

FM Tasks in Data Tracking		References
TASK	Maintain complete historical data concerning the facility in general and equipment and components in particular.	Magee (1988) after Arditi and Narwakowarit (1999)
TASK	Document all related work that is completed.	Levitt (2013)
TASK	Provide for easy and complete reporting and identification of necessary repair and maintenance work.	Magee (1988) after Arditi and Narwakowarit (1999)
TASK	Oversee Work Orders system and CMMS data for mechanical work being done across the campus.	Levitt (2013)
TASK	Update computer aided facility management systems.	Barrett and Finch (2013)
TASK	Accurately track the costs of all maintenance work.	Magee (1988) after Arditi and Narwakowarit (1999)

Table 9-12: FM Tasks in Outsourcing

FM Tasks in Outsourcing		References
TASK	Prepare documents to put out bids for contractors.	Levitt (2013)
TASK	Work directly with third-party contracts; ensure contractual obligations are being met.	Levitt (2013)
TASK	Negotiate service level agreements	Alexander (1994)
TASK	Establish effective purchasing and contract strategies	Alexander (1994)

Table 9-13: FM Tasks in Predictive Maintenance

FM Tasks in Predictive Maintenance		References
TASK	Schedule all planned work in advance, and allocate and anticipate staff requirements to meet planned and unplanned events.	Magee (1988) after Arditi and Narwakowarit (1999)
TASK	Maintain a proper level of material and spare parts to support timely repairs.	Magee (1988) after Arditi and Narwakowarit (1999)
TASK	Perform preventive, predictive (planned).	Becerik-Gerber (2012)
TASK	Schedule and supervise Building Maintenance Manager and Electrician on regular preventative maintenance work and events calendar.	Levitt (2013)
TASK	Develop and execute a system of regularly scheduled maintenance actions to prevent premature failure of the facility and its systems and components.	Magee (1988) after Arditi and Narwakowarit (1999)

Table 9-14: FM Tasks in Inspection and Testing

FM Tasks in Inspection and Testing		References
TASK	Work with maintenance staff to ensure in-house preventative maintenance issues are being done (for example, weekly testing of fire pump, monthly test of backup generator); document findings.	Levitt (2013)
TASK	Conduct predictive testing and inspection to maintain the built environment.	Becerik-Gerber (2012)

Table 9-15: FM Tasks in Corrective Maintenance

FM Tasks in Corrective Maintenance		References
TASK	Respond to trouble calls (e.g., a room is too cold).	Becerik-Gerber (2012)
TASK	Respond appropriately to emergencies or urgent issues as they arise.	Levitt (2013)
TASK	Promptly respond and repair minor discrepancies in the facility.	Magee (1988) after Arditi and Narwakowarit (1999)

FM Tasks in Corrective Maintenance		References
TASK	Perform corrective maintenance.	Becerik-Gerber (2012)

Table 9-16: FM Tasks in Miscellaneous

FM Tasks in Miscellaneous		References
TASK	Direct and plan essential central services such as reception, security, maintenance, mail, archiving, cleaning, catering, waste disposal, and recycling.	Levitt (2013)
TASK	Schedule and monitor all equipment on the Fire Alarm System.	Levitt (2013)
TASK	Schedule Fire Panel Monitor as needed per events schedule.	Levitt (2013)
TASK	Domestic services (cleaning, catering, etc.).	Atkin and Brooks (2015)
TASK	Perform daily housekeeping and cleaning to maintain a properly presentable facility.	Magee (1988) after Arditi and Narwakowarit (1999)

Table 9-17: Academic and Commercial Solutions to Support FM

Solution	Description	References
Category: Building Systems		
Multi-agent system for building control	"A multi-agent system that combines an EDA agent model, personalized space, policy management, building performance quotient, wireless sensor network, and building automation/management system to provide an intelligent work environment."	Qiao et al. (2006)
A "rule generation methodology, through the simultaneous use of historical sensor data and theoretical models"	"The production of energy optimization rules using a theoretical approach."	Howell et al. (2014)
Category: Tools and Data		
Information system for operations	"The major components of the system as we envision it are: (1) generic repositories of facility information, (2) a link farm, (3) XML documents recording design rationale, (4) server procedures that generate Web pages, and (5) electronic redlining."	Clayton et al. (1999), Song et al. (2002)
RFID-based building maintenance system	System is composed of three modules: "A data management module is first developed to collect building usage and maintenance data. A statistical module is then established to graphically display the collected data. To ensure that building functions perform normally, maintenance activities are arranged using a scheduling module. These three modules are integrated into a web-based RFID building maintenance system"	Ko (2009)
Integration of BIM and GIS	Case studies.	Zhang et al. (2009)
	An "integrated 3D framework based on building information modeling (BIM) and GIS technologies for managing and analyzing utility information."	Cheng and Deng (2015)
	A "software architecture for the effective integration of building information modeling	Kang and Hong (2015)

Solution	Description	References
	(BIM) into a geographic information system (GIS)-based facilities management (FM) system."	
eBIM	An "energy building information model which integrates a building management system with wireless sensing and metering tools."	Ahmed et al. (2010)
Building Energy Management Systems (BEMS) and energy visualization tools	Commercially available software includes – but is not limited to: • Noveda Technologies energy monitoring software products • Agilewaves' Building Optimization System and Resource Monitor • Lucid Design Group's Building Dashboard • Pulse Energy's applications • iBEnergy software suite and GreenTouchScreen by Quality Attributes software • Quality Automation Graphics with its Energy Efficient Education Dashboard • Prophet Suite	Lehrer and Vasudev (2011)
Integration of BIM and data obtained from sensors	Extension of a BIM model into a DBMS that can store data from sensors using RDBlink in Revit.	Wei and Li (2011)
Tool that automates the retrieval of HVAC-specific information	Tool that allows users to query information about HVAC-specific information. The intent is to use the outputs of the tool as inputs for computer algorithms that can automatically analyze the conditions of HVAC systems.	Liu et al. (2011), Liu et al. (2014), Yang (2014)
Automated Building Commissioning Analysis Tool (ABCAT)	"A prototype fault detection and diagnostic tool intended to aid in reducing excess energy consumption."	Dynum et al. (2012)
Photogrammetric image processing to document and verify	The "manual and image-based dimensions are then used to verify dimensions of an existing as-built Building Information Model (BIM)."	Klein et al. (2012)

Solution	Description	References
actual as-built conditions		
BIM for FM	Surveys and interviews to explore the benefits of using BIM for FM.	Becerik-Gerber et al. (2012)
	A knowledge-based BIM system for building maintenance.	Motawa and Almarshad (2012)
	A "model for BIM-enabled commissioning and handover."	Wu and Issa (2012)
	"Case studies were conducted on projects where BIM and COBie were used for facility management."	Lavy and Jawadekar (2014)
	Open BIM standards for operations and maintenance.	Orr et al. (2014)
Ontological framework to solve conflicts in home building automation systems	The framework "performs automatic environment actuations maximizing users comfort and energy efficiency."	Camacho et al. (2014)
GIS-BIM Based Virtual Facility Energy Assessment (VFEA)	Framework that "leverages location-based building information, dynamic simulation capacity of BIM and wireless sensor network (WSN) for real-time building energy performance detection, visualization, analysis and optimization across campuses."	Wu et al. (2014)
Method to model facility condition deterioration	A "method to estimate transition probabilities based on the simulation of long term behavior of a Markov chain model."	Jin and Mukherjee (2014)
Ecodomus	It "provides 3D view of facilities in an easy-to-use format for facility managers that links BIM with real-time facility operations data acquired via meters and sensors (Building Automation Systems, BAS) and facility management (FM) software."	Ecodomus (2015)

Solution	Description	References
Building Automation Systems	"A building automation system (BAS) consists of a system installed in buildings that controls and monitors building services responsible for heating, cooling, ventilation, air conditioning, lighting, shading, life safety, alarm security systems, and many more."	Domingues et al. (2016)
Category: Processes		
Constructability Review Process	"A model format for incorporating the best practices for maintainability into the constructability review process."	Dunston and Williamson (1999)
Model process for implementing maintainability	Process model developed to help companies to address maintainability during project delivery.	Meier and Russell (2000)
Handover of Building Operations (HOBO) protocol	"A protocol for handover that will enable managers to operate buildings as they were designed to perform."	Jaggs et al. (2002)
Information exchange model for integrating O&M knowledge into design	"Model for exchanging information between design teams and O&M using the principles and tools of lean production (…) a Kanban system to facilitate the exchange of information."	Dahl et al. (2005)
Situation Awareness approach to support FM decision-making	"SA requirements lay the foundation for future role-based decision support systems that can assist facility managers in their decision-making process within dynamic and information-rich environments of the operational phase of a facility."	Gheisari and Irizarry (2011)
Usability briefing process model	"An integrated usability briefing process model for continuous briefing, combining the four interrelated activities of (1) briefing, (2) user involvement, (3) evaluations and (4) design."	Fronczek-Munter (2014)
Integrated approach for lean, BIM, and maintenance	Application of "BIM and lean concepts into practical maintenance to improve efficiency"	Shou et al. (2014)
Category: Changes		

Solution	Description	References
Change prediction method for design	Prototype computer support tool to predict change propagation in design.	Clarkson et al. (2001)
Multiple Categories		
Fault Detection and Diagnosis (FDD)	FDD tools allow the "detection of specific problems and helps target the causes of these problem." Tools include – but are not limited to: • Model-based feed-forward • Information monitoring and diagnostics system (IMDS) • Principal Component Analysis (PSA) method for sensors • Combination of Model Based Fault Detection and Diagnosis (FDD) method with Support Vector Machine (SVM) • Transient analysis of residual pattern • Air handling unit Performance Assessment Rules (APAR) • Diagnostic Agent for Building Operation (DABO) • Cite-AHU tools • Emma-CTA	Djuric and Novakovic (2007), Ginestet et al. (2013)
Facility Management Handover View	"An open-standard information exchange format that may replace current construction handover document requirement."	East et al. (2013)
Model to select maintenance activities that optimize building performance and reduce life cycle costs	A "model for optimizing the selection of building maintenance repair and renovation activities over a multiyear period."	Grussing and Liu (2014)
Augmented Reality glasses for FM	Multiple companies have investigated into augmented reality to support FM during maintenance operations.	DAQRI (2017), Intel (2017)
Navigational algorithm in BIM for utility	"The goals are to locate and navigate any user and/or utility in an unfamiliar facility."	Costin et al. (2013)

Solution	Description	References
maintenance management		
Facility Management Classes (as in "Industry Foundation Classes")	A "framework for the development of Facilities Management Classes and computer-integrated facilities management systems, including objectives, methodologies, implementation issues."	Yu et al. (2000)
Framework using agent modeling to facilitate decision making for facility management	A framework conceived to "help facility managers analyze and prioritize tasks according to factors such as degree of emergency, budget, and occupant satisfaction level."	Cao et al. (2014)
Automation of construction document classification	A "prototype of a document classification system was developed to provide easy deployment and scalability to the classification process."	Caldas and Soibelman (2002), Caldas et al. (2002)

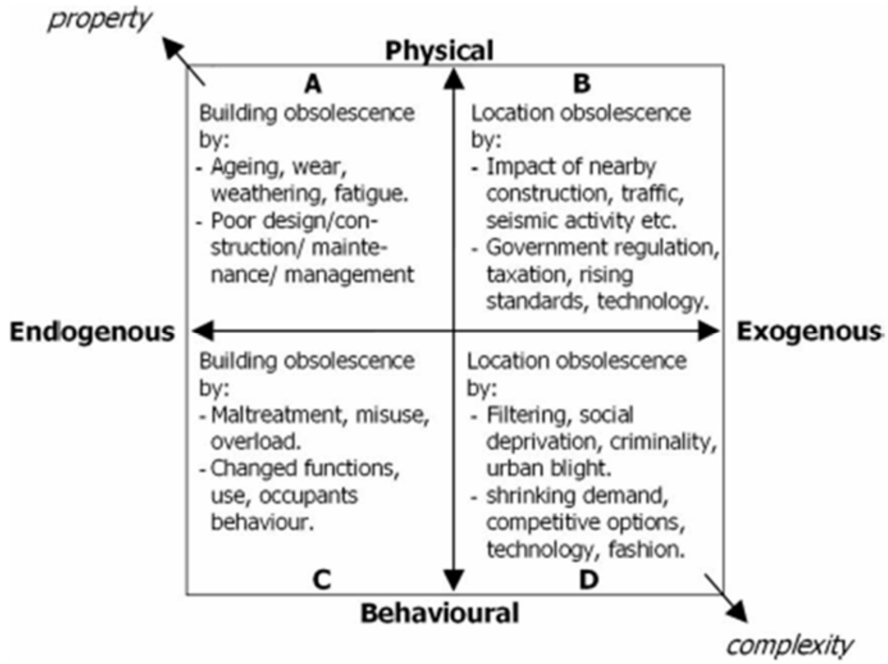

Figure 9-1: Conceptual Model of Obsolescence (Figure 1 in Thomsen and Van der Flier 2011)

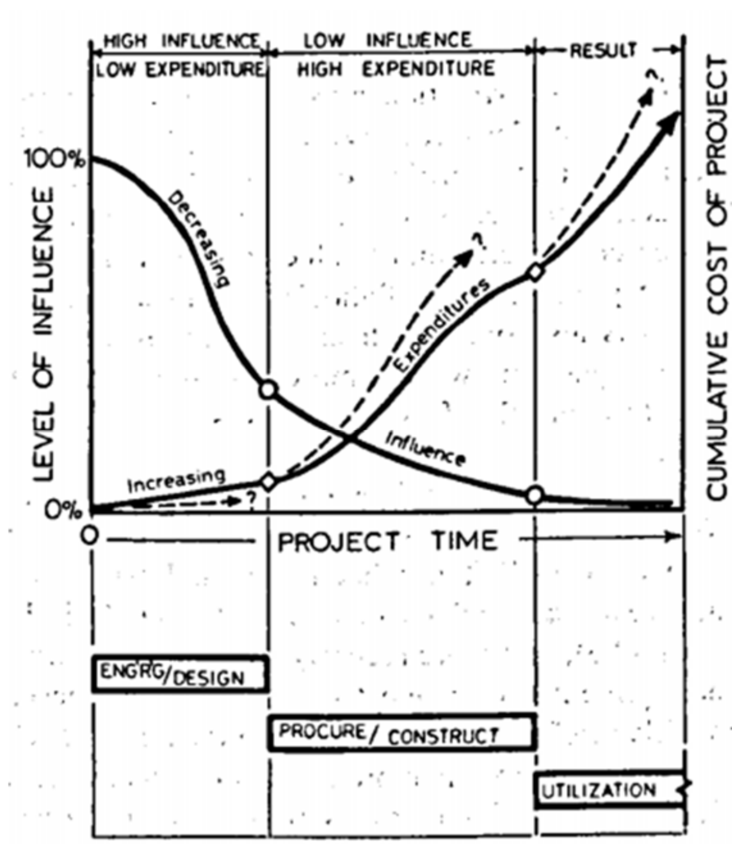

Figure 9-2: Level of Influence on Project Costs (Figure 1 in Paulson 1976)

Table 9-18: Codes and Regulations Applying to the Cooling Tower Project

Codes and Regulations Applying to the Cooling Tower Project

- California Code of Regulations (CCR),
  - Title 8, Industrial Relations
  - Title 17, Public Health
  - Title 19, Public Safety
  - Title 20, Public Utilities and Energy
  - Title 21, Public Works
  - Title 24, California Building Standards Code (Part 1 to 12)
  - Title 26, Toxics
- American Society of Civil Engineers ASCE 7 Minimum Design Loads for Buildings and Other Structures, edition adopted by referenced CBC
- American Society of Civil Engineers ASCE 41-13 Seismic Evaluation of Retrofit of Existing Buildings
- NFPA National Fire Codes, latest edition.
- NFPA 70: National Electrical Code (NEC), latest edition.
- National Electrical Safety Code, ANSI C2, latest edition.
- NFPA 70E: Standard for Electrical Safety in the Workplace, latest edition.
- Illuminating Engineering Society of North America (IES), latest edition.
- Occupational Safety and Health Act (OSHA).
- General Services Administration 41 CFR Part 101-19, Construction and Alteration of Public Buildings.
- Americans with Disabilities Act (ADA).
- American National Standards Institute (ANSI) Standards.
- The American Society of Heating and Air Conditioning Engineers (ASHRAE) Handbooks and Standards, latest edition.
- Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) Standards, latest edition. Exception: For seismic bracing refer to "Lateral Force Design Criteria," RD3.22 of the LBNL Construction Details and Design Guidelines, Volume 4 - RDs.
- The American Society of Mechanical Engineers (ASME) Standards and Codes, latest edition.
- The American Society for Testing and Materials (ASTM) Standards, latest edition.
- Air Moving and Conditioning Association (AMCA) Fan Test Code, latest edition.
- Associated Air Balance Council (AABC) National Standards for Total System Balance.

Codes and Regulations Applying to the Cooling Tower Project
• Factory Mutual Engineering Corp. (FM) Approval Guide and Loss Prevention Data Sheets, latest edition. • Underwriters' Laboratories, Inc. (UL) Standards and “Building Materials, Fire Protection Equipment, and Fire Resistive Directories.” • LBNL Long-Range Development Plan (LRDP), current version as approved by the University and the DOE. • Lawrence Berkeley Laboratory Health and Safety Manual, Publication 3000, latest edition. • Lateral Force Design Criteria,”RD3.22 of the CDDG, Volume 4 - RDs. • Checking of Architecture and Engineering Documents,” RD3.8 of the CDDG, Volume 4 - RDs. • Life Cycle Costing Manual for the Federal Energy Management Program, National Institute of Standards and Technology, Handbook 135.26. LBNL Energy Conservation Report Specifications.27. Manual of Professional Practice, Quality in the Construction Project, a manual published by the American Society of Civil Engineers. Refer to “Checking of Architecture and Engineering Documents,” RD3.8 of the CDDG, Volume 4 - RDs. • The Project Design follows the Design Program developed, as noted in the LBNL Project Design Requirements (PDR).

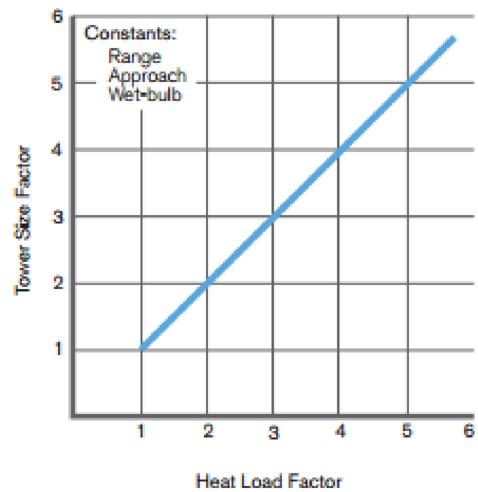

Figure 9-3: Tower Size Factor as a Function of Heat Load Factor (Figure 4 in SPX Cooling Technologies 2016b)

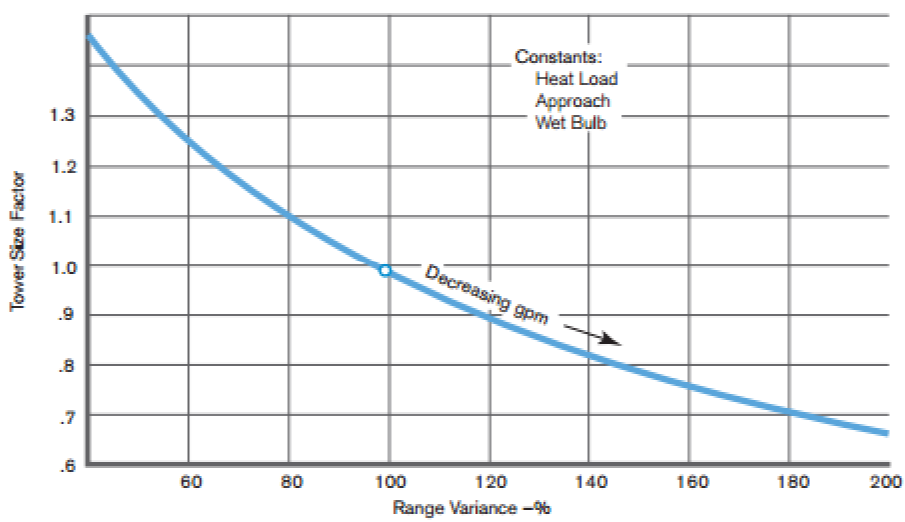

Figure 9-4: Tower Size Factor as a Function of Range Variance (Figure 5 in SPX Cooling Technologies 2016b)

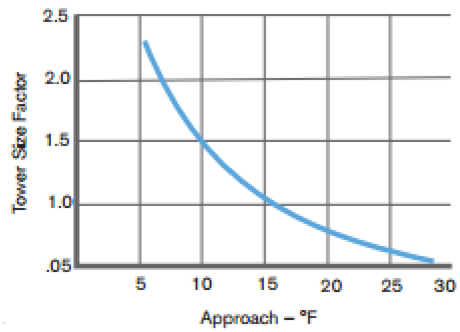

Figure 9-5: Tower Size Factor as a Function of the Approach (Figure 6 in SPX Cooling Technologies 2016b)

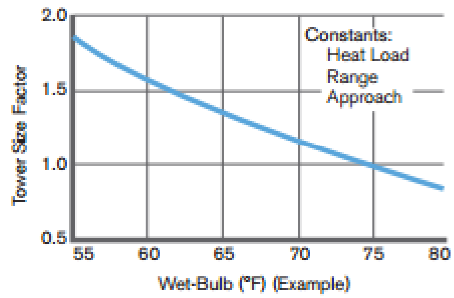

Figure 9-6: Tower Size Factor as a Function of the Wet-Bulb Temperature (Figure 7 in SPX Cooling Technologies 2016b)

Table 9-19: First Selection of Crossflow Cooling Tower Models Options A and B

	Marley Tower Model	Dimensions			Option A - 67 / 77 / 87					Option B - 67 / 77 / 87				
		L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
1	NC8414	13.9'	22.42'	26.99'	47530	1200	3600	60	71.6	48130	1392	4175	100	48.4
2	NC8412	13.9'	22.42'	23.24'	43170	1200	3600	100	44.9	43170	1283	3848	100	44.9
3	NC8412 2-cell	28.09'	22.42'	23.24'	83660	1200	3600	2 x 15	168	83660	1400	4200	2 x 15	168

	Evapco Crossflow Tower Model	Dimensions			Option A - 67 / 77 / 87					Option B - 67 / 77 / 87				
		L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
4	AXS 14-2R24	14'	24.75'	22.57'	51270	1200	3600	100	43.48					
5	AXS 12-2K22	23.66	22.75'	23.71'						83380	1400.0	4200	40	123.76
6	AXS 14-2Q24	13.94'	24.75'	23.7'										
7	AXS 14-2S24	14'	24.75'	22.57'										
8	AXS 12-2N22	23.66	22.75'	23.71'										

Table 9-20: First Selection of Counter Cooling Tower Models Options A and B

	Evapco Counterflow Tower Model	Comparative Dimensions				Option A - 67 / 77 / 87					Option B - 67 / 77 / 87			
		L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
1	UT-114-826	14'	26'	23.6'	44510	1200	3600	80	54.82					
2	UT-114-726	14'	26'	23.6'										
3	UT-114-926	14'	26'	23.6'										

	Marley Tower Counterflow Model	Comparative Dimensions			Option A - 67 / 77 / 87					Option B - 67 / 77 / 87				
		L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
4	MD5016 2-cell	11.83'	24.17'	19.38'	28410	994	2982	2 x 40	43.9	Same as Option A				
5	MD5018 2-cell	36.17'	11.83'	20.67'	40840	1200	3600	2 x 30	72	41750	1400	4200	2 x 50	50.9

Table 9-21: First Selection of Crossflow Cooling Tower Models Options C and D

Marley Tower Crossflow Model		Dimensions			Option C - 65 / 75 / 87					Option D - 65 / 75 / 87				
		L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
1	NC8414 Crossflow	13.9'	22.42'	26.99'	47530	1200	3000	60	71.6	48130	1400	3500	100	48.4
2	NC8412 Crossflow	13.9'	22.42'	23.24'	42900	1200	3000	75	54.5	43170	1332	3329	100	44.9
3	NC8412 2-cell Crossflow	28.09'	22.42'	23.24'	83660	1200	3000	2 x 15	168	83660	1400	3500	2 x 15	168

Evapco Crossflow Tower Model		Dimensions				Option C - 65 / 75 / 87					Option D - 65 / 75 / 87			
		L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
4	AXS 14-2R24	14'	24.75'	22.57'										
5	AXS 12-2K22	23.66	22.75'	23.71'										
6	AXS 14-2Q24	13.94'	24.75'	23.7'	51570	1200.0	3000	75	54.5					
7	AXS 14-2S24	14'	24.75'	22.57'						51680	1400.0	3500	125	37.2
8	AXS 12-2N22	23.66	22.75'	23.71'										

Table 9-22: First Selection of Counterflow Cooling Tower Models Options C and D

Evapco Counterflow Tower Model		Dimensions				Option C - 65 / 75 / 87					Option D - 65 / 75 / 87			
		L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
1	UT-114-826	14'	26'	23.6'										
2	UT-114-726	14'	26'	23.6'	44190	1200.0	3000	60	67.22					
3	UT-114-926	14'	26'	23.6'						44530	1400.0	3500	100	46.72

Marley Tower Counterflow Model		Dimensions			Option C - 65 / 75 / 87					Option D - 65 / 75 / 87				
		L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
4	MD5016 2-cell Counterflow	11.83'	24.17'	19.38'	28410	1040	2600	2 x 40	43.9	Same as Option C				
5	MD5018 2-cell Counterflow	36.17'	11.83'	20.67'	40700	1200	3000	2 x 25	80.9	41650	1400	3500	2 x 40	59.3

Table 9-23: First Selection of Crossflow Cooling Tower Models Options E and F

Marley Tower Crossflow Model		Dimensions			Option E - 67 / 75 / 85					Option F - 67 / 75 / 85				
		L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
1	NC8414 Crossflow	13.9'	22.42'	26.99'	48130	1192	3575	100	48.4	Same as Option E				
2	NC8412 Crossflow	13.9'	22.42'	23.24'	43170	1092	3275	100	44.9	Same as Option E				
3	NC8412 2-cell Crossflow	28.09'	22.42'	23.24'	83660	1200	3600	2 x 15	168	84000	1400.0	4200	2 x 25	119

Evapco Crossflow Tower Model		Dimensions				Option E - 67 / 75 / 85					Option F - 67 / 75 / 85			
		L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
4	AXS 14-2R24	14'	24.75'	22.57'	51270	1195.2	3585	100	44.6					
5	AXS 12-2K22	23.66	22.75'	23.71'	83380	1200.0	3600	40	123.76					
6	AXS 14-2Q24	13.94'	24.75'	23.7'										
7	AXS 14-2S24	14'	24.75'	22.57'										
8	AXS 12-2N22	23.66	22.75'	23.71'						83380	1400.0	4200	40	76.19

Table 9-24: First Selection of Counterflow Cooling Tower Models Options E and F

Evapco Counterflow Tower Model		Comparative Dimensions				Option E - 67 / 75 / 85					Option F - 67 / 75 / 85			
		L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
1	UT-114-826	14'	26'	23.6'										
2	UT-114-726	14'	26'	23.6'										
3	UT-114-926	14'	26'	23.6'										

Marley Tower Counterflow Model		Comparative Dimensions			Option E - 67 / 75 / 85					Option F - 67 / 75 / 85				
		L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
4	MD5016 2-cell Counterflow	11.83'	24.17'	19.38'	28410	858	2574	2 x 40	43.9	Same as Option C				
5	MD5018 2-cell Counterflow	36.17'	11.83'	20.67'	41750	1200	3600	2 x 50	50.9	42190	1297.3	3892	2 x 60	44.2

Table 9-25: Second Selection of Crossflow Cooling Tower Model Option C

Marley Tower Crossflow Model	Comparative Dimensions			Option C - 65 / 75 / 87				
	L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
NC8414 Crossflow	13.9'	22.42'	26.99'	47530	1200	3000	60	71.6

Cooling Tower Efficiency ASHRAE 90.1 GPM/HP	
Minimum ASHRAE 90.1	42.1
Low	45 to 60
Medium	65 to 75
High	80 to 100

Advantages:
Using the same cooling tower casing as for 1400 ton and therefore will not require adding new fills.

2. Can Change the motor size to 75 horsepower without changing anything else and still increase the capacity to 1332 tons.

3. More efficient than the counterflow cooling tower.

4. Less maintenance required than counterflow cooling tower due to use of gravity flow in lieu of spray nozzles for the counterflow cooling tower.

5. Crossflow cooling tower can be turned down to 30% to allow water savings as compared to the counterflow cooling tower can only be turned down to 50%.

6. Less footprint than the counterflow cooling tower.

7. Mechanical equipment, screens, float valves, etc. are more accessible through door for maintenance as opposed to the counterflow which requires dismantling the fan blades to access the motor.
8. Less installation cost due to simplified rigging, support and piping.
9. Uses direct drive fans

Disadvantages:

1. If increasing the motor horsepower in the future from 60 or 75 hp to 100 hp, a new geareducer will be installed.
2. Will be limited to increasing the capacity up to 1,332 tons if changing the motor size.
3. Need to enter the cooling tower for maintenance. Although it is not a confined space.
4. Approximately 3.5 feet taller than a counterflow cooling tower.
5. Heavier than the counterflow cooling tower by 3,340 pounds.
6. If one of the cell is in service, the capacity is only 50%.

Table 9-26: Second Selection of Crossflow Cooling Tower Models Options D

Marley Tower Crossflow Model	Comparative Dimensions			Option D - 65 / 75 / 87				
	L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
NC8414 Crossflow	13.9'	22.42'	26.99'	48130	1400	3500	100	48.4

Cooling Tower Efficiency ASHRAE 90.1 GPM/HP	
Minimum ASHRAE 90.1	42.1
Low	45 to 60
Medium	65 to 75
High	65 to 75

Advantages:
1. Using the same cooling tower casing as for 1200 ton cooling tower.

Will not require changing gearbox since the use of variable frequency driver will reduce the brakehorsepower and get the same efficiency and energy consumption as the 1200 ton cooling tower.

3. More efficient than the counterflow cooling tower.

4. Can be more water efficient since the fan can operate at higher velocity with less water.

5. Less maintenance required than counterflow cooling tower due to use of gravity flow in lieu of spray nozzles for the counterflow cooling tower.

6. Crossflow cooling tower can be turned down to 30% to allow water savings as compared to the counterflow cooling tower can only be turned down to 50%.

7. Less footprint than the counterflow cooling tower.

8. Mechanical equipment, screens, float valves, etc. are more accessible through door for maintenance than the counterflow cooling tower.

9. Less installation cost due to simplified rigging, support and piping.

10. Uses direct drive fans.

Disadvantages
1. Heavier than the counterflow cooling tower by 3,600 pounds.
Approximately 3.5 feet taller than a counterflow cooling tower.

3. Need to enter the cooling tower for maintenance. Although it is not a confined space.

4. If one of the cell is in service, the capacity is only 50%.

Table 9-27: Second Selection of Counterflow Cooling Tower Model Option C

Evapco Counterflow Tower Model	Dimensions				Option C - 65 / 75 / 87			
	L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
UT-114-726 Dual Cell	14'	26'	23.6'	44190	1200.0	3000	2x30	67.22
UT-114-926 Dual Cell	14'	26'	23.6'					

Advantages:
1. Using the same cooling tower casing as for 1400 ton and therefore it will not require adding new fills.
2. Lower height than the crossflow cooling tower.
3. Weigh less than the crossflow cooling tower.
4. Easier fill replacement than crossflow tower.
5. Counterflow cooling tower can operate at 75% if one of the cell needs fan/motor replacement or repair.

Disadvantages:
1. Requires more maintenance than crossflow due to pressurized spray nozzles, need to dismantle fan to replace the motor and uses belt driven fans in lieu of direct driven fans.
2. Will need to change two motors (2X40 horsepower) as compared to a 75 horsepower for the crossflow to get the same 1,332 ton capacity as the crossflow.
3. Less efficient than the crossflow cooling tower.
4. More space required than the crossflow cooling tower.

Table 9-28: Second Selection of Counterflow Cooling Tower Model Option D

Evapco Counterflow Tower Model	Comparative Dimensions				Option D - 65 / 75 / 87			
	L	W	H	Weight	Capacity (tons)	Flow (gpm)	Motor Hp	ASHRAE 90.1 gpm/Hp
UT-114-726 Dual Cell	14'	26'	23.6'					
UT-114-926 Dual Cell	14'	26'	23.6'	44530	1400.0	3500	2x50	46.72

Adavantages:

1. Using the same cooling tower casing as for 1400 ton and therefore will not require adding new fills.
2. Lower height than the crossflow cooling tower.
3. Weigh less than the crossflow cooling tower.
4. Will not require changing gearbox since the use of variable frequency driver will reduce the brakehorsepower and get the same efficiency and energy consumption as the 1200 ton cooling tower.
5. Easier fill replacement than crossflow tower.
6. Counterflow cooling tower can operate at 75% if one of the cell needs fan/motor replacement or repair.

Disadvantages

1. Requires more maintenance than crossflow due to pressurized spray nozzles, need to dismantle fan to replace the motor and uses belt driven fans in lieu of direct driven fans.
2. Less efficient than the crossflow cooling tower.
3. More space required than the crossflow cooling tower.

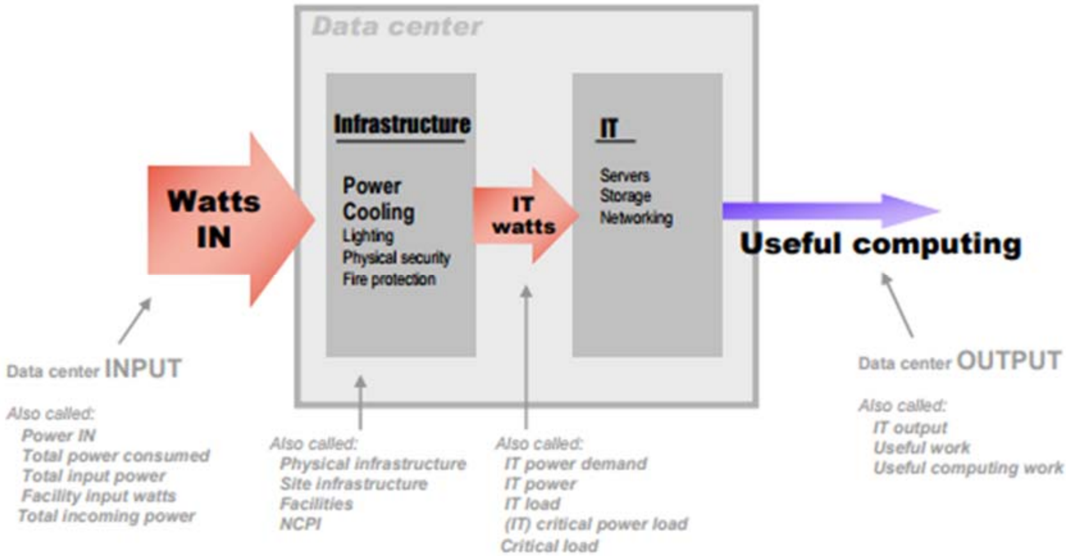

Figure 9-7: Terminology used for DCiE Analysis (Figure 1 in Rasmussen 2008)

Table 9-29: LBNL's and GC's Work Scope Divisions on CRTF project (LBNL 2015c)

LBNL's Points of Contact	**A**	**B**	**C**	**D**	**E**	**F-G**
GC's Points of Contact	**4, 8, 9**	**6, 8, 9, 11**	**1, 6, 8, 9, 10, 11**	**5, 7**	**2, 3, 5, 7**	**8, 12**
Cost Control	• Monthly budget & contingency updates. • Funding. • Claim negotiations for Overaa and PSEC. • NRP risk registry. • Soil - split cost with Serc.	• Monthly budget & contingency updates. • Change order log. • Manage consultant contracts and additional services. • Claim negotiations for Overaa and PSEC. • NRP risk registry • Final review of invoices/change orders. • LBNL meetings regarding cost. • P&W E&O – ductbank. • Soil - split cost with Serc.	• Detailed review of change orders. • DPR pay applications. • Review some consultant invoices.	• Review 3 or 4 CQ's/ week	• Manage T&M tags. • Review T&M change orders. • IOR/CEL/ • surveyor/ digital conc. invoices.	• Processing change orders. • Processing invoices. • Processing billings. • Updating change order log - with Jack. • Putting CQ's on G:Drive and printing one copy for "D".

LBNL's Points of Contact	**A**	**B**	**C**	**D**	**E**	**F-G**
Schedule Control	• Big picture.	• Big picture.	• DPR schedule reviews.		• 4-week look-ahead schedule. • Shift work management.	• Print monthly schedule updates/ files.
Quality Control	• Quality Assurance periodic meeting.	• Review difficult/problem RFIs. • Soil disposal from Bevatron. • Soil disposal diesel fuel. • MEP coordination.	• Submittals. • RFIs. • Field orders. • MEP Coordination review. • ASI and construction bulletins. • Fire Marshal. • Manage Architect.	• Posting ASIs on drawings. • Proces-sing submittals. • Rolling comple-tion list.	• Inspections. • Manage IOR and CEL. • QC on DPR's work. • Coordinate with LBNL work & other buildings. • Track soil. • Noise readings.	• Distributing ASIs.
Misc.	• Client relations. • Monthly Principals meeting.	• Additional Scope - Tape Room, N7 & N8, Shake Table Test, Power Quality, CFD, Control Room.		• Help "E". • Cover some weekends.	• Safety. • Penetration permits. • LOTO. • Road closures. • SWPPP.	• Project filing. • Setting up meetings. • Trailer issues.

LBNL's Points of Contact	A	B	C	D	E	F-G
	• Monthly safety walk.	• Nyingma Institute construction noise. • Monthly Principals meeting. • Monthly safety walk. • NERSC meetings.				

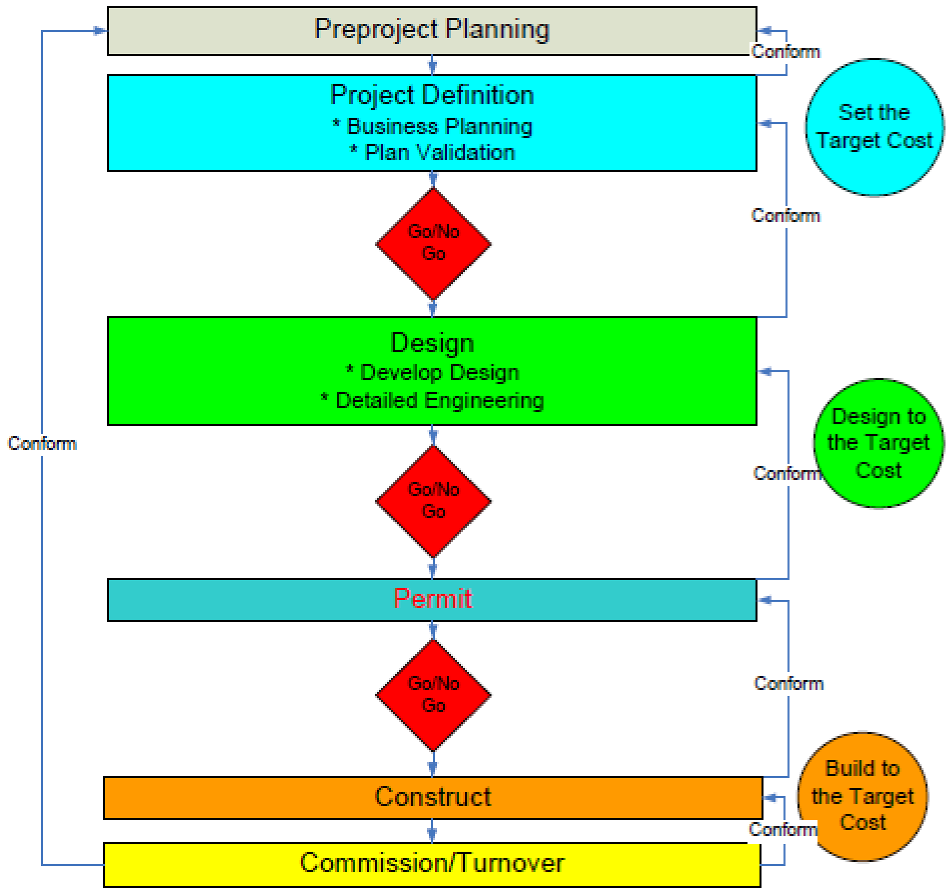

Figure 9-8: Project Phases and Target Value Design (Ballard 2008)

	Issue-based Planning	Formal Strategic Planning	SAA—Dialetic Inquiry	Hoshin Planning
Why?	Change initiation	Portfolio mangement; perpetuate status quo	Challenge status quo or potential change	To see breakthrough acievement and continuous improvement
When?	Sporadic, as needed	Annual or bi-annual	Planned, as needed	Routinized and ongoing; periodic review
Who initiates?	Initiated by an individual, grows to a coalition through selling	Planning group 'presents' to senior management for ultimate organizational deployment	Initiated by senior managment with possible planning group participation	Hierarchically stratified participation of entire organization
Who's involved?	Active (dominant or emerging) coalitions	Functional organization—SBU and above	Conducted by facilitator and two or more groups	Senior management, middle managment and implementation teams
How?	Iteractive process of seeing, screening, signing-up and signalling	Formal procedures	Structured process; unstructured data	Stepwise process; PDCA driven
Where?	Covert initially, only visible to coalition; growing visibility	Detached function	Detached, retreat-like atmosphere	Pervasive through organization at the 'shop floor' level
What?	Issue focused learning and building case/energy for change	Budgeting focused analysis	Devils advocacy; mental/quasi game theoretic	Initiative focused; communication based

Figure 9-9: Strategic Planning Methods Considered for CBA (no figure number in Mulligan et al. 1996)