



CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

**Dynamic Decision Breakdown Structure:
Ontology, Methodology, & Framework
for Information Management
in Support of Decision-Enabling Tasks
in the Building Industry**

By

Calvin Kam

**CIFE Technical Report #164
DECEMBER 2005**

STANFORD UNIVERSITY

COPYRIGHT © 2005 BY
Center for Integrated Facility Engineering

If you would like to contact the authors, please write to:

*c/o CIFE, Civil and Environmental Engineering Dept.,
Stanford University
Terman Engineering Center
Mail Code: 4020
Stanford, CA 94305-4020*

DYNAMIC DECISION BREAKDOWN STRUCTURE:
ONTOLOGY, METHODOLOGY, AND FRAMEWORK FOR
INFORMATION MANAGEMENT IN SUPPORT OF
DECISION-ENABLING TASKS IN THE BUILDING INDUSTRY

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF
CIVIL AND ENVIRONMENTAL ENGINEERING
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Calvin Ka Hang Kam

December 2005

ABSTRACT

The development of AEC (architecture-engineering-construction) projects depends on the ability of decision makers to make informed and quick decisions. This requires the AEC decision facilitators to carry out decision-enabling tasks using methods and tools that are informative and rapid, so that they can integrate discipline-specific information from heterogeneous project stakeholders, evaluate choices, identify alternatives, refine decision criteria, and iterate these tasks throughout the decision-making processes. My research on industry case studies shows that current decision-support tools do not enable decision makers to make informed and quick decisions, because a structured and explicit approach to represent and organize heterogeneous information is lacking. My studies also demonstrate that current methods do not give facilitators the flexibility to manage this information while completing decision-enabling tasks. Consequently, facilitators cannot build on prior decision-enabling tasks to resume the decision process when the decision context changes.

To address these limitations, I have developed the Dynamic Decision Breakdown Structure (DBS) Framework with three underlying contributions. First, my formalization of an AEC Decision Ontology allows facilitators to establish an explicit, informative, and hierarchical representation of heterogeneous decision information and its interrelationships. Second, I formalized a dynamic methodology—the Decision Method Model (DMM)—that interacts with the Ontology and enables facilitators to combine, evaluate, and recombine formally represented information, and to complete other decision-enabling tasks flexibly and quickly. Finally, I contribute an AEC decision-making framework that formalizes the sequences, characteristics, and requirements of information management throughout the changing decision context. This framework leverages the application of the hierarchical DBS and the dynamic DMM to support the continuity of decision-enabling tasks as the decision process evolves.

I validated my contributions by evaluating the relative performance of the Decision Dashboard, a prototype computer application implemented with my ontology and methodology, with respect to a variety of methods and tools, used by renowned professionals involved in large-scale industry projects across the nation. Based on validation using six industry cases, eight decision-enabling tasks, and by twenty-one professionals and researchers, I claim that the Dynamic Decision

Breakdown Structure enables more informative, flexible, resumable, and faster management of decision information than current methods.

ACKNOWLEDGEMENT

I dedicate this dissertation to my family—my dad, mom, and sister who have always been fully supportive of my studies and development. Their total love and care empower my devotion to both research and practice.

My deepest gratitude also goes to Professor Martin Fischer, my principal advisor. Martin is amazingly thoughtful and sharp. His constructive advice, from macro strategy to micro writing styles, has been invaluable. Martin has given me trust and freedom to develop a research topic that I am truly passionate about, continual guidance on every aspect of research, and extraordinary opportunities to work with renowned researchers and industry experts.

Dr. John Kunz has been instrumental in my research journey as well. I appreciate John for the many challenging and enlightening iterations to develop my research, for the big ideas, and for his references on breakdown structures. I also thank Professor Bob Tatum for his insightful comments on my research and for his teaching that vividly highlighted the challenges of the building industry and the needs for integration during my early graduate studies. I thank Professor Ray Levitt for his advice on my research methodology and contributions.

At Stanford University's Center for Integrated Facility Engineering (CIFE), I enjoy the collaboration and exchange opportunities with my colleagues, including John Haymaker, Kathleen Liston, Arto Kiviniemi, Timo Hartmann, Nayana Samaranayake, and many other wonderful colleagues and mentors. Special thanks also go to Teddie Guenzer for all her administrative supports.

I appreciate the recognition and awards, in forms of fellowships, scholarships, etc., from the following organizations and individuals in their support of my studies: Stanford University School of Engineering Dean Stephan/Charles Pankow Builders Fellowship, Stanford University School of Engineering George Wheaton Fellowship, the American Institute of Architects (national, state council, and local chapter, respectively), the American Architectural Foundation, the American Society of Civil Engineer, the Construction Management Association of America, Skidmore, Owings & Merrill Foundation, the University of Southern California, the Asian

American Architects/Engineers Association, the Asian Pacific American Support Group, as well as the Office of the Chief Architect of the Public Buildings Service of the United States General Services Administration.

In addition, I would like to acknowledge the following individuals who have inspired my studies, research, teaching, and practice in the building industry: Hank Koffman, Douglas Noble, and Karen Kensek (University of Southern California); Eduardo Miranda, Melody Spradlin, and Renate Fruchter (Stanford University); John Mutlow (John V. Mutlow Architects); Tom McKinley and Mark Liew (Hathaway Dinwiddie Construction Company); Jim Sharpe and his team (Affiliated Engineers, Inc.); Dean Reed (DPR); Jim Bedrick and Jes Pederson (Webcor Builders); Tony Rinella (Anshen+Allen Architects); Kent Reed (National Institute of Science and Technology); Chris Holm and Walt Smith (Walt Disney Imagineering); Seppo Lehto, Auli Karjalainen, Reijo Hänninen, Markku Jokela, Tuomas Laine, Jarmo Laitinen, Jiri Hietanen, and their knowledgeable colleagues from respective organizations in Finland; as well as Charles Matta, Thomas Graves, Stephen Hagan, and my colleagues at the United States General Services Administration.

TABLE OF CONTENTS

TITLE PAGE	I
COPYRIGHT NOTICE PAGE	II
SIGNATURE PAGE	III
ABSTRACT.....	IV
ACKNOWLEDGEMENT.....	VI
TABLE OF CONTENTS	VIII
LIST OF TABLES	XI
LIST OF ILLUSTRATIONS	XII
CHAPTER 1—INTRODUCTION	1
1.1 RESEARCH MOTIVATION AND BACKGROUND	2
1.2 MOTIVATING CASE EXAMPLE.....	7
1.2.1 <i>Case Summary</i>	8
1.2.2 <i>Case Analysis—Characteristics, Limitations, and Intuition</i>	17
1.3 SCOPE OF RESEARCH	24
1.3.1 <i>AEC</i>	25
1.3.2 <i>Decision Information</i>	25
1.3.3 <i>Management of Decision Information (Information Management)</i>	27
1.3.4 <i>Decision-Enabling Tasks</i>	27
1.3.5 <i>Decision-Support Tools</i>	28
1.3.6 <i>Dynamic Decision Breakdown Structure</i>	28
1.3.7 <i>Decision Dashboard</i>	29
1.4 READER’S GUIDE.....	32
CHAPTER 2—OBSERVATIONS FROM CURRENT PRACTICE	34
2.1 TEST CASE #1: HEADQUARTERS RENOVATION—SCHEMATIC DESIGN	36
2.1.1 <i>Representation of Decision Information in Current Practice</i>	37
2.1.2 <i>Decision-Enabling Tasks in Current Practice</i>	38
2.2 TEST CASE #2: NEW CAMPUS HEADQUARTERS	41
2.2.1 <i>Representation of Decision Information in Current Practice</i>	42
2.2.2 <i>Decision-Enabling Tasks in Current Practice</i>	43
2.3 TEST CASE #3: HEADQUARTERS RENOVATION—PROGRAMMING	48
2.3.1 <i>Representation of Decision Information in Current Practice</i>	48
2.3.2 <i>Decision-Enabling Task in Current Practice</i>	49
2.4 TEST CASE #4: NEW RETAIL COMPLEX	51
2.4.1 <i>Representation of Decision Information in Current Practice</i>	51
2.4.2 <i>Decision-Enabling Task in Current Practice</i>	53
2.5 TEST CASE #5: THE FATE OF AN AGING FACILITY	56
2.6 TEST CASE #6: SEISMIC UPGRADE PROJECT	56
2.7 ANALYSIS—THE NATURE OF AEC DECISION INFORMATION AND DECISION MAKING.....	57
2.7.1 <i>Heterogeneous</i>	58
2.7.2 <i>Evolutionary</i>	59
2.8 ANALYSIS—LIMITATIONS & IMPACTS OF CURRENT MANAGEMENT OF DECISION INFORMATION..	60

CHAPTER 3—RESEARCH QUESTIONS AND CONTRIBUTIONS OVERVIEW... 64

3.1 REQUIREMENTS OF AEC DECISION-SUPPORT TOOLS AND METHODS.....	65
3.2 INTUITION.....	66
3.3 RESEARCH METHODOLOGY.....	68
3.4 RESEARCH QUESTIONS, CONTRIBUTIONS, AND VALIDATION STUDIES	71
3.4.1 <i>Research Question #1</i>	74
3.4.2 <i>Research Question #2</i>	75
3.4.3 <i>Research Question #3</i>	76
3.5 METRICS OVERVIEW	78
3.5.1 <i>Re-constructability</i>	79
3.5.2 <i>Quickness</i>	79
3.5.3 <i>Informativeness</i>	79
3.5.4 <i>Flexibility</i>	80
3.5.5 <i>Resumability</i>	80

CHAPTER 4—AEC DECISION ONTOLOGY 81

4.1 POINTS OF DEPARTURE.....	82
4.1.1 <i>Representation in Decision Analysis</i>	83
4.1.2 <i>Representation of Decision Information in Virtual Design and Construction</i>	88
4.1.3 <i>Computer Ontology</i>	91
4.2 CONTRIBUTION #1—AEC DECISION ONTOLOGY	92
4.2.1 <i>Ontology Elements</i>	95
4.2.2 <i>Ontology Relationships</i>	96
4.2.3 <i>Ontology Attributes</i>	99
4.2.4 <i>Decision Breakdown Structure</i>	100
4.3 VALIDATION STUDY #1—RECONSTRUCTABLE ONTOLOGY.....	104
4.3.1 <i>Test Case #1: Headquarters Renovation—Schematic Design</i>	104
4.3.2 <i>Test Case #2: New Campus Headquarters</i>	107
4.3.3 <i>Test Case #3: Headquarters Renovation—Programming</i>	109
4.3.4 <i>Test Case #4: New Retail Complex</i>	112
4.3.5 <i>Integrated Analysis</i>	114
4.4 CHAPTER CONCLUSION	116

CHAPTER 5—AEC DECISION METHOD MODEL 117

5.1 POINTS OF DEPARTURE.....	118
5.1.1 <i>Decision Analysis Methods</i>	119
5.1.2 <i>Virtual Design and Construction-Based Computer Methods</i>	121
5.1.3 <i>Other AEC-Based Computer Methods</i>	125
5.2 CONTRIBUTION #2—DECISION METHOD MODEL.....	127
5.2.1 <i>Base Methods</i>	129
<i>B1: Manage Decision Information, Relationships, and Attributes</i>	129
<i>B2: Couple, De-couple, and Re-couple Decision Information</i>	134
<i>B3: Distinguish Decision Information between Selected and Candidate States</i>	136
<i>B4: Reference external decision information</i>	138
<i>B5: Filter Graphical Representation of AEC Decision Ontology</i>	141
<i>B6: Evaluate in different contexts and across different levels of detail</i>	141
5.2.2 <i>Composite Methods</i>	144
<i>C1: Formulate a Decision Breakdown Structure</i>	145
<i>C2: Swap Decision Information Between Selected and Candidate States</i>	148
<i>C3: Interact in the iRoom Environment</i>	148
<i>C4: Filter Graphical Representation of a Decision Breakdown Structure</i>	149
5.2.3 <i>Conclusion from Contribution #2</i>	152
5.3 VALIDATION STUDY #2—INFORMATIVE, FLEXIBLE, RESUMABLE, & QUICK METHODOLOGY	153
<i>Decision-Enabling Task #1</i>	156

<i>Decision-Enabling Tasks #2 and #3</i>	157
<i>Decision-Enabling Tasks #4 and #5</i>	159
<i>Decision-Enabling Task #6</i>	161
<i>Decision-Enabling Task #7</i>	163
<i>Decision-Enabling Task #8</i>	165
5.4 CHAPTER CONCLUSION	167
CHAPTER 6—DYNAMIC DBS FRAMEWORK	169
6.1 POINTS OF DEPARTURE.....	171
6.1.1 <i>Decision Process Based on Decision Analysis</i>	171
6.1.2 <i>AEC Processes & Relationships with the AEC Decision Process</i>	173
6.1.3 <i>AEC Processes & Information Management Requirements on AEC Decision Process</i>	174
6.2 CONTRIBUTION #3—DYNAMIC DBS FRAMEWORK	176
6.2.1 <i>Definition Phase</i>	182
6.2.2 <i>Formulation Phase</i>	184
6.2.3 <i>Evaluation Phase</i>	187
6.2.4 <i>Iteration Phase</i>	190
6.2.5 <i>Decision Phase</i>	192
6.2.6 <i>Conclusion from Contribution #3</i>	194
6.3 VALIDATION STUDY #3—INFORMATIVE, FLEXIBLE, RESUMABLE & QUICK DECISION PROCESS .	195
6.3.1 <i>Analysis of Dynamic DBS Framework During the Decision Definition Phase</i>	195
6.3.2 <i>Analysis of Dynamic DBS Framework During the Formulation Phase</i>	197
6.3.3 <i>Analysis of Dynamic DBS Framework During the Evaluation Phase</i>	202
6.3.4 <i>Analysis of Dynamic DBS Framework During the Iteration Phase</i>	206
6.3.5 <i>Analysis of Dynamic DBS Framework During the Decision Phase</i>	210
6.3.6 <i>Conclusion from Validation Study #3</i>	212
6.4 VALIDATION STUDY #4—EXPERT FEEDBACK	213
6.4.1 <i>Objectives</i>	214
6.4.2 <i>Participants</i>	214
6.4.3 <i>The Sessions</i>	214
6.4.4 <i>The Survey</i>	215
6.4.5 <i>Quantitative and Qualitative Feedback</i>	218
6.4.6 <i>Post-Demonstration Refinement—The Decision Breakdown Structure</i>	222
6.5 CHAPTER CONCLUSION	222
CHAPTER 7—SUMMARY, SIGNIFICANCE, AND CLOSING REMARKS	223
7.1 RESEARCH SUMMARY	223
7.1.1 <i>Limitations of Current Practice</i>	223
7.1.2 <i>Research Questions and Points of Departure</i>	224
7.1.3 <i>Research Contributions</i>	226
7.1.4 <i>Research Validation</i>	229
7.1.5 <i>Power and Generality</i>	231
7.2 THEORETICAL SIGNIFICANCE.....	234
7.3 IMPACT ON PRACTICE	236
7.4 LIMITATIONS AND FUTURE WORK	237
7.5 CLOSING REMARKS	242
REFERENCES	244
1. ACRONYMS AND GLOSSARY	244
2. BIBLIOGRAPHY	252

LIST OF TABLES

Table 1. Examples of decision-enabling tasks, decision stakeholders involved, mode of decision-making, and duration for the motivating case example	8
Table 2. An overview of research scope, contributions, and validation studies	33
Table 3. Six industry test cases and their key characteristics, background, challenges, validation, and metrics to support this research.	36
Table 4. The nature of AEC decision stakeholders, decision information, and decision-making processes based on six industry test cases.	58
Table 5. A table summarizing the ontology relationships between different ontology element combinations in the AEC Decision Ontology	101
Table 6. Table summarizing the number of ontology elements and relationships that are explicitly represented and distinguished based on the decision information used on the four test cases. The left-most column presents the number of ontology elements present in the test cases (e.g., 78 instances of ontology element “Topic”); the second-left through the right-most columns present the number of relationships between different elements (e.g., 77 instances of ontology relationships between ontology elements “Topic” and “Topic”)	115
Table 7. An overview of the eight decision-enabling tasks (DET) that form the validation basis of the dynamic Decision Method Model.	155
Table 8. An overview of the contribution of an information management framework for the application of the dynamic Decision Breakdown Structure.	181
Table 9. A table summarizing the application of the AEC Decision Ontology and the Decision Method Model in the evidence examples across different phases in the Dynamic DBS Framework	212
Table 10. Summary data for the rating of the Dynamic DBS versus conventional practice, averaged for the six questions of Figure 34.....	218
Table 11. Summary of the broad class of project types, project phases, decision information, decision stakeholders, and mode of decision making of the six industry cases used to validate the Dynamic DBS Framework.....	234

LIST OF ILLUSTRATIONS

- Figure 1. AEC decision making involves multidisciplinary stakeholders (left) and iterative processes (right). Hence, AEC decision information (center, to be explained in the following section) is heterogeneous and evolutionary in nature, which poses a unique challenge and opportunity for decision-support methods and tools in the building industry.6
- Figure 2. A diagram of the many discipline-specific options (some with thumbnail graphics highlighting their concept) that are proposed by the professionals. It is the facilitator's responsibility to sort through the interrelationships among these heterogeneous decision options to couple them into a few cross-disciplinary alternatives for recommendation to the decision makers.11
- Figure 3. During the decision review meeting, the decision facilitator presents two distinctive project alternatives to the decision makers. However, the heterogeneous forms, types, and states of decision information, the rationale for coupling various options into an alternative, and the knowledge about the interrelationships between individual options are not maintained in the motivating case study. ...13
- Figure 4. Dashboard examples in airplane (left, image from www.airbus.com) and for an internet-based information visualization solution (right, www.visualmining.com).30
- Figure 5. A computer screenshot of the Decision Dashboard (DD) prototype. The Graphical Window (top) is an interface for facilitators to formulate and re-formulate a Decision Breakdown Structure (DBS) that represents a decision solution and its choices. The symbols (squares, pentagons, circles, etc.) and arrows in the graphical window are model representations of the AEC Ontology elements and relationships that make up a DBS (Chapter 4). The Dashboard Panel (bottom) provides facilitators with a dynamic methodology to manage (e.g., control, isolate, evaluate, etc.) the DBS.....31
- Figure 6. The DD dynamic methods enable facilitators to quickly compare and access specific decision options (e.g., 4D models of the baseline construction case on the left screen and an acceleration case on the right screen) that are integrated by the DBS (middle screen) in the three-screen CIFE iRoom.32
- Figure 7. The CIFE iRoom supports cross-highlighting of P, O, P decision information, but is limited in highlighting the interrelationships between different decision alternatives and options across different POP models. Two 4D models of acceleration proposals involving the steel crew (left screen) and the concrete crew (middle screen) are displayed; decision stakeholders can then utilize the project schedule and a date slider (right screen) to automate the playback, and hence the review, of the two 4D models using existing iRoom functionalities (Kam et. al. 2003).52
- Figure 8. A diagram illustrating examples of the implicit knowledge (e.g., which discipline-specific software application to choose from, which files and naming conventions, which isolated cases, and which specific field in a file, etc.) that a decision facilitator need to master in order to bring up specific decision information in response to an impromptu decision-enabling task.....55
- Figure 9. Fischer and Kunz (2001) outline the CIFE research model.68
- Figure 10. This doctoral research is organized into three main areas, which address the performance and current limitations of representation, method, and process (top) and their corresponding research questions (bottom).73
- Figure 11. Howard (1998) gives an example of a Strategy-Generation Table.85
- Figure 12. Elements, relationships, and attributes are the three parts of the AEC Decision Ontology, with which decision facilitators can represent decision information (e.g., choices) and its interrelationships in their formulation of a Decision Breakdown Structure.....94
- Figure 13. A list of the ontology attributes present in the Decision Dashboard prototype.100

Figure 14. The core structure of the DBS in TC#2 has 5 levels of detail, as evidenced by the number of “topic” tiers that are interconnected by “aggregate” ontology relationships.	102
Figure 15. A screenshot of the Decision Breakdown Structure built in the Decision Dashboard based on the existing decision information in TC#1.	106
Figure 16. A screenshot of the Decision Breakdown Structured built in the Decision Dashboard based on the existing decision information in TC#2.	108
Figure 17. A screenshot of the overall Decision Breakdown Structure built in the Decision Dashboard based on the existing decision information in TC#3.	110
Figure 18. The overall DBS in Figure 17 is broken into three screenshots (top, middle, and bottom screenshots of Fig. 18 correspond to the left, middle, and right, respectively, of Fig. 17).	111
Figure 19. A screenshot of the Decision Breakdown Structured built in the Decision Dashboard based on the existing decision information in TC#4.	113
Figure 20. Product, Organization, and Process (POP) models are displayed in the left (product), middle (organization and process), and right (process) screens in the CIFE iRoom, which supports the automatic cross-referencing of decision information across different screens by a common set of names and date format.	123
Figure 21. The AEC Decision Method Model provides a dynamic methodology for AEC decision facilitators to perform decision-enabling tasks with the AEC Decision Ontology.	128
Figure 22. DMM Base Method B1 enables decision facilitators to create and populate instances of ontology elements and relationships, while associating them with Level-1 decision information that can be propagated within the Decision Breakdown Structure.	130
Figure 23. Examples of coupled decision information from the DBS in TC#4. Left: coupling originates from decision topics that help form a hierarchical DBS. Right: coupling originates from alternative that explains what micro decisions (i.e., option selection) are entailed in an alternative.	135
Figure 24. DMM Base Method B3 enables decision facilitators to distinguish ontology elements between their candidate (e.g., fixed window option in TC#2) and selected (e.g., operable window) states based on the ontology relationships connecting them (aggregate relationship between topic “ventilation” and option “operable window, and choice relationship between option “fixed window” and option “operable window”).	138
Figure 25. In TC#1, the decision topic "Swing Space" in the DBS references two digital files using the reference method (DMM Base Method B4). This method allows DD users to associate specific decision information with a particular ontology instance.	140
Figure 26. DD users can highlight a particular decision topic ("Renovation Plan" in this illustration) and evaluate its associated alternatives, topics, and/or options (“Alternative 1” and “Alternative 2” in this illustration) pertaining to a specific attribute performance (“cumulative cost” in this illustration). ...	142
Figure 27. This figure illustrates a partial DBS in which there are 4 levels of details, as evidenced by the presence of four tiers of decision topics connected by unidirectional aggregate relationships. It also highlights the concepts of attribute propagation in the DBS. The attributes of a selected decision option (cost in this example) propagate across a chain of aggregate relationship in accordance to the semantics of the AEC Decision Ontology.	147
Figure 28. A screenshot of the graphical filter tool (DMM Composite Method C4) in the Decision Dashboard.	150
Figure 29. With the DMM, a DD user can quickly highlight an option (i.e., "Zoning Variance for 2 Additional Floors") and quickly identify all the ripple consequences on/from other decision topics (i.e., “loading and additional floor construction” and “elevators”).	164
Figure 30. The DMM in TC#4 allows DD users to dynamically focus on any of the four acceleration alternatives (e.g., steel acceleration in the illustration) and learn about the specific composition (e.g., which options are selected and not) of those alternatives.	166

Figure 31. The Dynamic Decision Breakdown Structure Framework dissects the AEC decision-making process into five information management phases, each of which is associated with a set of phase-specific decision-enabling tasks, requirements, and applicable ontology components and methods.	178
Figure 32. The Dynamic DBS enables decision facilitators to test what-if combinations of decision options (entry locations) and obtain instantaneous feedback (budget) in the evaluation table.....	209
Figure 33. A photo from the fourth demonstration session that took place on June 24, 2004.....	215
Figure 34. A copy of the survey form given out after the demonstration sessions.....	217
Figure 35. Building upon Figure 10 in Chapter 3, this figure summarizes the three primary focus areas of this doctoral research, their corresponding research questions, and contributions.	228
Figure 36. Interrelationships among the stakeholders, process, decision information, validation studies, decision basis, and the quality of AEC decision making (building upon the concepts presented in Figure 1).	230

CHAPTER 1—INTRODUCTION

We face decision-making scenarios all the time. Whether it is a personal commitment, corporate strategy, or national policy—whenever information, choices, and preferences are present, decisions must be made. Decisions made during the planning, design, and construction of a building project have major impacts on its occupants as well as the capital investment in the facility throughout its life cycle. Since decision making in building projects involves multiple stakeholders and iterative processes, the information and choices that affect the quality of decisions are heterogeneous and evolutionary in nature. In this dissertation, I examine the needs, challenges, consequences, and opportunities of information management with respect to decision making in the building industry. Based on an in-depth assessment of current practice and theories in Decision Analysis, Virtual Design and Construction, and Project Management in Architecture, Engineering, and Construction (AEC), my research has documented six industry case studies in AEC decision making.

AEC decision facilitators, such as lead design or construction project executives, are constantly applying their professional knowledge to coordinate, synthesize, and communicate the many competing and evolving decision criteria of building owners and the many professional recommendations made by the multidisciplinary technical team. Without a theoretical basis to manage AEC decision information, these decision facilitators are hindered by the limitations of the generic decision-support tools used in current practice. Such limitations, including the homogenizationⁱ and static management of information, have ripple consequences on AEC decision making. They adversely affect the ability of AEC decision facilitators to effectively and efficiently complete decision-enabling tasks and consequently, undermine the ability of AEC decision makers to make informed and quick decisions. Striving to improve decision making in the building industry, my research has established 11 concepts (AEC Decision Ontology) and 10

ⁱThis research defines the homogenization of information as the inability of the decision-support tools and/or decision stakeholders to maintain the distinctive characteristics (e.g., types, states, forms, etc.) of AEC decision information, e.g., whether an information item is an option under recommendation or under consideration.

methods (AEC Decision Method Model) to represent, organize, and manage heterogeneous decision information throughout the evolutionary AEC decision-making process. These concepts and methods give rise to my research contribution of the Dynamic Decision Breakdown Structure (DBS) Framework, which supports the management of decision information and the completion of decision-enabling tasks by AEC decision facilitators throughout the decision-making process.

First in this chapter, I introduce the main concepts and the focus of my research—the management of decision information in support of AEC decision making. Through a motivating case example, I provide a summary of my doctoral research, which also serves as a reader’s guide of this dissertation.

1.1 RESEARCH MOTIVATION AND BACKGROUND

A decision is an irrevocable allocation of resources (Howard 1966). The decision-making process involves the framing of a decision problem as well as the logical evaluation, analysis, and appraisal of the recommended decision alternatives. Information, preference, and choice are the three parts of the “Decision Basis” (Howard 1988). According to Decision Analysis theory, the quality of a decision is judged by the decision basis rather than the outcome of a decision. The more informed the decision stakeholders are about the information, preference, and choice (e.g., the information about a patient’s conditions, the choices of medical treatments, and the preference of a patient), the better the decision basis (e.g., the basis to decide upon a particular medical treatment), and the better the decision quality (e.g., the decision to undergo a surgery regardless of the outcome of the surgery). My research centers on the unique needs, characteristics, limitations, consequences, and opportunities associated with the information that affects the decision basis in the building industry.

In the building industry, decisions have profound impacts on the building occupants as well as the function, performance, aesthetics, sustainability, and value of a capital investment throughout its life cycle. The AEC (i.e., architecture-engineering-construction, which is equivalent to the term “building industry” in this dissertation) decision-making process is the course of information finding, solution exploration, negotiation, and iterations with the aim of arriving at a decision. It is an essential part of the building planning, design, and construction process. Pre-project planning, conceptual design, design development, construction documentation, and construction are processes that depend critically on the

decision-making capacity of the related organizations. The project teams from these organizations strive to decide upon the design concept, the design details, the construction methods, etc. through a course of explorations, studies, and refinements. The introduction of Virtual Design and Construction (VDC) methods into professional practice provides increasing amounts of decision information in computer-based form to project teams.

In spite of these VDC methods, there are few and limited theories that specify the means and methods to generate a good information basis for AEC decision making and help project teams to manage the evolving and heterogeneous information basis proactively. In particular, existing theories have not addressed the formulation, evaluation, and iterative re-formulation of choices and their interrelationships throughout the AEC decision-making process. Theories related to AEC decision making establish the theoretical requirements for AEC decision making, but do not specify the decision-support means and methods to improve the decision basis. For instance, value engineering theories (Dell'Isola 1982, 1997), set-based design (Ballard 2000), the "Level of Influence" concept (Paulson 1976), and industrial case studies (Fischer and Kam 2002) rationalize the benefits of gathering an extensive, balanced, and timely information basis, setting up public and explicit criteria, and generating multiple choices. However, there is no formal framework to guide the management of decision information in support of the AEC decision-making process. Existing AEC and Virtual Design and Construction (VDC) theories and methods support the generation of decision information supporting a particular solution choice, but they do not formalize the representation and management of multiple choices (e.g., how these choices may be coupled or decoupled throughout the changing decision-making context). On the other hand, Decision Analysis theories formalize the representation (e.g., strategy generation, influence diagram, binomial representation; Chapter 4) and management (e.g., stochastic modeling) of decision choices, but they are not directly applicable given the unique characteristics of AEC decision making (e.g., large number of participants with diverse perspectives, long and dynamic decision-making process, changing decision criteria, and constant development of solution choices).

As my industry test cases illustrate, these limitations have undermined the capability of current decision-support tools, on which stakeholders rely to complete decision-enabling tasks. Thus, the limitation adversely impacts the basis and hence, the quality of AEC decision making (Chapter 2). To better understand the nature of AEC decision basis, I first

examine the people and processes that influence the information basis of AEC decision making. I submit that theories and methods shall respond more proactively to the unique characteristics of AEC decision information, which is heterogeneous and evolutionary, given the combined influences of people and processes in AEC decision making.

1.1.1 AEC DECISION STAKEHOLDERS

Stakeholders are all the groups of individuals involved in the decision-making process. The groups are comprised of individuals representing their respective organizations, e.g., the owner, occupant, decision facilitator, and professional organizations. To foster idea generation and to address the many technical challenges in construction projects, the participants in the AEC decision-making process come from multiple disciplines and are therefore, multidisciplinary and diverse. In this dissertation, I categorize the many participants involved in AEC decision making into three categories of decision stakeholders: decision makers, decision facilitators, and professionals.

Decision makers (such as owners, end-users, management team, and developers) make the decisions. They are usually not directly involved in the technicalities of design and construction. Therefore, the technical expertise, recommendations, and moderation skills of the decision facilitators (or facilitators in short), such as owner representatives, project managers, project executives, and leading design or construction professionals, play a crucial role in guiding the decision makers to comprehend and analyze the specialty inputs from the professionals (such as architect, engineers, contractors, specialty contractors, and estimators, etc.). Hence, the AEC decision stakeholders are multidisciplinary. They share very different perspectives and technical backgrounds while playing different roles in the decision-making process.

1.1.2 AEC DECISION PROCESS

In building planning, design, construction, and management, the decision process is about developing new solutions and uncovering cross-disciplinary impacts. The process is iterative and dynamic. Decision facilitators and professionals guide the decision makers in making decisions that have both strategic and tactical implications for the quality, cost, duration, and resource allocation of a building project. Once a decision need or challenge arises in a building project, professionals apply their

technical skills and experiences to interpret the decision problem and come up with a number of discipline-specific options. They predict and evaluate the performance of such options. Based on the decision makers' criteria such as budget, risk attitude, specifications, and milestones, the decision facilitators mix and match different options in order to package them into a few distinctive alternatives for recommendation to the decision makers. The facilitators provide briefings to the decision makers, who comprehend, evaluate, and analyze the recommendations. As the decision stakeholders learn more about the project from the process and the interactions among one another, they discover cross-disciplinary issues (i.e., ripple consequences) and areas for improvement. These discoveries often lead to an iterative decision process, in which decision makers refine their criteria, professionals update their options, while the facilitators optimize the mixing and matching of options, and re-package them differently as new or hybrid alternatives for recommendations. Hence, the AEC decision process is iterative and dynamic until a decision has been made.

This iterative and dynamic decision process is part of many different phases of AEC capital projects. In pre-project planning, developers compare financial prospects of different property sites for investment decisions; in schematic design, building owners compare aesthetics, cost, and the life-cycle performance of different design proposals for development decisions; and in construction planning, the contractors compare different phasing proposals to streamline the construction process.

1.1.3 PEOPLE, PROCESS, AND THE MOTIVATION OF RESEARCH ON DECISION INFORMATION

Both people and process influence the information basis of AEC decision making (Figure 1). The diverse backgrounds, expectations, technical skills, and the different levels of project involvement across all decision stakeholders mean that decision information is heterogeneous and distributed among all the multidisciplinary project participants. However, information dispersal does not support an informative decision-making process since it limits the decision stakeholders from accessing decision information quickly and informatively. Therefore, information management should mitigate this limitation by making decision information easily accessible (i.e., quickly accessible) and informative for all stakeholders. Given the iterative and dynamic AEC decision process, the decision information is evolutionary. Therefore, AEC decision

information needs to be easily manipulated (i.e., flexible) and easily refined (i.e., resumable) as quickly as possible (sections 1.3.2, 2.8, 3.2, and 3.6 discuss the requirements of informativeness, flexibility, resumability, and quickness in further detail).

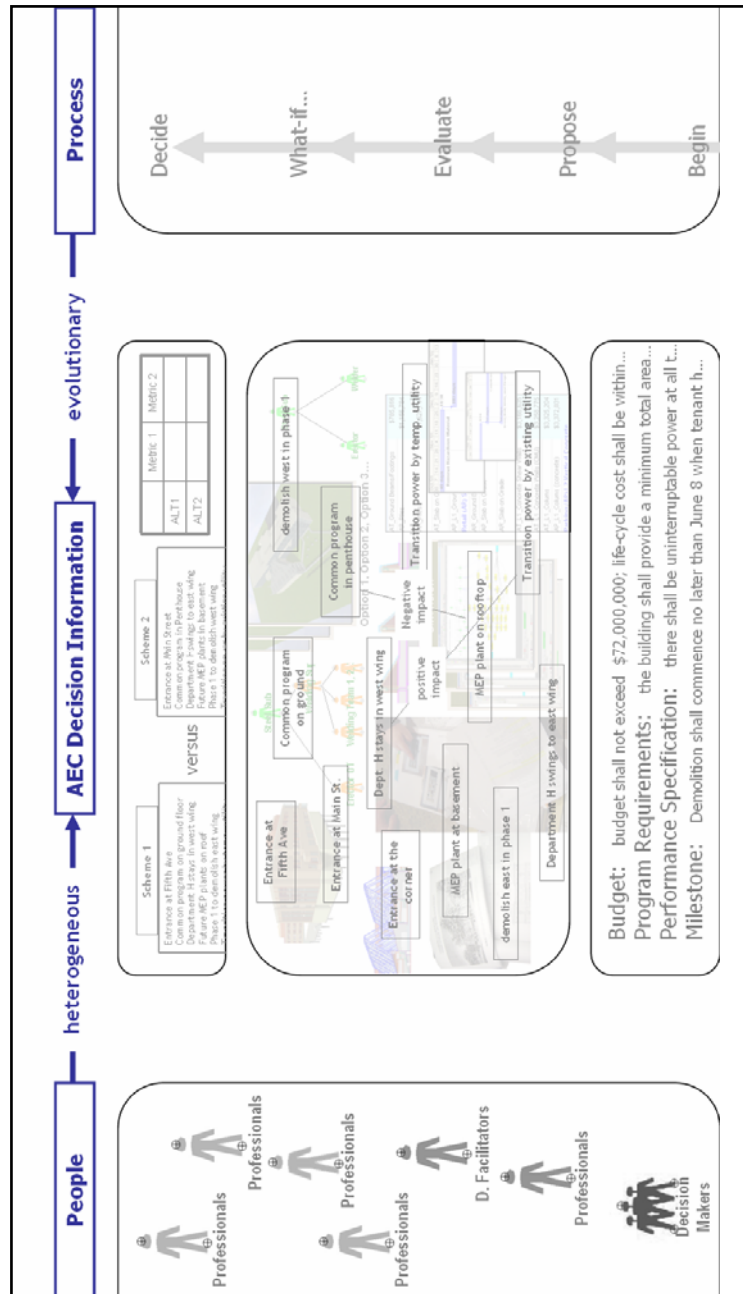


Figure 1. AEC decision making involves multidisciplinary stakeholders (left) and iterative processes (right). Hence, AEC decision information (center, to be explained in the following section) is heterogeneous and evolutionary in nature, which poses a unique challenge and opportunity for decision-support methods and tools in the building industry.

Because existing AEC theories and methods primarily focus on the generation, but not the management, of choices and their interrelationships, my research focuses on the management (i.e., representation and methodology) of decision information in support of AEC decision making. Before I further explain the scope of my research and the related terminology, the following section presents a motivating case example to illustrate these characteristics of people, process, and information in AEC decision making.

1.2 MOTIVATING CASE EXAMPLE

The following is a case example based on one of my six test cases (i.e., my first test case or “TC#1” in short throughout this dissertation, section 2.1 introduces the case in further detail). Because TC#1 involves the most diverse set of decision topics, I have filtered out details to simplify it as a motivating case example in the following. The case is based on the completion of a number of decision-enabling tasks, with a choice of a particular decision-support tools (e.g., MS Word, MS PowerPoint), on an actual capital project in current practice. It illustrates some of the key limitations in current practice, such as the lack of distinction (i.e., the homogenization) between the types (options, alternatives, criteria, topics), the states (recommended or candidate choices), and the interchangeability of decision information.

In section 1.3.1, I first summarize the decision scenario, decision stakeholders, and decision-enabling tasks that make up this motivating case example. Based on the limitations of current decision-support methods and tools, I present my observations and analysis in section 1.3.2. While this particular case example serves as a primary motivating example, the rest of the dissertation investigates the broader limitations of current practice. Based on my research on six industry cases (Chapter 2), I draw more general insights into other types of decision-enabling tasks, decision information, decision-support tools, and information management phases beyond the scope of this motivating case example.

1.2.1 CASE SUMMARY

A business corporation is undergoingⁱⁱ a headquarters renovation project. During the schematic design and pre-construction planning phase, owner representatives from the business corporation (i.e., the decision makers) have to decide upon the design approach (product decision), the transitional plan (process decision), and the move plan for its departments (organization decision). Not only do these decisions affect one another, they also have significant influence on the experience of the occupants in the headquarters as well as the quality, cost, and schedule of the renovation project. However, current decision-support tools and methods used by the lead project architect (i.e., the decision facilitator) do not enable him to complete decision-enabling tasks (Table 1) effectively. This limitation adversely affects the decision basis of the owner representatives to make informed and quick decisions.

Section	Decision-Enabling Task	Decision Stakeholder(s)	Mode—Duration
1.2.1.1	Define Decision Criteria	Decision Makers and Facilitator	Synchronous—Half Day
1.2.1.2	Formulate Decision Options	Professionals	Asynchronous—Three Weeks
1.2.1.3	Formulate Decision Alternatives	Decision Facilitator	Asynchronous—One Week
1.2.1.4	Recommend Decision Alternatives	Decision Facilitator	Synchronous—One Hour
1.2.1.5	Explain/Access Decision Information	Decision Facilitator	Synchronous—One Hour
1.2.1.6	Predict/Evaluate Decision Information	Decision Makers and Facilitator	Synchronous—N/A
1.2.1.7	Iterate What-If Adjustments	Decision Facilitator	Synchronous—N/A

Table 1. Examples of decision-enabling tasks, decision stakeholders involved, mode of decision-makingⁱⁱⁱ, and duration for the motivating case example.

ⁱⁱ I report this case in present tense because it embodies concepts, decision-enabling tasks, and limitations that are common in current practice.

ⁱⁱⁱ The synchronous mode refers to decision stakeholders completing decision-enabling task at the same place at the same time; the asynchronous mode refers to the opposite, when stakeholders do not need to complete tasks at the same time or at the same place.

1.2.1.1 DECISION-ENABLING TASK: DECISION MAKERS AND FACILITATOR DEFINE DECISION

CRITERIA

The owner representatives define the project criteria along with the lead project architect. Together, they define the following decision criteria using a word processing tool in an afternoon meeting, a synchronous mode of decision making that lasts for half a day. With the Dynamic DBS framework, this decision-enabling task takes place during the decision definition phase (see sections 6.2.1 through 6.2.5 for specific information management characteristics and requirements pertaining to the definition, formulation, evaluation, iteration, and decision phases, respectively).

Decision Information: Criteria

- the headquarters renovation shall not exceed the established budget
- the aesthetics and spatial configuration of the proposed design shall be approved by the corporate review committee
- at least half of the building shall be operational during the first phase of construction (since department H, which takes up 50% of the headquarters building, is launching a critical business operation)
- the proposed design shall meet the minimum program requirement (e.g., the total rentable area shall not be less than 380,000 square feet)

1.2.1.2 DECISION-ENABLING TASK: PROFESSIONALS FORMULATE DECISION OPTIONS

The owner representatives and the renovation project team believe in the merit of having parallel sets of competing decision choices (options and alternatives) for evaluation in the decision-making process. Bounded by the owner criteria, the design and construction consultants (i.e., the professionals) have come up with discipline-specific options. The design architects, MEP engineers, and construction schedulers have each proposed (i.e., formulated) several distinctively different options that pertain to the decision topics of their respective disciplines. They utilize their professional domain knowledge, personal experience, and disciplinary software applications (e.g., product modeling, process modeling, cost estimating applications) to propose over ten decision options (Figure 2), which will then be packaged by the lead architect into alternatives prior to the decision review meeting. This decision-enabling task to formulate options takes the professionals about three weeks to complete in an

asynchronous mode of decision making, in which the professionals work independently from one another.

Decision Information: Topic—Options

- entrance locations—at Fifth Avenue, at Main Street, or at the corner
[product options^{iv}]
- common program locations—on ground floor or on penthouse
[product options]
- department H arrangement—stay in west wing or swing (i.e., temporarily move) to east wing
[organization options]
- MEP plant locations—at basement (east or west) or on roof
[product options]
- construction sequence—phase 1 demolishes west wing or east wing
[process options]
- utility services during construction—feed from existing plant at east basement or from temporary utilities
[resource options]

^{iv} Virtual Design and Construction methods allow one to categorize AEC decision information with product, organization, and process designations (sections 1.3.2 and 4.1.2), all of which may influence one another as well as the overall decision basis.

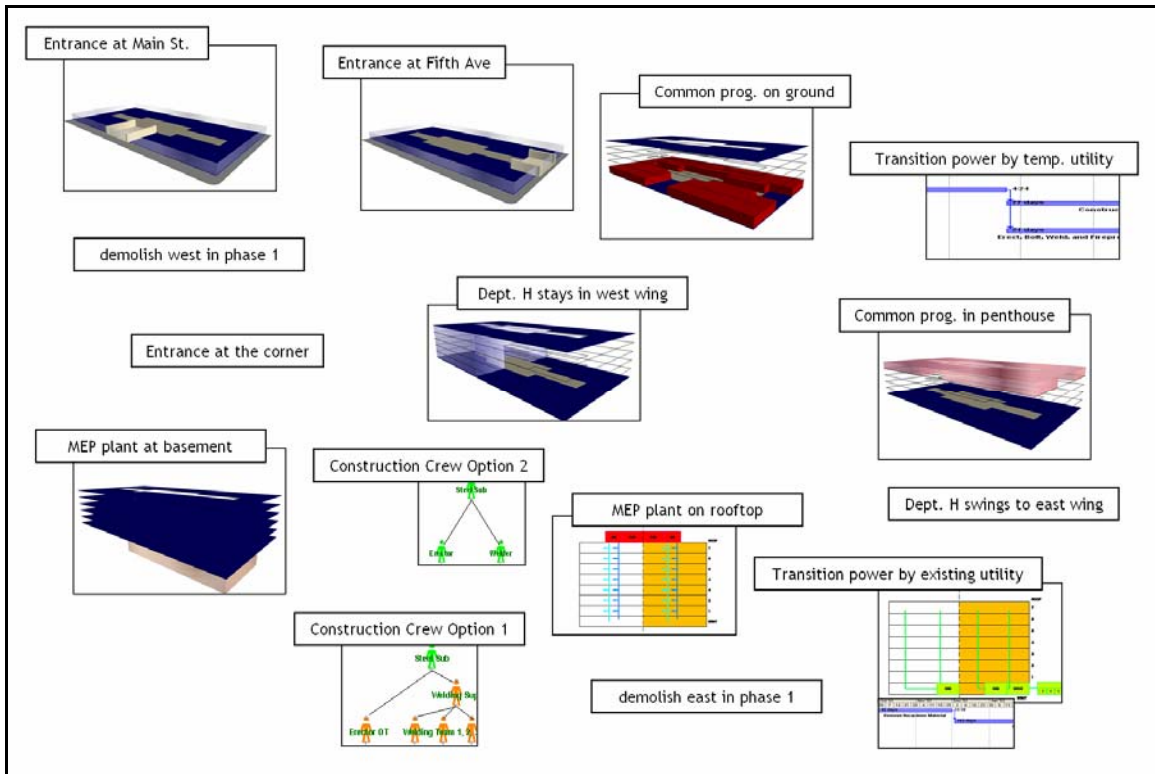


Figure 2. A diagram of the many discipline-specific options (some with thumbnail graphics highlighting their concept) that are proposed by the professionals. It is the facilitator's responsibility to sort through the interrelationships among these heterogeneous decision options to couple them into a few cross-disciplinary alternatives for recommendation to the decision makers.

1.2.1.3 DECISION-ENABLING TASK: FACILITATOR FORMULATES DECISION ALTERNATIVES

Not only is the lead architect a professional who is responsible for the architectural design of the renovation project, he is also the facilitator of the decision-making process. He orchestrates the presentation to the owner's decision-making team. In preparation for the decision review meeting, the architect carefully interprets the decision criteria set forth by the owner and sorts through the interrelationships among the heterogeneous options. Based on his interpretation and recommendation, the lead architect packages (i.e., couples) the product, organization, and process options into two cross-disciplinary decision alternatives. He makes his recommendation based on his professional intuition, project knowledge, and the information about the merit, behavior (i.e., performance) prediction, and interrelationships of the options (e.g., conflict between the decision to locate the MEP plant on the rooftop and the decision to assign common program in the penthouse, Figure 3). The coupling of options to formulate a decision alternative

involves the synthesis of different information forms (e.g., images, drawings, remarks, and annotations) contributed by multiple disciplines. This formulation takes place in MS PowerPoint—the only decision-support tool used in the decision review meeting between the facilitator and the decision makers. This decision-enabling task takes the decision facilitator approximately one week to complete.

Decision Information: Alternatives

- Scheme 1—entrance at Fifth Ave.; common program to be located on the ground floor; department H will stay in the west wing; future MEP plant to be located on roof; phase 1 construction will begin with the demolition of the east wing; and rely on temporary utility supplies.
- Scheme 2—entrance at Main Street; common program to be located on the penthouse; department H will swing to the east wing; future MEP plant to be located at west basement; phase 1 construction will begin with the demolition of the west wing; and rely on existing plant in east basement for utility supplies.

1.2.1.4 DECISION-ENABLING TASK: FACILITATOR RECOMMENDS ALTERNATIVES TO DECISION MAKERS

After a month of formulation by the professionals and subsequently the facilitator, the decision review meeting takes place with the decision makers (i.e., project executive and review committee from the business corporation) in attendance along with representatives from the architectural firm. During the first hour of the face-to-face meeting, the lead architect presents the two alternatives (Figure 3) in a computer slide show while verbally facilitating the decision-making process.

These two alternatives presented are represented homogeneously as individual slides in a computer slide show. The rationale for coupling various options into an alternative and the knowledge about the interrelationships among individual options (examples such as the negative impact between “MEP plant to be located on the roof” and “common program to be located on the penthouse” are shown with arrows in the top box in Figure 3) are not publicly nor explicitly available to the decision makers during the decision review meeting.

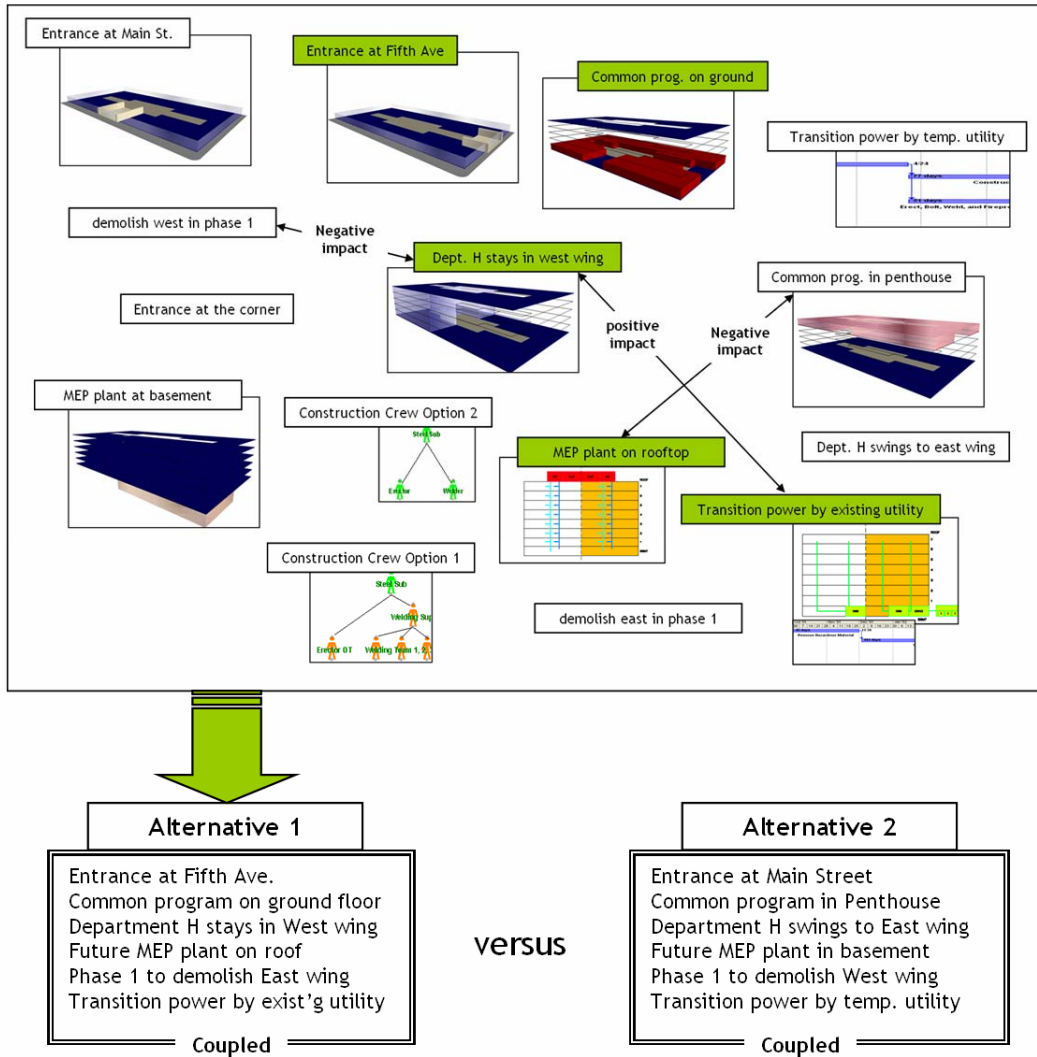


Figure 3. During the decision review meeting, the decision facilitator presents two distinctive project alternatives to the decision makers. However, the heterogeneous forms, types, and states of decision information, the rationale for coupling various options into an alternative, and the knowledge about the interrelationships between individual options are not maintained in the motivating case study.

1.2.1.5 DECISION-ENABLING TASK: FACILITATOR ACCESSES DECISION INFORMATION FOR EXPLANATION

After the facilitator has presented the alternative schemes, the decision makers ask the following questions that relate to the business and functional criteria of the corporation:

- What is the rentable area requirement set forth in the criteria?
- What is the total rentable office area in alternative 1? And alternative 2?
- What are the collateral benefits of swinging department H to the east wing in phase 1?
- How much does an internal swing cost? How does the swing impact the operation of department H (in terms of downtime and subsequent productivity improvement/reduction)?

Responses to these questions require a mastering of the cross-disciplinary knowledge about the aforementioned decision criteria as well as the characteristics of the proposed options and alternatives. The first two questions above, for instance, relate to the gross and usable areas of the proposed office, support, and common spaces in the headquarters. The answers to these questions translate in terms of rentable area, which is a crucial business criterion to certain decision makers in the decision review meeting. On the other hand, the third and fourth questions pertain to a series of inquiries about the arrangement of department H in support of a tradeoff decision between different process and organizational decisions.

In response to these questions, the facilitator needs to complete several decision-enabling tasks by accessing heterogeneous decision information pertaining to specific decision criteria (e.g., programmatic information), alternatives (e.g., architectural design), rationales (e.g., in a written report customized for department H), and values (e.g., space report). However, as the facilitator has coupled options into alternatives in a decision-enabling task (section 1.3.1.3) prior to this decision review meeting, specific predictions (e.g., area information) for individual options are merged into a macro prediction (e.g., total area). After an hour of verbal explanation, the lead architect still cannot complete this decision-enabling task. This is because the decision-support tool and the decision information available do not provide the flexibility for the decision facilitator to query decision information at the option and alternative levels. In addition, this homogenized representation of decision alternatives does not inform decision makers about the interchangeability of options or the interrelationships between options (e.g., the ripple consequences of the different utility decision options on the operation of Department H).

1.2.1.6 DECISION-ENABLING TASK: FACILITATOR EXPLAINS FORMULATED INFORMATION AND MAKES PREDICTIONS IN SUPPORT OF DECISION EVALUATION

During the meeting, the decision makers review different choices and criteria. To support an informative evaluation, they come up with the following questions to aid in their decision evaluation:

- How many square feet do we lose by having the entry at the corner of Fifth Ave. and Main St.?
- How do the options of MEP plant location (in the basement or on the roof) impact the amount of net office area?
- How do the options of the common program location (on the ground floor or in the penthouse) affect the efficiency ratio between office and common areas, and hence the program requirements of the building?
- How do the proposed phasing plans satisfy the criterion that requires uninterruptible utility supplies (e.g., electricity and data) for department H?

In response to these impromptu inquiries, the decision facilitator needs to complete decision-enabling tasks that focus on decision information across different levels of detail (e.g., area information for design alternatives and the area information for entry options). They need to uncover the decision rationale pertaining to the proposed options and alternatives. They need to generate evaluation tables that compare specific options against a specific criterion. However, the decision-support tool available in the meeting does not support impromptu explanation, evaluation, or prediction based on the existing form of decision information (e.g., there is no area information about the options of entry and MEP plant locations). The pre-packaged presentation conveys graphical diagrams and high-level information that pertain to the specific decision alternatives. It lacks quantitative data or qualitative rationale about individual design and construction options. The facts, data, and rationale are not explicitly documented and are not readily available for inquiry, evaluation, or adjustments by the decision makers. Knowledge about particular options, rationale, and interrelationships between decision information is often dispersed in the minds of the consulting team. Thus, explanations about options and alternatives rely on the presence of the technical team, clear minds, and the verbal skills of the meeting participants. This decision-enabling task cannot be performed given time available during the brief synchronous (i.e., face-

to-face) meeting in the absence of the technical team as well as the discipline-specific decision information. As a result and as sections 2.1, 5.3, and 6.3 explain in greater detail, the decision facilitator attempts to respond to these questions by performing rough approximations and mental calculations. Such an ad hoc workaround is not informative and is therefore not satisfactory from the decision makers' perspectives. Thus, the inability to complete these decision-enabling tasks undermines the decision basis of the decision makers while delaying the decision-making process.

1.2.1.7 DECISION-ENABLING TASK: FACILITATOR ITERATES WITH WHAT-IF ADJUSTMENTS

Given the opportunity to better understand the constraints and opportunities based on the facilitator's briefing, the decision makers prefer to mix and match several options based on a tradeoff among aesthetic, programmatic, and business reasons. The decision makers refine their decision criteria (e.g., having two entrances instead of a single entry) as they believe that a hybrid assembly of design/construction options from the two fixed alternatives is preferable in meeting their refined decision criteria. Hence, the following alternative-generating questions regarding the opportunities of decoupling pre-packaged alternatives and re-coupling existing options arise:

- What are the design and construction impacts of leaving department H stay in the west wing while using the existing utility supplies from the east wing basement?
- Can there be a hybrid case with department H in the west wing; relying on existing utility supplies from the east wing; the common program in the penthouse; entrances from both Fifth Ave. and Main St; and a rooftop MEP plant?

To these what-if questions and suggestions for new alternatives, the facilitator does not only need to access the decision information in different formats that span across a number of disciplines (e.g., architectural, construction phasing, tenant liaisons, building systems, etc.), he also has to adjust the decision information (e.g., the coupling of options to adjust the alternative) and obtain as many predicted behaviors of the adjustment (e.g., the predicted cost and area) as quickly as possible. This decision-enabling task requires the decision-support tools to be informative, flexible, quick, and

resumable, such that the architects can resume a fact-based and informative exchange with the decision makers as quickly as possible.

However, current practice lacks a formal method to document these valuable thinking processes and knowledge during the formulation phase. The representation of decision information in current practice is homogenized. There are no distinctions between the types (options, alternatives, criteria, topics), the states (recommended or candidate choices), and the interchangeability of decision information. This ad hoc process and method for information management adversely skew the decision-making process. Specifically, the decision makers from the business corporation, the lead architect (i.e., decision facilitator), and the professionals present in the meeting approve a hybrid design in which the common program will be located in the penthouse whereas the MEP plant will be located in the rooftop. Thus, they approve a solution without realizing an internal conflict between the MEP option and the common program option. Knowledge about this particular interrelationship between decision information resides only in a professional's (i.e., the mechanical engineer's) mind and the paper-based study prepared by this professional, but not the decision-support tool available during the meeting. As neither the mechanical engineer nor the paper-based study is present, the decision stakeholders have no means or methods to uncover this ripple consequence. Consequently, another week of design development time is wasted until the conflicting interrelationship between these decision options surfaces again, causing rework and wasting additional time before the decision stakeholders can reconvene and resume the decision-making process.

1.2.2 CASE ANALYSIS—CHARACTERISTICS, LIMITATIONS, AND INTUITION

An analysis of this motivating case example validates my earlier observation that a multidisciplinary group of stakeholders is involved in AEC decision making, in an iterative and dynamic process (sections 1.1.1 and 1.1.2). The many stakeholders and the changing decision context influence the characteristics of AEC decision information and decision making. The following two subsections summarize these characteristics and assess the limitations of current decision-support methods and tools as evidenced in the case example. While the following analysis focuses on the motivating case example

and provides a preview of my research contributions, I present five additional industry test cases in Chapter 2, which further validate the following analysis.

1.2.2.1 THE CHARACTERISTICS OF AEC DECISION INFORMATION

Given the number of stakeholders, teams, and individuals involved in decision making as well as the complexity and scale of an AEC project, AEC decision information involves many perspectives, forms, types, levels of detail, and interrelationships. These characteristics lead to my conclusion that AEC decision information and decision making are heterogeneous in nature (section 2.7.1).

(1) Many Perspectives

The motivating case example illustrates the diverse perspectives of the many participants involved in the decision-making process. Decision makers such as the project executive, the financial specialists, and the corporate review committee focus on different decision topics, such as project coordination, rent projection, and the aesthetics of the headquarters building. There are also a number of professionals involved spanning across many different disciplines, such as architectural designers, structural engineers, construction phasing specialists, cost estimators, and mechanical engineers, etc. While the lead architect also plays the role of a decision facilitator, each of these individuals bring a different perspective to the decision making process. These teams or individuals possess different criteria, knowledge, perspectives, and therefore, often focus on a particular set of decision information. While current decision-support tools rely on the decision facilitators to employ ad hoc methods to organize and interrelate multidisciplinary decision information, the need to formally categorize, organize, and manipulate such information has motivated this research.

(2) Many Forms

A number of information forms are present in the motivating example. They include rendered images, design drawings, technical reports, discipline-specific statements and narratives, area calculations and space reports, etc. Even though the majority of such information is available in digital forms, there are no formal methods or processes to incorporate different information forms into the primary decision-support tool.

Consequently, decision stakeholders cannot access pertinent information (e.g., area calculation) during the decision review meeting. Thus, there is a need to formalize the representation and management of decision information to support the making of quick and informed decision. In Chapters 4 and 5, I explain how different digital information forms can be represented and referenced as attributes in the Decision Breakdown Structure, for quick and informative retrieval of pertinent decision information throughout the decision-making process.

(3) Many Types

While information form categorizes decision information by its format, type categorizes information by its influence or role in the decision-making process. Assessing the decision scenario from the motivating case example, I generalize that decision topics (e.g., architectural design and construction phasing), criteria (e.g., budget and minimum office space requirement), choices (e.g., alternate design schemes and entrance location options), and details (e.g., area of a particular space, duration of a specific construction task) are the basic information types. Although there are distinctive topics, criteria, choices, and details that can be identified, the decision facilitator in the case example did not use any categorization approaches to process or balance the representation of decision information. The prompting for topics, criteria, and details by the decision makers in the decision review meeting signals the importance of balancing the many types of information in AEC decision making. In Chapter 4, I introduce an AEC Decision Ontology that formalizes the representation and organization of these basic types of information.

(4) Many Levels of Detail

Within each discipline, form, or type, AEC decision information also entails different levels of detail (LOD). At the macro level, the decision makers may be concerned about the total rentable area of the headquarters; on a micro level, they may focus on specific rooms or spaces. Similarly in terms of choices, the basic decision may be between two design alternatives, whereas a micro-decision would involve specific option selections of entrance location or MEP plant. As I further explain in Chapter 4, AEC and project management theories have specific breakdown structures for

managing product, process, and organization-specific information across different LOD. However, there are no existing theories that specify the handling of choices at different LOD. As illustrated from the motivating case example, the decision review focuses on a macro LOD of choice (i.e., design alternative scheme 1 and scheme 2) but offers minimal support for the approval of choices at a micro LOD (e.g., different entry locations and different MEP plant options). Hence, my research contributes to an explicit differentiation between an alternative and an option, complemented by a Decision Breakdown Structure (Chapter 4) and a dynamic methodology (Chapter 5) that specifies the different handling of a decision choice at different levels of detail.

(5) Many Interrelationships

There are many interrelationships among AEC decision information present in the case example. However, there is no formal representation of these interrelationships in the current decision-support tool. For instance, different decision topics are constrained by different decision criteria (e.g., architectural design needs to be approved by the owner's review committee, construction phasing needs to satisfy the requirements set forth by Department H, etc.). In addition, different decision options have different ripple consequences on other decision options. For instance, there is a positive (i.e., mutually beneficial) impact between the decision to use existing utility during construction and the decision for Department H to stay in the existing building. On the other hand, there is a negative consequence between the decisions to choose a rooftop MEP plant and to locate common program in the penthouse. Last, there is a neutral relationship between the location decisions of the entrance and the MEP plant. The absence of such interrelationships among decision information has delayed the uncovering of negative ripple consequences in the case example. In Chapter 4 and 5, I explain how the Dynamic DBS supports the representation and management of interrelationships among AEC decision information.

1.2.2.2 THE CHARACTERISTICS OF THE AEC DECISION-MAKING PROCESS

Change is another key characteristic that has led to my conclusion that AEC decision information and decision making are evolutionary in nature (section 2.7.2). The

following presents an analysis of the changing modes, states, and aggregation needs that arose from the motivating case example.

(1) Changing Modes of Decision Making

I have documented eight different decision-enabling tasks in the motivating case example (Table 1 in section 1.3.1). One observation is that there are different characteristics for decision-enabling tasks performed under different modes of decision making. Under an asynchronous mode of decision making, decision stakeholders are working in a less intensive environment where collaboration does not take place at the same time or at the same place. In the case example, the formulation of decision options by the professionals and decision alternatives by the facilitator are examples of decision-enabling tasks completed under an asynchronous mode of decision making. In contrast, the synchronous mode of decision making involves a number of meeting participants gathering in the same room at the same time, e.g., the recommendation, explanation, evaluation, and what-if adjustment of decision information during the review meeting.

My observation is that the value of time (or the cost of a delay) is different between the synchronous and asynchronous modes of decision making. The ability to make quick and informed decisions during synchronous meetings is more valuable and important than during asynchronous decision settings. Considering the effort to coordinate the many meeting participants' schedules and the cost of time of these individuals being in the same place at the same time, an effective decision-support tool shall respond to the changing needs of the decision stakeholders as informatively and quickly as possible. Thus, it is worthy for decision facilitators and professionals to enrich the decision basis during the asynchronous formulation and reformulation stages, rather than wasting valuable time and effort to process decision information during the synchronous mode of decision meetings.

(2) Changing States of Decision Information

The decision review meeting allows the decision makers to better understand the tradeoffs of the available choices, whose predicted behavior (e.g., total construction

cost) do not meet the owner's criteria (e.g., budget). Therefore, the meeting also requires the architects (i.e., the facilitators) to assist the owner team in making trade-off decisions and refining their criteria to bridge the gap between what the owners want (e.g., certain design quality within a specific budget) and what the professionals currently offer (e.g., certain design quality out of a specific budget). As the decision-making process iterates, owners refine decision constraints whereas consultants seize new opportunities in problem solving. Consequently, neither of the two pre-packaged alternatives fully satisfies the changing needs of the decision stakeholders.

Since it is not possible for the facilitator to anticipate all the questions that may arise during the meeting, the decision-support tools should allow the facilitator to access decision information informatively and quickly upon impromptu queries. The tools should clearly distinguish the many states of decision information, enabling decision makers to realize what the choices are and what the current solution entails. However, information dispersal, homogenized representation of information, and the inability of the decision-support tool to access decision information in impromptu situations adversely impact the informativeness and the flow of the decision-making process in this case example (sections 3.2, 5.3, and 6.3).

First, there is no formal representation of decision rationale in the decision-support tool. The reasoning about the recommendations resides in the memory of the decision facilitator and the professionals (e.g., the mechanical engineer), most of whom are not present in the meeting to explain the recommendation rationale. Second, the content, focus, and values in the evaluation tables are pre-determined before the meeting. An impromptu inquiry about area information in this situation requires the decision facilitator to spend additional effort to access and compile the newly required decision information.

In other words, the homogenized representation and static (e.g., pre-packing and pre-determined) management of decision alternatives in current practice separate the decision makers from the richness of decision information available during the decision formulation phase. Being the only available decision-support tool, the pre-packaged slide show does not support informative inquiries; does not offer flexible evaluations; nor allow quick and resumable adjustments of decision information in the meeting.

Thus, current practice makes the iterative adjustment process slow and difficult to resume. In Chapters 5 and 6, I explain how my formalization of a dynamic methodology and a decision-making framework can build upon the Decision Breakdown Structure to support decision making in ways that are more informative, fast, flexible, and resumable.

(3) Changing Aggregation Needs

In the motivating case example, the lead architect couples different cross-disciplinary decision options to formulate two distinctive alternatives for recommendation to the decision makers. While coupling is necessary to shield decision makers from an overburden of options, an informative, flexible, quick, and resumable de-coupling and re-coupling mechanism is missing for inquiring about the performance of recommended options, for evaluating candidate options, and for readjusting the criteria or the re-packaging of options.

The generation of alternatives is necessary because the decision makers do not have the time or technical background to sort through an exhaustive number of possibilities to combine these options (as many as 96 possible combinations in this simplified example) before or during the brief decision review meeting. Neither does the facilitating architect consider every single possible alternative. By pre-coupling project options into alternatives, the owners only need to choose between two candidate alternatives, rather than facing over 10 options and 96 possible ways to mix and match those options. Coupling allows the architect to inject his professional knowledge and filter out bad combinations of options based on the cross-disciplinary interrelationships among the options. For instance, the option of the MEP plant on the rooftop is not combinable with the option of a common program in the penthouse due to design conflicts and zoning requirements. Hence, the facilitator makes his recommendation based on his professional intuition, project knowledge, and the information about the merit, performance prediction, and interrelationships of the options. However, the decision-support tool employed by the facilitator in the case example is not informative or flexible in handling “what-if” adjustment needs. The tool has not informed the stakeholders about the ripple consequences of mixing and matching different options in response to a what-if suggestion.

This motivating case example illustrates the adverse impacts on AEC decision making caused by the lack of means and methods to represent and manage heterogeneous and evolutionary AEC decision information. In chapter 2, I reinforce these characteristics and limitations with additional test cases. These observations become the design criteria for my design and specification of the Decision Breakdown Structure (section 4.3) and its associated dynamic methodology (section 5.3). Meanwhile, in the following bullets, I list some of my questions (section 3.2 includes an extended list of questions) that have motivated and guided my doctoral research.

- Why is it difficult for generic (i.e., non AEC-context specific) decision-support tools and methods, such as those used in the motivating case example, to manage (e.g., access, evaluate, and adjust) decision information?
- Are the limitations of current practice simply caused by the lack of decision-support tools and computer applications for the AEC industry? Or are they due to the lack of theories?

1.3 SCOPE OF RESEARCH

This research contributes to a deeper understanding of AEC decision-enabling tasks, decision information, and decision-making processes. The results of this research support decision facilitators to complete decision-enabling tasks that involve major discrete choices (e.g., to build a green roof or a conventional roof, to make predictions based on best case or worst case scenario, etc.) related to the planning, design, construction, and operation of building construction. As introduced earlier in this chapter, the decision basis affects the decision quality and is composed of information, choice, and preference. The information basis in AEC involves a variety of information forms, types, and disciplines, and affects how choices and preferences can be introduced in AEC decision making. I use the term decision information to cover all parts of the decision basis. In other words, the term decision information generalizes information, choice, and preference in this dissertation.

Because existing AEC theories and methods primarily focus on the generation, but not the management, of choices and their interrelationships (sections 4.1, 5.1, and 6.1), my research centers on decision information and its management, enabled by decision-support tools, in support of decision stakeholders in completing decision-enabling tasks in AEC decision

making. Better decision information can be achieved by improving both the quality and quantity of information or by improving the management of information. This research centers on the latter. Given the same set of underlying decision information, my research contributions strive to enable better decision making by better management of the decision information. Specifically, my research investigates how information management supports decision-enabling tasks. The following sections define the foundation and main concepts of my research.

1.3.1 AEC

In this research, the term “AEC” (architecture-engineering-construction) refers to the whole building industry, which also includes real estate and facility management in addition to the literal meaning (i.e., only the design and construction aspects) of AEC. Unless there are specific notes of exception, the AEC context applies to all of the following terms in this dissertation, such as decision-making process, phases, professionals, decision information, decision ontology, decision dashboard, methodology, decision-enabling tasks, and formal framework, etc. In other words, all “decision-making processes” in this dissertation are “AEC decision-making processes,” “professionals” are “AEC professionals,” and so on.

1.3.2 DECISION INFORMATION

Decision information covers the decision basis—preference, choice, information; it also covers all the data and knowledge that serve as the background, basis, and prediction of the decision basis. Examples of decision information are criteria (e.g., turnover milestone, budget), facts (e.g., site conditions), rationale (e.g., recommendation basis), assumptions (e.g., unit cost), and predictions (e.g., cost estimate) pertaining to decisions and their choices. Meanwhile, decision information also covers various information forms (e.g., photos, text, slides, spreadsheets, reports, 3D models, etc.) and disciplines (e.g., architecture, structural engineering, construction estimating, etc.). In Chapter 4, I formalize these information types and their incorporation of choices with an AEC Decision Ontology. In Chapter 5, I explain how my contribution of a Decision Method Model offers the methodology to manage decision information represented with the AEC Decision Ontology (e.g., to incorporate preference with selected and candidate states).

Although my contribution of the AEC Decision Ontology is presented in Chapter 4, I need to provide a preview of the following key terms and concepts to establish a more precise definition of specific types of decision information.

Criteria

Criteria are explicit decision requirements, such as specifications, milestones, and budgets, that are established by the decision makers. They may be quantitative (e.g., a budget that cannot exceed a certain amount) or qualitative (e.g., the design must be approved by the review committee). They may be predefined or evolutionary as well as rigid or flexible. Criteria form the basis for evaluation against the anticipated performance of the recommended decision plan or solution.

Choice

In this dissertation, “choice” is a generic term that is applicable to a parallel subset of decision information. For instance, decision choices can refer to one or multiple set(s) of competing topics, competing criteria, competing options, and/or competing alternatives under consideration.

Options (Product, Organization, Process, and Resource Options)

Options are candidate intra-disciplinary interventions. Design theories establish “FFB” (Function, i.e., criterion, Form or Structure, and Behavior; Gero 1990 and Clayton et. al., 1999; see sections 4.1, 5.1, and 6.1); theory in Virtual Design and Construction (VDC) categorizes FFB under Product, Organization, and Process as “POP” (Fischer and Kunz 2005; see sections 4.1, 5.1, and 6.1). Building upon these concepts, my research examines the incorporation of choices for the function, form, and behavior of AEC products, organizations, processes, and resources. For instance, options may represent product forms (e.g., a 3-level or a 5-level parking structure), product behaviors (e.g., the different scenarios of the life-cycle costs of a green roof), organization forms (e.g., employing 1, 2, or 3 welding teams), process forms (e.g., finish-to-start relationship or a start-to-start concurrent relationship; an 8-hour work day or a 11-hour overtime work day), and resource forms (e.g., using 1 set of formwork or 2 sets of formwork), etc.

Alternatives

An assembly of multi-disciplinary options yields a project alternative, which is a coherent project plan that addresses inter-disciplinary factors and heterogeneous information. Examples of project alternatives include a concrete (product form option) acceleration (process form option) under the best case scenario (process behavior option), a structural steel (product form option) baseline (process form option) alternative, and a hybrid steel and concrete (product forms) under a worst case (process behavior option) acceleration (process form) alternative. Each of these alternatives specifies a unique combination of FFB options in POP.

1.3.3 MANAGEMENT OF DECISION INFORMATION (INFORMATION MANAGEMENT)

Better decision basis can be achieved by improving both the quality and quantity of information or by improving the management of information. This research focuses on information management, which refers to the handling of AEC decision information in general. Such handling includes the generation, population, organization, propagation, query, editing, reorganization, duplication, archiving, and/or deletion of information. The term “information management” is equivalent to “management of decision information” in this dissertation.

1.3.4 DECISION-ENABLING TASKS

Decision making in the AEC context requires that specific actions be taken to support the decision-making process. Such actions may include the explanation of a decision scenario, the evaluation of multiple decision choices, and the response to a “what-if” situation. This dissertation refers to these actions as AEC decision-enabling tasks, and my research formalizes the enabling methodologies, which manage decision information to accomplish these tasks. For each AEC decision-enabling task specified in this research, there is a specific methodology to prescribe the procedural techniques (which utilize the AEC Decision Ontology and the decision dashboard) to perform the task.

1.3.5 DECISION-SUPPORT TOOLS

Decision-support tools are the tangible means (in physical forms or computer systems) of conducting decision-enabling tasks. The tools empower the decision stakeholders to complete decision-enabling tasks, which in turn assist decision makers to specify decision needs, formulate action plans, evaluate proposals, and re-formulate action plans. Examples of such tools include the Decision Dashboard (my research prototype), Microsoft Office^v (MS Word, MS PowerPoint, and MS Excel), Mindjet^{vi}, and the CIFE iRoom (interactive workspace, Johanson et. el. 2002). The experience and brainpower of individual decision-making stakeholders to mentally relate and predict decision information are intangible and, hence, not considered as decision-support tools.

When formulating a set of proposed alternatives for recommendation, current decision-support tools often require decision facilitators and professionals to re-generate decision information (e.g., slide presentations and paper-based reports, see Chapter 2) that have no integration or reference relationships with the working set of decision information. Consequently, the use of current decision-support tools may serve the short-term decision-enabling tasks, but do not support information management needs at later points (i.e., subsequent decision-enabling tasks) in the decision process under different decision circumstances.

1.3.6 DYNAMIC DECISION BREAKDOWN STRUCTURE

The concepts of a Decision Breakdown Structure (DBS), its associated dynamic methodology, and its application framework form the core contributions of my doctoral research. Adapting from project management theories on various breakdown structures for work processes and organizations, the DBS entails an ontology (i.e., a structured vocabulary) for decision stakeholders and computers to represent and organize decision information as well as its interrelationships (Chapter 4). The DBS categorizes decision information and its relationships based on their characteristics, and hence, provides a foundation to formalize a

^v <http://office.microsoft.com>

^{vi} <http://www.mindjet.com>

methodology to manage information in support of AEC decision making. Because the methodology (i.e., the AEC Decision Method Model in Chapter 5) enables decision facilitators to complete decision-enabling tasks with flexibility and quickness, it is dynamic in nature. While my third contribution—the Dynamic DBS Framework—extends the application of the DBS and its dynamic methodology across different phases of the AEC decision-making process (Chapter 6), I use the term “Dynamic Decision Breakdown Structure” to denote this contribution as well.

1.3.7 DECISION DASHBOARD

Decision Dashboard (DD) is the name of my research prototype of the Dynamic Decision Breakdown Structure. I have developed it as a decision-support tool for decision stakeholders, by implementing it as a software application for personal computers. The DD incorporates the AEC Decision Ontology and the Decision Method Model to support information representation and the application of dynamic methods to complete decision-enabling tasks.

Dashboard—a panel extending across the interior of an automobile vehicle below the windshield and usually containing dials and controls (Merriam-Webster Online Dictionary^{vii}). In fact, the term “Dashboard” applies to non-automotive industries as well. For instance, a dashboard in the cockpit of an airplane (Figure 4 left) informs the pilot about the state of the airplane (e.g., position, altitude, speed, fuel level, etc.); it also provides lead and lag indicators for the pilots to evaluate the history (e.g., distance traveled, fuel consumed, etc.) while making what-if predictions on the performance of the airplane (e.g., anticipated arrival time based on a certain flight route). Meanwhile, internet-based dashboards offer users a single portal to access and assess heterogeneous information (Figure 4 right). Griffin (2002) defines an executive dashboard as “a one-screen display that enables executives and knowledge-workers to monitor and analyze an organization’s key performance indicators.”

^{vii} <http://www.m-w.com/dictionary.htm>

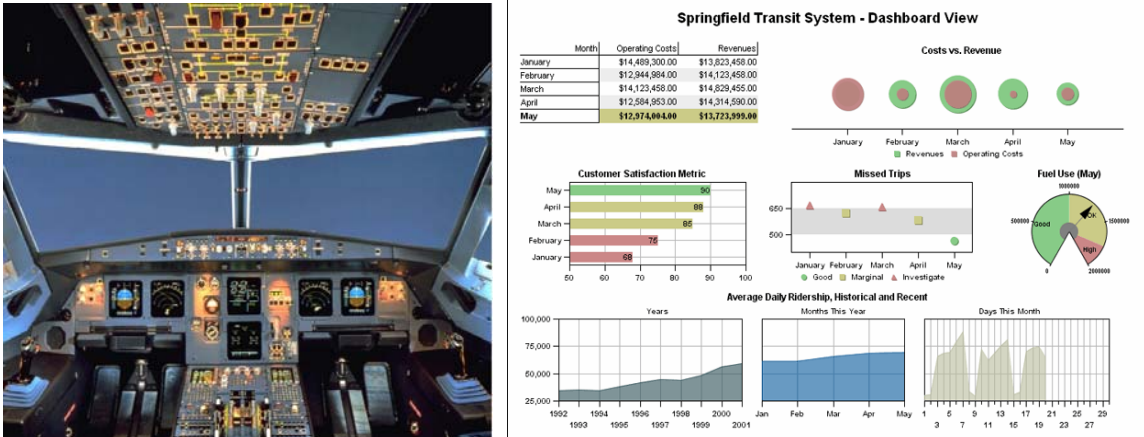


Figure 4. Dashboard examples in airplane (left, image from www.airbus.com) and for an internet-based information visualization solution (right, www.visualmining.com).

My research prototype is analogous to dashboards that gather essential information and enable drivers and pilots to make informed decisions about the future courses of action. It supports the decision facilitators to complete decision-enabling tasks by integrating and referencing dispersed information into a central reporting and controlling interface, and thereby, empowering all stakeholders to make informed decisions quickly. Therefore, the prototype is called the Decision Dashboard. As a decision-support tool, the DD enables AEC decision facilitators to complete decision-enabling tasks more informatively, flexibly, resumably, and faster than current decision-support methods. Facilitators can formulate a Decision Breakdown Structure in the DD (Figure 5, Graphical Window in the DD), with which they can distinguish decision information between its many states, levels of detail, and disciplines. Furthermore, they can leverage the DD as a test bed by using a set of dynamic methods (Figure 5, Dashboard Panel) to run what-if scenarios. For instance, facilitators can use the DD's dynamic methodology to access and compare domain-specific decision information quickly and informatively in an interactive workspace (Figure 6). They can also use the DD's dynamic methodology to evaluate different solution choices flexibly in a real-time evaluation table while formally and informatively documenting their ripple consequences on one another (i.e., the domino effects of a particular decision option on other decision options).

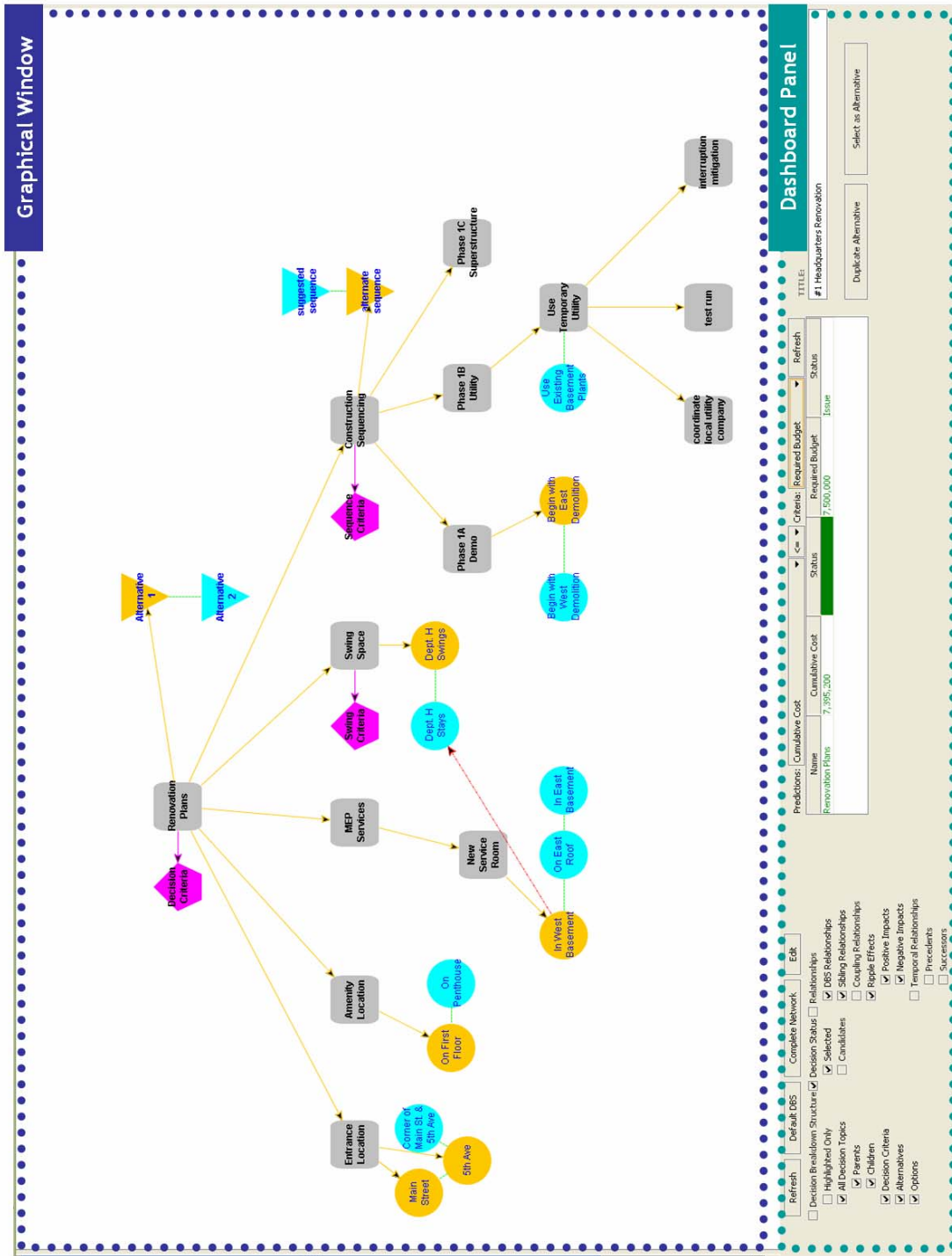


Figure 5. A computer screenshot of the Decision Dashboard (DD) prototype. The Graphical Window (top) is an interface for facilitators to formulate and re-formulate a Decision Breakdown Structure (DBS) that represents a decision solution and its choices. The symbols (squares, pentagons, circles, etc.) and arrows in the graphical window are model representations of the AEC Ontology elements and relationships that make up a DBS (Chapter 4). The Dashboard Panel (bottom) provides facilitators with a dynamic methodology to manage (e.g., control, isolate, evaluate, etc.) the DBS.

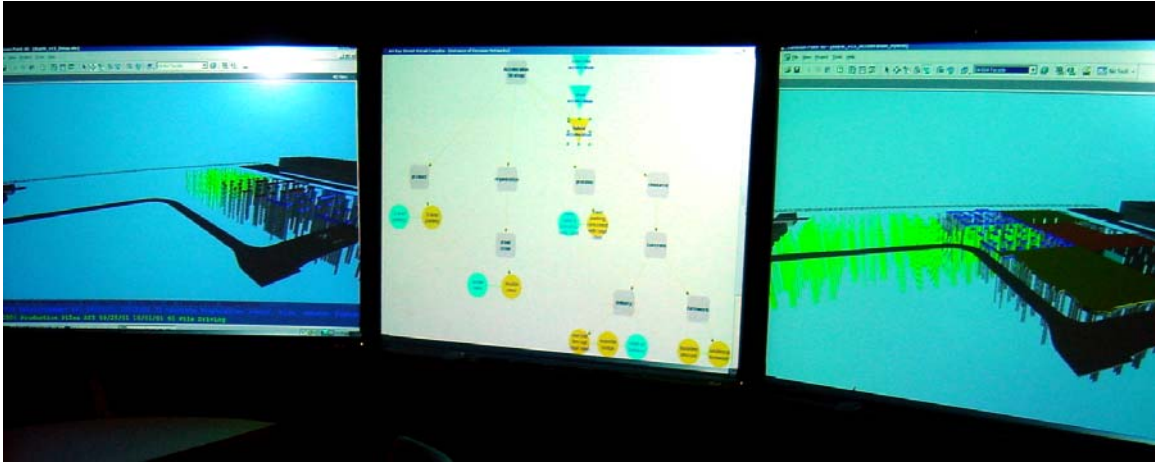


Figure 6. The DD dynamic methods enable facilitators to quickly compare and access specific decision options (e.g., 4D models of the baseline construction case on the left screen and an acceleration case on the right screen) that are integrated by the DBS (middle screen) in the three-screen CIFE iRoom.

1.4 READER'S GUIDE

Motivated to improve the current state of AEC decision making, as partially illustrated in the above case example, I analyzed current practices (in AEC decision information management and decision making) as well as the underlying theories, including Decision Analysis and Virtual Design and Construction theories. This analysis became the foundation of my logical formalization and intuitive design of my research contribution—a framework for the dynamic Decision Breakdown Structure (DBS). To refine and validate this research contribution, I documented six industry test cases to understand how management of decision information is carried out on AEC projects (Chapter 2). I have developed a computer software prototype (the Decision Dashboard or the DD), built six Dynamic DBS's based on industry test cases, and conducted four validation studies that provide evidence of power and generality for my research contribution (Chapter 3). My research has validated that my formalization of an AEC Decision Ontology (the computer-based vocabulary that makes up the DBS) out-performs current practice in representing decision information. My validation evidence also demonstrates that my formalization of a Dynamic DBS methodology out-performs current decision-support tools and methods in managing evolutionary decision information. Table 2 serves as a summary of my doctoral research as well as a reader's guide of this dissertation. For readers who would like to read a more

succinct summary of my research, I present a detailed summary in Chapter 7, followed by an assessment of the research impacts on practice and theory.

Research Areas	Research Question #1: Representation of Decision Information	Research Question #2: Methodology for Managing Decision Information	Research Question #3: Process for AEC Decision Making
Current Methods/ Tools/ Theories	homogenized implicit dispersed	static, e.g., pre-determined evaluation, pre-coupled options	lack of continuity
	adversely limit stakeholders' ability to manage decision information; not informative, inflexible, not resumable, slow undermine the basis and quality of AEC decision making		
Research Contributions	Ch. 2: A study of current practice in AEC decision making based on 6 industry test cases		
	Ch. 4: Decision Breakdown Structure (DBS) Ontology to represent decision information AEC Decision Ontology: 4 Elements 5 Relationships Attributes	Ch. 5: Dynamic DBS Methodology to complete decision-enabling tasks Decision Method Model (DMM): 7 Base Methods 4 Composite Methods	Ch. 6: DBS Management Framework to represent information and complete decision-enabling tasks across different phases of AEC decision making Dynamic DBS Framework: 5 Phases, requirements and characteristics Applicable ontology & DMM
Validation of Research Contributions	Validation Study #1 Metrics: reconstructability across 4 test cases evaluate between representation in current practice and AEC Decision Ontology	Validation Study #2 Metrics: informativeness, flexibility, resumability, and quickness across 8 decision-enabling tasks from 4 test cases evaluate between methods in practice and DMM	Validation Study #3 Metrics: informativeness, flexibility, resumability, and quickness across 5 phases over 6 test cases Validation Study #4: expert feedback by 15 professionals and 6 researchers
	better information management capabilities; making a positive contribution to informativeness, flexibility, resumability, and quickness and thus, improving the basis and quality of AEC decision making		

Table 2. An overview of research scope, contributions, and validation studies.

CHAPTER 2—OBSERVATIONS FROM CURRENT PRACTICE

Problem observation has played a critical role throughout my research. Existing literature lacks an in-depth documentation and assessment of the unique characteristics and challenges of the AEC decision-making process—including the AEC decision stakeholders, decision-enabling tasks, decision-support tools and methods, as well as the representation and management of AEC decision information. To gain insight into the nature of the abovementioned issues, I have conducted ethnographic research to document current practice. Myers (1999) suggests that ethnographic research is one of the most in-depth research methods possible because the researchers gain rich insights into the human, social, and organizational aspects of the research area. Genzuk (2003) explains that ethnography relies heavily on up-close, personal experience and possible participation in the research topic, all of which also describes my involvement in the six industry test cases that I present in this Chapter.

These six test cases involve decision scenarios from a range of AEC issues (e.g., architectural design, sustainability features, structural issues, construction phasing, etc.), decision formats (face-to-face presentations and report submission), as well as project phases (programming, schematic design, and construction planning). The cases represent recently completed and ongoing capital projects that average above \$50,000,000 in project cost^{viii}. These projects are owned, planned, designed, and constructed by renowned owners, designers, contractors, and consultants across the United States. Based on my discussion with different project participants, my access to the project information, and my personal participation in some of these test cases, I was able to document the performance of a number of current decision-support tools and methods. Such evidence and performance of current practice form the basis for validating the power and generality of my research contributions. Table 3 summarizes the test cases and the following subsections document my observations of the stakeholders, decision-enabling tasks, decision-support tools and methods, and representation of decision information for the six industry cases.

^{viii} For confidentiality reasons, I have replaced specific project information (such as project names, cost, stakeholders, etc.) with generic information, while omitting illustrations of decision information (e.g., images, computer screenshots, etc.).

Test Cases	Characteristics and Background	Current Practice	Dynamic Decision Breakdown Structure	Validations and Metrics (current practice vs. DD)
TC#1 Headquarters Renovation—Schematic Design	professionals develop schematic design options; facilitators recommend alternatives to the decision makers in a review meeting	pre-determined slide presentation: inability to access and recombine information	Dynamic DBS: access to integrated and referenced information, flexibility to mix and match choices	reconstructability, informativeness, flexibility, resumability, and quickness
TC#2 New Campus Headquarters	professionals prepare cost-benefit analysis of sustainable design features; facilitators submit a report to seek approval by the decision makers	paper-based report: inability to access, correct, evaluate, adjust information and comprehend its relevance in the “big picture”	Dynamic DBS: access to integrated information; flexibility to correct information; change evaluation focus; provides an explicit view of the decision scenario	reconstructability, informativeness, flexibility, resumability, and quickness
TC#3 Headquarters Renovation—Programming	professionals analyze design opportunities during program development; facilitators coordinate information and submit a comprehensive study report	paper-based report: inability to quickly distinguish heterogeneous info; ripple consequences, interrelationships within info are difficult to uncover	Dynamic DBS: representation and methods for handling heterogeneous information enable fast uncovering of ripple consequences and interrelationships	reconstructability, informativeness, and quickness
TC#4 New Retail Complex	professionals develop construction acceleration options; researchers integrate POP models and VDC approach to explain the alternatives	current VDC approach and POP modeling: no formal representation of decision assumptions; implicit interrelationships between POP models	Dynamic DBS: links POP models and provides explicit representation of assumptions and interrelationships	reconstructability, informativeness, and quickness
TC#5 The Fate of An Aging Facility	professionals and facilitator define the decision scenario to handle an aging facility	brainstorming session: personal hand-notes and white board ideas are not reusable and require authors’ explanation	Dynamic DBS: flexible population of ideas with explicit interrelationships; attribute propagation enables the testing of accounting impacts; reusable	informativeness and quickness

TC#6 Seismic Upgrade Project	professionals and facilitator analyze professional inputs and come up with decision recommendation	paper-based, spreadsheet, and slide presentation: inability to integrate and propagate information	Dynamic DBS: one decision-support tool enables integration and propagation of information, which contributes to the uncovering of a major cost error	informativeness
---------------------------------------	--	--	--	-----------------

Table 3. Six industry test cases and their key characteristics, background, challenges, validation, and metrics to support this research.

2.1 TEST CASE #1: HEADQUARTERS RENOVATION—SCHEMATIC DESIGN

My first test case (or TC#1 in short) captures a decision-making scenario during the schematic design phase of a major renovation project. The project entails a substantial modernization effort to transform an aging 600,000 square feet office building, which houses over 3,000 workers, into a world-class workspace equipped with state-of-the-art amenities and building systems. The owner’s representatives (i.e., decision makers) have commissioned a team of AEC professionals to come up with various design concepts and construction phasing proposals based on the performance, budget, and schedule criteria established in a prior programming study. Coordinating design and construction options from over a dozen disciplines (e.g., structural, phasing, cost estimating, mechanical, etc.), the lead architects (i.e., the decision facilitators) analyzed the owner’s criteria, put together three modernization alternatives, and recommended the alternatives to the owner’s representatives in a series of design review meetings. These meetings provided the opportunities for the owner’s representatives to receive briefings by the lead architects and to provide further directives concerning the criteria and preferences associated with the workspace, characteristics, amenities, building systems, sustainability, and life-cycle facility management plans of the owner’s organization. The lead architects explained their recommendations to the owner representatives. By the end of the decision-making process, the owner’s representatives decided upon one design solution that embodied the best innovative ideas and satisfy the project criteria.

While the team of renowned AEC professionals was able to inspire the owner with extraordinary modernization suggestions, the limitations I illustrate from this test case in the subsequent subsections are that the decision-support tool did not allow the decision stakeholders to handle impromptu inquiries or evaluations. The lead architects only

represented the coupled options in form of alternatives in the meeting, leaving pertinent decision information dispersed and inaccessible. This became a hindering factor when the lead architects were trying to provide an informative response to the questions posed by the owner's representatives. Furthermore, interrelationships and ripple effects among discipline-specific options were not explicitly represented in the decision-support means. Even though the alternatives presented were all thought out by the AEC professionals, the interchangeability of options within those alternatives were not clear during the meeting.

2.1.1 REPRESENTATION OF DECISION INFORMATION IN CURRENT PRACTICE

The documentation below centers around the decision information that the decision facilitators used in a series of design review meetings between the owners and the professionals in TC#1. In current practice, the professionals brought the following decision-support tools and resources to the meeting: MS PowerPoint slide presentation, color poster boards, massing models (hand-crafted model), cost estimate report, and multiple sets of drawings (that covered architectural, civil, structural, mechanical, electrical, and plumbing disciplines). The design architects (a team of 4 architects who also served as the decision facilitators) used MS PowerPoint as the primary decision-support tool to complement their verbal meeting moderation.

In the MS PowerPoint presentation, the architects represented the 12 options (e.g., entrance locations, mechanical system configuration, common space location, etc.) as individual slides in the presentation. They organized these slides, each of which corresponded to a discrete option, sequentially in order to group them into two distinctive alternatives. The alternatives were distinguished by the entrance locations (i.e., 5th Ave versus Main Street), while other independent options (e.g., MEP configurations, common space location, etc.) were appearing as sub-features under the "entrance" alternatives. The PowerPoint presentation integrated colored diagrams into the slides; it also integrated an overall area calculation for the two alternatives in a summary table. The presentation did not make explicit linkages to other decision information such as cost estimates, drawings, models, etc. The architects themselves were the source of references to such detailed decision information from multiple disciplines.

2.1.2 DECISION-ENABLING TASKS IN CURRENT PRACTICE

DECISION-ENABLING TASK #1: RE-FORMULATE A HYBRID SOLUTION—REWORK OR A SIMPLE TASK?

This decision-enabling task took place during the final 100% concept design review meeting in TC#1. A director from the owner's organization suggested to the design team to incorporate two entrance locations, which were presented in separate design alternatives, to improve building accessibility and circulation. In particular, the owner's team inquired about the impacts of the two entrances on total rentable space and construction cost.

METRICS: RESUMABILITY, FLEXIBILITY, INFORMATIVENESS, AND QUICKNESS

To respond to the director's suggestion and inquiry, the design team had to rely on a decision-support tool that built upon the existing knowledge about the design options and continued with (or resumed) the response to what-if inquiries. The methods employed by the decision-support tool had to generate informative results as quickly as possible and, thus, allow the owners to make an informed decision without delaying the overall project schedule.

CURRENT METHODS AND PERFORMANCE

The design team strongly believed that the director's suggestion required a new design effort. The existing decision-support tool (i.e., MS PowerPoint) did not allow the design team to re-formulate or query for a hybrid design solution. To include a hybrid design in the decision-support tool, the team had to modify the current design, come up with a hybrid design in the CAD-tool, and generate new area and cost calculations from the authoring software applications. Therefore, the team questioned the potential impact on their scope of services and offered to respond to the inquiries in a subsequent design briefing. On the other hand, the director from the owner's organization argued that his suggestion is merely combining two existing design features into a hybrid solution and, thus, should not be treated as a new design effort. Although the director won the argument, it still took another 4 weeks for the designers to reformulate the design using current decision-support methods and schedule a meeting with the owner representatives to review the hybrid design.

DECISION-ENABLING TASKS #2 AND #3

The design team discussed different conceptual design schemes (i.e., alternatives) during the owner's review meeting in TC#1. The design schemes embedded different design approaches towards common public spaces such as fitness center, training/conference facilities, cafeteria, atrium, etc. For instance, one scheme envisioned the common public space as a catalyst to energize the lobby, and hence, it called for a double-story public space on the ground level. Other schemes took advantage of other opportunities within the building and anchored the public space on the second or penthouse levels.

The owner's review team (i.e., a team of decision makers) was made up of representatives from various departments in the owner organization. While most representatives were experts in design and construction issues, there was one financial specialist present. This financial specialist was responsible for portfolio management and rental income, and therefore, was particularly interested in ensuring that the project investment would maximize the projected revenue throughout the facility life cycle. The projected rental income was computed based on a market rate unit rent, which was multiplied by the total rental area of the office spaces. Areas such as common space were considered joint use space. From the portfolio management perspective, the specialist preferred to have larger office space rather than joint use space. During the review meeting, the specialist brought up two requests that required the design team to perform Decision-Enabling Tasks #2 and #3.

DECISION-ENABLING TASK #2: IMPROMPTU QUERY

Decision-Enabling Task #2 was assigned to the design team when the financial specialist made an impromptu query about the spatial information. In the query, the specialist wanted to know the common space area and the total building area for every single design alternative.

METRICS: INFORMATIVENESS, FLEXIBILITY, AND QUICKNESS

Informativeness, flexibility, and quickness are the performance metrics for this decision-enabling task. The impromptu query required the design team to provide an informative response as quickly as possible during the review meeting. The specialist needed prompt response to his query such that he could give relevant advice to the owner's representatives and design professionals present in the meeting. Therefore, not

only did the decision-support tool used by the design team need to present the pre-determined recommendation informatively and quickly, the tool also had to be flexible enough to address impromptu query and management of decision information.

DECISION-ENABLING TASK #3: IMPROMPTU EVALUATION

The financial specialist gave an evaluation directive during the meeting, resulting in Decision-Enabling Task #3. The specialist requested to evaluate the area information among the available design schemes and compare them against the owner's criteria. In addition, the specialist would also need to ensure that the total construction cost of all recommended proposals were all within the budget set forth in the owner's criteria.

METRICS: INFORMATIVENESS, FLEXIBILITY, AND QUICKNESS

As in Decision-Enabling Task #2, this impromptu evaluation also required the design team to provide informative access and explanation of decision information, make flexible adjustments to focus on the specific evaluation needs that had not been prepared ahead of the meeting, and to manage the information as quickly as possible. It was not practical for the design team to anticipate all potential impromptu questions exhaustively. Therefore, the ability of the decision-support tools to access and manipulate AEC decision information plays a critical role in supporting these decision-enabling tasks.

CURRENT METHODS AND PERFORMANCE (TASKS #2 AND #3)

The slide presentation was the primary decision-support tool and method available to the design team at the review meeting, whereas the secondary decision-support tools included reports of discipline-specific findings, poster boards, and chipboard models. As these tools fell short in supporting the design team to perform the above two decision-enabling tasks, the team members relied on their collective brainpower to come up with vague responses or promises, which were not satisfactory for the financial specialist. In the end, the design team suggested to defer formal responses as follow-up tasks after the meeting.

The MS PowerPoint-based proposals that were generated in advance of the design review meeting did not enable the design team to informatively, flexibly, or quickly satisfy the impromptu query or evaluation needs. In response to the impromptu query and evaluation, a designer first verbally claimed that all schemes presented met the

minimum area requirements. However, this verbal promise was not specific or quantitative, and therefore informative, enough for Decision-Enabling Task #2, neither was it informative enough for comparative needs in Task #3. As the financial specialist prompted for specific area loss/gain data and comparative evidence pertaining to the different locations of the common space, the designer then attempted to provide a rough estimate in real time. The designer used structural bay spacing as an approximate visual reference for dimension, performed mental calculations on the spot, and provided rough estimates of the loss/gain differences between the two design schemes. In spite of the ad-hoc approximation effort, the design team was not able to quantify the common space area, detail the owner's criteria pertaining to area requirements, or provide a means to evaluate the proposals against the budget and area criteria. When further questioned by the financial specialist, the designers deferred the responses as tasks to be followed up after the review meeting.

In section 2.1, I have documented the current practice of TC#1. Sub-section 2.1.1 documents the different types of decision information present in this decision-making case, as well as the decision-support tools and methods used by the decision facilitators in current practice. This documentation serves as a benchmark for analysis in Chapter 4 Validation Study #1 (section 4.3). As I participated in the review meetings at the 35%, 50%, 90%, and 100% completions of the schematic design, I captured three decision-enabling tasks that are detailed in section 2.1.2. The performance of conventional decision-support means and methods in these decision-enabling tasks become the benchmark evidence for analysis in Validation Study #2 in section 5.3) Validation Study #3 (section 6.3) categorizes the handling of decision information based on different information management phases. Because this case involves the most diverse set of product, organization, process (POP) decision topics, I have filtered out details to simplify it as a motivating case example in Chapter 1. This simplified version of the case has also become the case example for expert feedback in Validation Study #4 (section 6.4).

2.2 TEST CASE #2: NEW CAMPUS HEADQUARTERS

Test Case #2 (TC#2) illustrates a common way for decision facilitators to compile and present decision information, which in this case centered around various sustainable design features, to the decision makers. While TC#1 was about a series of face-to-face (i.e.,

synchronous) review meetings, decision facilitators in TC#2 relied on a more passive mode (i.e., asynchronous mode) of paper-based reports to convey their findings. The decision scenario is taken from the design of a new headquarters for a major corporation. The design professionals strived to emphasize an excellent work place environment for the employees, which would in turn cultivate a positive image for the corporation through the architecture of its headquarters in its corporate campus. In this decision scenario, the key for the decision facilitators was to provide a good (i.e., informative, flexible, resumable, and quick) information basis for the decision makers to review and decide upon which sustainable design features, if any, to be incorporated in their new corporate headquarters building.

In the following subsections, I explain that the limitation from the current practice in TC#2 is that pre-determined presentation and evaluation tables are not flexible or resumable. First, they are not informative because the decision makers cannot trace the sources of decision information and its assumption basis. Second, the evaluation focus is fixed in advance. It is difficult to shift decision focus from macro to micro or hybrid levels of detail and consequently, it is difficult to get multiple perspectives or to ensure that the evaluation is drawn on a fair basis. Third, when errors are noted or when needs to change the decision information arise, current decision-support tools do not allow the decision process to resume smoothly. The stakeholders have to spend extra time and attention in rework, which causes delays to the decision-making process.

2.2.1 REPRESENTATION OF DECISION INFORMATION IN CURRENT PRACTICE

This case focuses on the decision information that the designers submitted to the owners as a cost-benefit analysis of various sustainable features in the new campus headquarters.

The design architect led four other consulting and construction companies in compiling a cost-benefit report for the development manager representing the owner. The professionals (i.e., design architect, consulting, and construction companies) used a word-processing software as a primary decision-support tool. They compiled 8 tables along with summary analyses with the word-processing software, which generated a 23-page report as the final and only format for submission to the owner.

The printed report contained “the results of a series of interrelated Cost-Benefit Analyses studying the primary advanced green building strategies and designs proposed for the [new] campus.” There was an executive summary as well as four sections, three of which covered the design strategies (i.e., forms in FFB classification, see section 4.1.2) of (1) green roof, (2) indoor air quality, and (3) daylighting whereas the fourth section presented the predicted productivity improvement (i.e., behaviors in FFB classification, see section 4.1.2). In the word-processing software, the professionals represented the sustainable components as separate section headings and specific feature options as bullet points within the sections. The whole document became a single proposed alternative, with which the professionals organized different decision topics as sections. They predefined and laid out 8 evaluation tables to list different costs, savings, payback, cost benefits, and productivity improvement data. They integrated quantitative data into the document to support the established position in the document, e.g., data on estimated labor savings and data on productivity gain from energy-efficient design, etc. They referenced their assumptions and sources of their findings in 25 footnotes and 9 bibliographic listings. The professionals had not incorporated any specific decision criteria or data for the benchmark (i.e., basic design without additional sustainable features) design alternative.

2.2.2 DECISION-ENABLING TASKS IN CURRENT PRACTICE

In TC#2, the cost-benefit analysis report made references and conclusions based on specific decision information on initial costs, reduced HVAC costs, net first costs, annual energy savings, annual operations savings, and simple payback period.

DECISION-ENABLING TASK #4: EXPLAIN ASSUMPTIONS & MAKE NECESSARY CORRECTIONS

Decision-Enabling Task #4 in TC#2 involved two interrelated subtasks. The first subtask required the decision facilitators (i.e., the architects) to explain the assumption basis of a value that was presented in the evaluation table. The decision-support tool needed to be informative in supporting this explanative decision-enabling task. The second subtask came up after the stakeholders uncovered an error in the table, when they had to make necessary corrections to update a numerical value presented in the table. Resumability matters in this subtask, since it measures the amount of rework

involved in reflecting the corrected values in the evaluation table before the stakeholders can resume with the evaluation.

DECISION-ENABLING TASK #5: EVALUATE MACRO AND MICRO IMPACTS AMONG THREE CASE SCENARIOS

Decision-Enabling Task #5 was about evaluating the impacts of different proposed design (i.e., product) forms on the productivity of the building occupants. In the paper-based report, the decision facilitators had pre-categorized three probable productivity gain scenarios based on eight case studies on productivity improvement evidenced in completed buildings. These scenarios included the worst case, most likely case, and best case scenarios with varying improvements in productivity and absenteeism, and hence worst, most likely, and best predicted benefit of underfloor plenum and daylighting.

METRICS: INFORMATIVENESS AND FLEXIBILITY

For decision makers to evaluate the information basis and decide on the scenarios to follow, this decision-enabling task required the decision-support tool to be informative about the assumptions for the values and formula leading to the cost benefit. The decision-enabling task also required the tool to be flexible to change assumption values or change the combination of assumptions. Furthermore, the tool should inform the decision stakeholders about the interrelationships between these cases and specific design features and choices, such that they would be aware of possible impacts when the selection of the design features changed.

CURRENT METHODS AND PERFORMANCE

The decision-support method used by the decision facilitators involved disjointed decision information replicated in a paper-based report. Such replicated information did not lead to decision stakeholders being informed about the assumptions, to flexibly change or correct the numerical values, and to flexibly and resumably recombine design features or predictive cases. In all cases, ad hoc mitigations were not informative, flexible, resumable, or quick.

For instance, the “green roof” design required an additional first cost of \$434,550, which would reduce HVAC first costs by \$4,250, and hence, resulting in a net first cost of \$430,300. Dividing the net first cost by the sum of annual energy savings of \$24,000

and annual building operations savings of \$4,250, the simple payback period should be 15 years. However, the cost-benefit analysis table in the paper-based executive summary showed a payback of 11 years. Since there were no direct dependencies between different numeric values in the paper-based tables, one had to use mental judgments to relate the numbers and uncover such errors or else, one had to make decisions based on an entry error that translated to a 26%^{ix} competitive advantage of the reported green roof option.

Furthermore, this lack of formal representation and method to report numeric findings to the decision makers also exposed another potentially unfair evaluation of decision information. Specifically, there was a lack of consistency between the executive summary and the subsequent section devoted to “green roof cost-benefit analysis.” As mentioned in the above paragraph, \$430,300 was the net first cost for “green roof”. However, the subsequent section reported the net first cost of a green roof to be \$659,500 whereas the cost increase from a conventional roof to a green roof was \$355,400^x. None of these values relate to the net first cost reported in the executive summary. The presented decision information was not informative enough for decision stakeholders to query its basis. In addition, since the information was pre-determined in the evaluation table, it was not easy for stakeholders to resume the decision-enabling task by correcting the values across all copies of the printed reports. To mitigate the assumption errors and the table information, one had to apply the changes with the source word-processing tool and reprint the corrected report for all stakeholders. Or else, one had to inform stakeholders about these errors and request them to make personal notes to update the decision information.

The productivity and absenteeism impacts on the cost benefit of the design features were not informative or flexible as well. First, the tables in the executive summary or in the subsequent section did not explain whether all or parts of the sub-design features

^{ix} $[15 \times (1 - 11/15)] \times 100\% = 26\%$

^x A conventional roof cost \$355,400, therefore the cost increase was $\$(659,500 - 355,400) = \$304,100$.

of underfloor plenum and daylighting were required to catalyze the suggested gains. Second, the tables had pre-determined the assumption values and the combination of scenarios, leaving no flexibility to the decision stakeholders to test new assumptions or a new coupling of scenarios.

DECISION-ENABLING TASK #6: EVALUATION CONTENT IN THE EXECUTIVE SUMMARY

In TC#2, a decision-enabling task occurred when the decision makers (i.e., the owner's representatives) assessed the cost-benefit predictions of various sustainable design features and presented their findings in a summary report. Based on the evaluation of the decision information compiled by the design team, the decision makers would decide whether or not to commit to an investment in the sustainable design features.

METRICS: INFORMATIVENESS, FLEXIBILITY, RESUMABILITY, AND QUICKNESS

Informativeness, flexibility, resumability, and quickness are the important interrelated qualities that the decision makers relied upon in the design evaluation and approval process. Among all the four metrics, resumability matters most in this task. A resumable decision-support tool allows its users to build upon existing decision information, with minimal rework and as quickly as possible, to continue with further decision-enabling tasks (e.g., to evaluate a different set of options and to inquire about a what-if scenario). On the other hand, the decision makers need to be informed about the significance of the decision information they evaluate, for instance, whether the comparison is drawn between systems or between sub-systems. Similarly, they should have the flexibility to access decision information across systems and sub-systems. Should such a need to evaluate across different levels of detail arise, the decision makers ought to be able to count on a resumable decision-support tool.

CURRENT METHODS AND PERFORMANCE

With current methods in this test case, evaluation tables were prepared with a word-processing software tool in advance of the publishing of the summary report. The authors from the design team (i.e., the decision facilitators) had predetermined both the foci and contents (rows and columns) in the evaluation tables.

The resulting "summary of cost-benefit analysis" table in the paper-based executive summary showed 3 rows (green roof, underfloor plenum, and daylighting) that

represented design concepts at different levels of detail. This evaluation table showed that underfloor plenum had a payback period of 2.6 years, these data (or row in the evaluation table) were compared against green roof and daylighting, with payback periods of 11 and 18 years, respectively. However, this table failed to explain that while green roof and daylighting both denoted a design package, the underfloor plenum was in fact a sub-feature of the indoor air quality package. If decision makers were to be fair and compare between design packages, the payback period of the indoor air package (not one of its features) should be 3.5 years instead of 2.6 years.

For green roof and daylighting packages, the values shown in the executive summary table reflected those of the total package. For instance, the total package of daylighting accounted for four contributing design features, which included skylights, savings credit for green roof, light shelves, and lighting controls. However, the second row showed the predicted cost-benefit values for the underfloor plenum, which was in fact a sub-feature of the indoor air quality “package.” Other comparable sub-features under the indoor air quality package included operable windows as well as sustainable materials and finishes. A full documentation of the “package” predictions was organized in sections that followed the executive summary.

Decision makers could not notice this shifting levels of detail by merely reading the executive summary. They needed to also read through the detailed chapters and make relevant analytical connections to identify the shift. As the tables and the report were static and dispersed throughout different chapters in the report, the decision makers needed to use an additional method (e.g., mental connection, paper and pencil, computer spreadsheet, etc.) to complement the existing decision-support tool (i.e., printed report from a word-processing software application) to compare the indoor air quality package against other packages, i.e., green roof package and daylighting package.

In this section, I have highlighted the decision information and the decision-support methods that the design professionals had compiled and submitted in a 23-page summary report to the decision makers (section 2.2.1). This current decision-support means and methods to represent and organize AEC decision information becomes the benchmark for my validation of the Decision Breakdown Structure (Validation Study #1 in section 4.3). Similarly, my

Validation Study #2 in Chapter 5 (section 5.3) takes the three decision-enabling tasks that are documented in section 2.2.2 as a benchmark for comparative analysis. In Chapter 6 Validation Study #3 (section 6.3), I dissect the current practice performance in TC#2 from the perspectives of different information management phases.

2.3 TEST CASE #3: HEADQUARTERS RENOVATION—PROGRAMMING

As in TC#2, decision facilitators in TC#3 also relied on a paper-based report to communicate a 283-page Program Development Study (PDS). The decision facilitators, who are the lead project architects, coordinated with other professionals and compiled this comprehensive study during the programming project phase of the headquarters renovation project, the same project as TC#1. This programming phase is a decision scenario that precedes the schematic design phase of TC#1. The PDS contained detailed narratives about the constraints, opportunities, options, and recommendations from over 15 professional disciplines (e.g., urban planning, architecture, daylighting, historical preservation, workplace design, construction scheduling, and cost estimating, etc.). It provided expert inputs that became the information basis for the decision makers to decide upon the design approach, budget allocation, and performance criteria, all of which would guide the subsequent design and construction phases in the modernization project.

2.3.1 REPRESENTATION OF DECISION INFORMATION IN CURRENT PRACTICE

The evidence below focuses on the decision information that the lead designer submitted in the form of a PDS to the owner of the headquarters renovation project.

The lead designer used a word-processing software as a decision-support tool to integrate decision information contributed by different design and specialty consultants. The final PDS was submitted as a 283-page binder. The professionals primarily used descriptive narratives—supplemented by diagrams, plans, tables, worksheets, and photos—to represent their findings to the owner. The PDS organized these findings into 6 sections. The third section, titled “findings, analysis, and recommendations” took up the bulk of the report. It presented the narratives of raw facts, analysis, options, and recommendations sequentially for each of the 15 design areas (e.g., site, structural system, security, work space, daylighting, etc.), which in turn made up 15 subsections in the third section. Although there were

summary sections towards the end of the PDS highlighting the recommended alternative, key options, the cost impacts of those key options, and implementation plans, decision makers still needed to read through the body of the text to comprehend the ripple consequences, assumptions, and specific analyses about the key summary.

Furthermore, the PDS did not explicitly document any explanations or references among inter-related topics across different sections. For instance, the cost table in Section 6 included a line item for the cost impact of building additional floors. However, the cost item only provided a lump sum amount. It made no references to the analysis sections, whereas the interrelationships among zoning constraints, elevator options, structural systems, and additional floor construction were scattered throughout different sub-sections in Section 3. Different combinations (or couplings) of these interrelationships would yield different scenarios, and therefore cost impacts, with regard to the decision to build additional floors. The current word-processing decision support tool did not provide a formal solution for decision stakeholders to document and comprehend such interrelationships.

2.3.2 DECISION-ENABLING TASK IN CURRENT PRACTICE

DECISION-ENABLING TASK #7: COMPREHENDING THE RIPPLE CONSEQUENCES OF BUILDING ADDITIONAL FLOORS

A decision-enabling task occurred when an owner representative was reviewing the proposed options prepared by the project team. This representative had the responsibilities of going through the impacts (or ripple effects) of the proposed option, of evaluating the advantages and disadvantages associated with an option, and of making an analytical recommendation to other decision makers in the owner's organization. Specifically, the owner representative was trying to become informed about any decision information or associated knowledge pertaining to the option to build additional floors on top of the existing structure.

METRICS: INFORMATIVENESS AND QUICKNESS

The ability to acquire information as informatively and as quickly as possible is key to this decision-enabling task. The more complete the information basis, the more constraints and opportunities the decision maker can assess. The quicker the

uncovering of the interrelated ripple consequences between decision information, the earlier the decision maker can recommend a preliminary decision for further analysis.

CURRENT METHODS AND PERFORMANCE

As explained earlier in this section, the current practice relied on a word-processing tool to print a paper-based binder known as the Program Development Study (PDS) as the main decision-enabling tool. The PDS included a cost estimate with a line item for the option to add additional floors to the existing building. The description listed “Additional Floors—95,000 gsf (gross square feet) with 14,000 sf (square feet) of atrium space” with a specific cost amount per floor.

The cost for two additional floors was significant—representing 12% of the total budget that accounted for design, construction, contingency, and escalation costs. However, the line item description offered no detailed information on the ripple effects of this option on other design decisions (e.g., the impact of additional floors on zoning requirements, elevator design, structural issues, etc.). To search for these interrelationships, the owner representative had to go through the PDS binder—chapter by chapter—to uncover the interrelationships between additional floors and other design decisions. Moreover, the design professionals did not have a method to record these interrelationships consistently and explicitly. When a design consultant discussed about the specific interrelationships with another design aspect, the impacted design consultant did not reciprocally acknowledge the ripple consequence. For instance, when zoning requirements set a limitation on the construction of additional floors, this limitation (or ripple effect) was only documented in the “zoning” section of the PDS, but not in the “additional floor” section of the PDS. As a result, the owner representative had to spend several hours to go through the 283-page PDS carefully to look for the dispersed information pertaining to the construction of additional floors. This uncovering process was neither informative nor fast.

In summary, the limitation of this test case is that a very rich set of decision information was represented in a homogenized and dispersed manner. The lack of formal categorization and the current way of representing decision information made it cumbersome for stakeholders to consistently uncover important interrelationships between decision information. My explanation of the many types of decision information and its organization method in the

PDS in section 2.3.1 becomes the benchmark for comparative analysis in my Validation Study #1 (section 4.3). In Chapter 5 Validation Study #2 I contrast current decision-support means and methods (section 2.3.2) to that enabled by the dynamic Decision Breakdown Structure (section 5.3). Specifically, I compare what it takes to uncover the ripple consequences among multidisciplinary options with the PDS. As I focus on the application of the Dynamic DBS across successive decision-making phases and processes in Chapter 6, I investigate the implications of transferring the information and knowledge from the programming (i.e., Test Case #3) to the schematic design development (i.e., Test Case #1) of this Headquarters case example (section 6.3).

2.4 TEST CASE #4: NEW RETAIL COMPLEX

TC#4 is based on the information from a fast-track retail construction project. After unforeseen soil contaminants had halted and delayed the construction project for two critical months, the developers (decision makers) had to decide upon a project alternative that would best balance the conflicting criteria among on-time turnover, change order cost, and project risks. The developers requested the general contractor (decision facilitators) and their subcontractors (professionals) to come up with acceleration alternatives along with pertinent performance predictions such as cost estimates and acceleration schedules for consideration in an upcoming owner-architect-contractor (OAC) meeting. Based on this industry scenario and its project information, my CIFE research peers and I applied Virtual Design and Construction concepts and technologies on the test case. We developed product, organization, and process models as well as functionalities to enable cross-referencing of POP models in the CIFE iRoom (Kam et. al. 2003). In the following subsections, I document the representation of decision information and the completion of a decision-enabling task in current VDC practice.

2.4.1 REPRESENTATION OF DECISION INFORMATION IN CURRENT PRACTICE

The evidence below centers around the decision information used by the decision facilitators in an owner-architect-contractor review meeting. The meeting focused on the mitigation strategies to alleviate the impact of the unexpected delay in the construction project.

TC#4 has real and fictitious portions. The delay scenario, acceleration proposals, and quantitative data were all captured from the actual project. Based on this set of actual project information, my CIFE research colleagues and I built a POP-based client briefing scenario with state-of-the-art interaction and visualization tools in the CIFE iRoom. In this interactive environment, 5 project scenarios (alternatives) were represented by 5 sets of process models (i.e., 1 process model for each scenario), 4D (product-process) models, cost estimates, and organization-process models. The presentation, description, and explanation, and evaluation of the alternatives depended on Microsoft PowerPoint as the decision-support medium. My CIFE research team documented the assumptions, options, attributes, and rationales pertaining to each alternative with text boxes in PowerPoint. My team also presented evaluation tables by pre-determining the topics and criteria for evaluation and re-entering such topic and criterion information into PowerPoint. As we went through each baseline, impact, and acceleration scenario, a team member manually brought up each corresponding process, 4D, cost, and/or organization-process model individually. The CIFE iRoom enhanced the evaluation phase by enabling cross-highlighting features across any combination of POP models (e.g., Kam et. al. 2003, Figure 7). However, current decision-support tools did not contain knowledge about the inter-relationships or interchangeability among the POP models, their options, and their attributes.

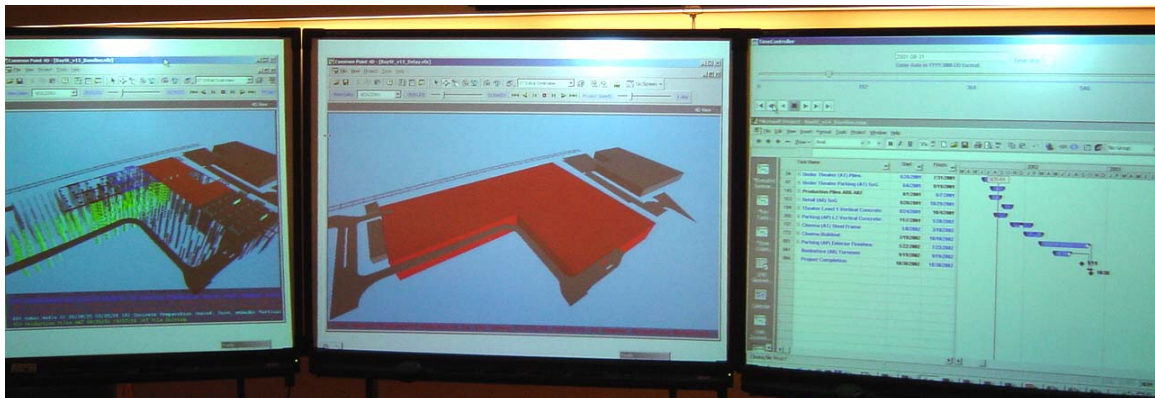


Figure 7. The CIFE iRoom supports cross-highlighting of P, O, P decision information, but is limited in highlighting the interrelationships between different decision alternatives and options across different POP models. Two 4D models of acceleration proposals involving the steel crew (left screen) and the concrete crew (middle screen) are displayed; decision stakeholders can then utilize the project schedule and a date slider (right screen) to automate the playback, and hence the review, of the two 4D models using existing iRoom functionalities (Kam et. al. 2003).

2.4.2 DECISION-ENABLING TASK IN CURRENT PRACTICE

DECISION-ENABLING TASK #8: EXPLAIN AND COMPREHEND ACCELERATION PROPOSALS

As the decision facilitator provided a briefing on possible acceleration proposals to the decision makers in TC#4, a decision-enabling task occurred when the decision stakeholders needed to comprehend the decision information (e.g., the assumptions and proposal details) of various competing acceleration proposals.

METRICS: INFORMATIVENESS AND QUICKNESS

As explained, the briefing and review meeting took place in the CIFE iRoom, where pertinent 3D/4D models, construction schedules, cost estimates, and process-organization information was stored digitally in case-specific project files. The decision facilitator relied on the decision-support tool to help explain the scope, the assumptions, the mitigation measures, and the anticipated time saving associated with the competing acceleration proposals. This explanation had to be informative and quick. A clear comprehension of this interrelated decision information was crucial for the decision stakeholders to make an informed decision. The quicker the explanation and comprehension process, the earlier the decision stakeholders could move on to the following phase of the decision-making process and the execution of the selected alternative.

The significance of this decision-enabling task, as detailed below, is that if the decision-support tool does not offer good explanation support, the decision facilitator is then required to spend additional time in verbal explanation to fill the void of the decision-support tool. Conversely, if the decision-support tool offers the decision stakeholders a clear understanding of the decision information on hand and its basic interrelationships, the decision facilitator can complete more decision-enabling tasks given the time available during a synchronous decision meeting (e.g., in facilitating the decision stakeholders to explore the benefits and challenges of the available choices).

CURRENT METHODS AND PERFORMANCE

Under current CIFE iRoom practice, there are methods that allow decision facilitators to cross-highlight decision information among competing 4D models or across inter-related POP models (e.g., using activity names or time controller, Kam et. al. 2003). However, there were no formal methods to support a decision facilitator in explaining

the acceleration proposals or in bringing up the relevant reference information during the explanation process.

The decision facilitator used MS PowerPoint as the decision-support tool to enable the explanation process in current practice. When explaining the acceleration proposals to the decision makers, the decision facilitator needed to explain the assumptions, scope, and the distinctions among the competing proposals. The decision facilitator either had to take personal notes to mentally memorize such decision information or had to custom create introductory slides in MS PowerPoint to document such decision information for subsequent explanation. The ad-hoc nature of this PowerPoint-based documentation process required the decision facilitator to take additional time to create custom slides to recapture the decision information in the decision-support tool. Because the facilitator did not spend extra time to create those custom slides, he had to spend valuable time during the synchronous meeting in offering verbal explanations to give the decision stakeholders full comprehension of the decision scenario. The limitation of the current decision-support tool required extra effort and time to ensure that the explanation process is quick and informative.

Similarly, there was no formal and explicit method for managing options or alternatives to form an integrated representation of the decision scenario based on the information or data coming from different AEC disciplines. To bring up a particular project file from a set of product, organization, and process models from the five scenarios for decision evaluation, the decision facilitator had to rely on his/her mental recollection or custom-create an organization scheme (e.g., by data directory and folder) and naming convention in the computer prior to the explanation process. Without this extra ad-hoc method, the decision facilitator would need to spend extra time during the explanation process to sort out and retrieve a relevant file from a set of case-specific decision information (Figure 8).

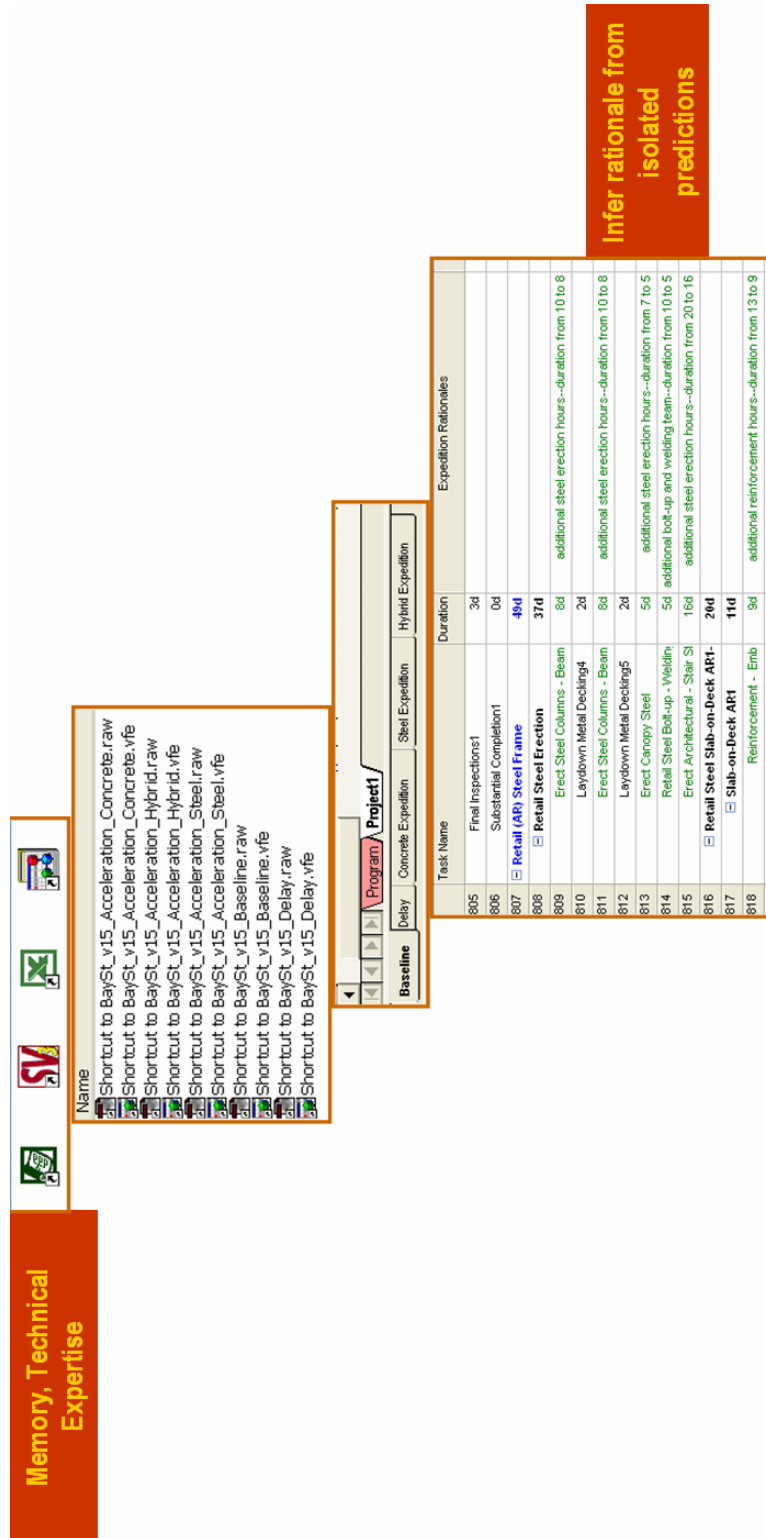


Figure 8. A diagram illustrating examples of the implicit knowledge (e.g., which discipline-specific software application to choose from, which files and naming conventions, which isolated cases, and which specific field in a file, etc.) that a decision facilitator need to master in order to bring up specific decision information in response to an impromptu decision-enabling task.

In summary, the limitation of this test case is that there are no explicit interrelationships among the many POP options, their corresponding intervention assumptions, and their interchangeability. These relationships reside in the memory of the decision facilitators, rather than an explicit decision-support tool. Taking this test case as a benchmark example of current VDC practice, Chapter 4 Validation Study #1 (section 4.3) and Chapter 5 Validation Study #2 (section 5.3) compare how current VDC practice fares against the practice embodying my research contributions of a dynamic Decision Breakdown Structure.

The first four test cases are retrospective case examples, in which I captured the current decision-making means, methods, and processes before reenacting the representation and management of the decision information with my research contributions. In contrast, the following two test cases involve the prospective applications of the dynamic Decision Breakdown Structure on two specific decision-making scenarios in live settings. While I was able to document the previous four cases with breadth and depth, the following two test cases supplement my retrospective analysis with concrete intervention results on large-scale industry projects.

2.5 TEST CASE #5: THE FATE OF AN AGING FACILITY

In TC#5, two industry professionals and I adopted the Dynamic DBS framework in an afternoon brainstorming session. The test case was about pre-project planning about the fate of an aging facility. In this decision scenario, we used the Decision Dashboard (i.e., the prototype I implemented based on my research contributions) to represent and organize the information while testing the options' implications on different project cost accounts. We were able to test different financial implications more informatively and flexibly than in current practice. Validation Study #3 (section 6.3) analyzes this test case in further detail.

2.6 TEST CASE #6: SEISMIC UPGRADE PROJECT

TC#6 entails the pre-construction planning of a major seismic upgrade and hazardous material mitigation project. The decision facilitators (i.e., project executive and project manager) analyzed the inputs from the scheduling and cost-estimating consultants, came up with different cost-benefit scenarios involving different tenant phasing options, made

recommendations, and presented them to the decision makers. The decision makers included the director of property development, who is responsible for design and construction funding, and the director of operations, who is responsible for rental revenue or loss due to temporary tenant relocation. They had to comprehend, evaluate, and approve the recommendations, in terms of project plans and the impacts on all existing tenants, set forth by the facilitators. This test case served as another application of my research contributions during the formulation phase of information management in AEC decision making (Validation Study #3 in section 6.3). In a nutshell, the DD's central integration of decision information and its propagation of attributes allowed me and the decision facilitators to uncover a major cost estimate error made by a professional cost estimator in current practice.

2.7 ANALYSIS—THE NATURE OF AEC DECISION INFORMATION AND DECISION MAKING

Based on my observations from the motivating case example (i.e., a simplified version of TC#1), I presented my analysis that the AEC decision information can be characterized by the presence of many discipline-specific perspectives, information forms, information types, many levels of detail, and many interrelationships (section 1.2.2.1); whereas changing modes, states, and aggregation needs characterize the AEC decision making (section 1.2.2.2). Additional test cases presented in this chapter concur with these characteristics found in the motivating case example (Table 4), leading to my conclusion that AEC decision information and decision making are heterogeneous and evolutionary.

AEC Decision Information and Decision-Making Processes	
Disciplines	owners, building officials, architects, engineers, consultants, contractors, etc.
Info Types	criteria, topics, alternatives, options, details
Info Forms	text, photos, diagrams, architectural/structural/mechanical/etc. drawings, tables, worksheets, 3D renderings, site maps, etc.
Info States	recommended, not recommended/under consideration, discarded
Decision Modes	Asynchronous (not face-to-face, not at the same time) e.g., paper-based reports Synchronous (same time—co-located and not co-located) e.g., design review meetings
Nature of AEC Decision Making	Heterogeneous - perspectives, information types, information forms, interrelationships, levels of detail Evolutionary - information states, decision-making modes, types of decision-enabling tasks, aggregation of information

Table 4. The nature of AEC decision stakeholders, decision information, and decision-making processes based on six industry test cases.

2.7.1 HETEROGENEOUS

AEC decision information is heterogeneous in nature. Decision information covers a number of different information types, information forms, information states, and disciplines. I submit that decision topics, criteria, options, alternatives, attributes (quantitative predictions or qualitative rationale), and their interrelationships form the basic information types in AEC decision information^{xi}. There are 8 forms of information found in the test cases, including text, photos, diagrams, architectural plans, tables, worksheets, 3D renderings, and site maps. Decision information also includes 2 states—“recommended” (e.g., underfloor HVAC system in TC#2) and “under consideration” (e.g., conventional HVAC system in TC#2) states. The presence of decision information in multiple levels of detail is evidenced from the macro, micro, and hybrid LOD of sustainable design features in TC#2. Meanwhile, the test cases I presented earlier encompassed contributions of

^{xi} These basic information types in AEC decision information form the basis of the AEC Decision Ontology that makes up the Decision Breakdown Structure (section 4.2).

information by 11 disciplines, including developers, the owners, the financial specialists, the architects, the structural engineers, the MEP engineers, the lighting consultants, the energy consultants, the cost estimators, the schedulers, and the facility managers. Therefore, the multidisciplinary background of these stakeholders have led to heterogeneous decision information as well. All together, the decision information covered in this chapter includes 8 forms, 2 states, multiple levels of details, and 11 disciplines and is therefore, heterogeneous in nature.

2.7.2 EVOLUTIONARY

The information basis of AEC decision making evolves frequently throughout the decision process. This is because in building planning, design, construction, and management, the decision process is about developing new solutions and uncovering cross-disciplinary impacts. Very often, there is no finite number of solutions to a decision scenario. Creativity in design concepts and construction means and methods can constantly add new decision information while changing the state and interrelationships between existing information. AEC professionals generate domain-specific options and focus on intra-disciplinary issues. Through subjective interpretation of the latest set of decision criteria, the facilitators filter and aggregate options to assemble alternatives for recommendation. However, as decision makers learn more about the behaviors of the recommended alternatives based on the evaluation of new decision information, they may refine (relax or constrain) their criteria while providing further directives on the design concepts or construction solutions. As a result, professionals have to iteratively generate and refine their options and alternatives. The decision information (i.e., decision topics, criteria, options, alternatives, attributes—quantitative predictions or qualitative rationale, and their interrelationships) continues to evolve until a committed decision can be reached by the decision makers.

My observation from a number of design review meetings in TC#1 concluded that in every meeting that would last between 1 to 3 hours, there were at least 5 decision-enabling tasks that were impromptu and iterative in nature. These tasks often involved what-if suggestions (e.g., Decision-Enabling Task #1 in TC#1) that impacted the basis of the decision information (e.g., choices, criteria). The synchronous meeting scenario detailed in TC#1 was only one of the 4 design review meetings (e.g., 35%, 50%, 90%, and 100% schematic design completion milestones) during one phase (i.e., schematic) of the 4 major project

phases (e.g., programming, schematic, design development, and construction documentation) over a 2-year period. Given the recurrence of impromptu and what-if decision-enabling tasks throughout an AEC project, I conclude that the AEC decision-making process is dynamic and iterative.

2.8 ANALYSIS—LIMITATIONS AND IMPACTS OF CURRENT MANAGEMENT OF DECISION INFORMATION

In terms of the management of AEC decision information in current practice, as described by the aforementioned test cases, there is tremendous room for improvement in terms of informativeness, flexibility, ability to resume the decision process (or resumability), and quickness. In a nutshell, current practice lacks decision-support methods and tools to manage AEC decision information in ways that recognize its heterogeneous and evolutionary nature.

Decision facilitators and professionals in the industry test cases use generic (i.e., non AEC context-specific) decision-support tools and their associated methods, such as word-processing applications, MS PowerPoint, pre-determined evaluation tables, descriptive narratives, sub-headings, paper-based reports, etc. These tools and methods are generic as they are widely used in non-AEC contexts as well. However, they are not informative, flexible, resumable, or quick. Thus, they provide limited support in managing decision information that is heterogeneous and evolutionary in nature. The following subsections discuss how the limitations of current decision-support tools and methods compromise the decision basis of AEC decision making. Current information management theories and methods do not respond to the heterogeneous and evolutionary nature of AEC decision information and thus, result in information homogenization and dispersal, pre-mature coupling and lock-in, and rework (refer to the following subsections). These limitations in information management adversely affect the decision stakeholders and the decision-making process as well, because mitigation requires stakeholders' attention and often delays the process. This is particularly significant during the synchronous mode of decision making (e.g., a decision review meeting, see section 1.2.2.2), when the fluid flow of the decision-making process is dependent on the ability of all meeting participants to make quick and informed decisions given the limited time available during a face-to-face meeting.

Lack of Informativeness

In current practice, there are no formal means of representing and organizing heterogeneous decision information. AEC decision stakeholders use generic decision-support tools and methods, which do not distinguish the types (e.g., criteria, options, and alternatives in TC#1) and states (e.g., recommended or under consideration in TC#2) of information. Hence, such tools and methods have homogenized (i.e., discarded the heterogeneous nature of) AEC decision information. In addition, current practice does not explicitly describe or explain whether an assumption would hold true across different decision choices (e.g., across different acceleration proposals in TC#4). Furthermore, heterogeneous decision information is often dispersed among multidisciplinary professionals. In TC#1, when an owner representative inquired about the cost estimates, the facilitators present in the meeting were not able to retrieve the information prepared by the cost estimators. This is because the decision-support tool did not integrate or reference the decision information prepared by the various disciplines.

Given the limitations of generic decision-support tools and methods, the management of decision information often relies on the recollection and implicit knowledge of the professionals, and thus undermines informativeness in AEC decision making. Consequently, AEC decision makers cannot acquire pertinent decision information (e.g., ripple consequences, available choices, discipline-specific concerns, etc.), which is crucial to making an informed decision, during synchronous decision meetings.

Inflexibility

Decision-support tools and methods used in current AEC practice are inflexible in managing evolutionary decision information. These generic tools and methods often require decision stakeholders to pre-determine the representation and organization of decision information. For instance, all evaluation tables in TC#2 were predetermined by the facilitators. In other instances (e.g., in TC#3), predefined evaluation tools and methods limit decision making to a macro perspective, keeping finer details away from the decision stakeholders. Such tables fix the contents and focus of the review and limit the flexibility of the decision facilitators to incorporate additional decision choices, to

shift decision focus, or to correct any errors that may be spotted after the tables are fixed.

Besides evaluation tables, current tools and methods also require stakeholders to pre-determine the coupling of options in the formulation of alternatives for recommendations. Even though some options presented in TC#1 were inter-changeable among the alternatives, the decision-support tools did not support the de-coupling and re-coupling of decision information (section 2.1). This inflexibility constrains the ability of decision stakeholders to come up with a new and better re-coupling of options as new decision information becomes available.

Inability to Resume the Decision Process

Given an impromptu intervention to change an assumption, a prediction, a coupling, or a recommendation, current practice often requires additional rework by decision stakeholders before they can incorporate the intervention and resume the decision-making process. In TC#1, as an owner representative suggested to re-combine two existing entrance options to formulate a hybrid alternative, the design team could not resume the impromptu inquiry right the way. Since generic decision-support tools only provide a static (i.e., one-way or unidirectional display of decision information with no ability to change or adjust the underlying information) representation and organization of decision information, they do not handle dynamic information management well. In addition, current tools often discard seemingly invalid choices, which may need to be re-used as the decision processes continue to evolve. As a result, additional rework and effort by decision stakeholders is often needed before a specific decision-enabling task can be performed.

Slowness

The uninformative, inflexible, and non-resumable management of AEC decision information also translate to rework and delay and hence, slowness in AEC decision making. When decision-support tools and methods do not inform decision makers about specific assumption details or criteria, facilitators have to spend additional time to uncover such decision information (e.g., TC#3 in sections 2.3 and 5.3). When

predetermined evaluation tables or couplings of options do not reflect the latest state of information, facilitators and professionals have to spend additional time in refining the tables or the alternatives (TC#2 in sections 2.3 and 5.3). When impromptu interventions cannot be incorporated, facilitators have to spend additional time in rework in order to resume decision-enabling tasks (TC#1 in sections 2.3 and 5.3).

Not only do these limitations impose rework and delay on the decision process, they also have a negative burden on the decision stakeholders. In particular, decision facilitators bear the burden to compensate for the limitations by applying their verbal explanations, mental recollection, and personal experience. In TC#1 for instance, when the decision-support tool failed to provide an informative and flexible response to an impromptu question asked by a decision maker, the facilitator used his vague recollection to come up with an approximate answer. If the facilitator could rely on the decision-support tool to provide informative, flexible, resumable, and quick responses, he/she could shift his/her focus and time commitment to other value-adding decision-enabling tasks rather than mitigating the aforementioned limitations. The adverse impacts of current information management on current practice are further analyzed in Validation Studies #1, 2, and 3 in sections 4.3, 5.3, and 6.3, respectively.

CHAPTER 3—RESEARCH QUESTIONS AND CONTRIBUTIONS OVERVIEW

As established in prior chapters, today's decision-support tools and methods are generic and do not satisfy the heterogeneous and evolutionary nature of AEC decision information, leading to decision making that is not informative, flexible, resumable, or fast. These observations and analyses motivate my research questions. My research methodology involves an iterative investigation among industry-based observations, literature review, formalization of new theories, and validation with the research results. I explain my research methodology and questions and offer an overview of my research contributions and validation in this Chapter.

Decision information, such as competing acceleration choices in TC#4, ripple effects of multidisciplinary issues in TC#3, decision assumptions in TC#2, and criteria in TC#1, fosters the making of informed decisions. Whether or not decision information is valuable depends on its quality and the management of decision information. While information is affected by its quality (e.g., accuracy of predictive information), it is beyond the scope of my research. As explained in Chapter 1, my research focuses on the management (i.e., representation, methodology, and management process) of decision information. Therefore, my three research questions are:

1. How to formalize AEC decision information and its interrelationships with a computer representation?
2. What computer-based reasoning methods can utilize formally represented decision information to support AEC decision-enabling tasks?
3. How to formalize the management of decision information during the AEC decision-making process?

Today's homogenized representation of decision information results in decision making that is slow and not informative. Existing AEC theories cover the representations of design, organization, work break downs, but not related choices and associated interrelationships. Based on the information representation needs identified from the test cases, my research investigates the applicability of Decision Analysis theories and offers an AEC Decision Ontology for decision

facilitators to explicitly document and categorize information according to its types, forms, states, and interrelationships. Furthermore, the static management of decision information causes inflexible and slow decision making in current practice. Recognizing the limitations of current theories in offering decision-support methods that align with the unique characteristics of AEC decision information, my research formalizes a Decision Method Model to manage information represented with the AEC Decision Ontology. Last, the ad hoc decision-support strategy across the many phases of a decision-making process leads to the inability to build upon prior decision tasks and resume the decision-making process. To address the limitations of AEC theories that focus on decision processes, I have adapted the DA process to offer a Dynamic DBS framework that addresses the unique information management requirements, methods, and solutions that correspond to the characteristics of the AEC decision-making process.

Together, my research contributions of an AEC Decision Ontology and a Decision Method Model form the theoretical basis of the dynamic Decision Breakdown Structure, bridging the void between AEC and DA theories in the management of AEC decision information. Applied under my third contribution of a formal decision-making framework, the Dynamic DBS provides a better (with respect to a number of validation metrics in section 3.5) decision information basis than available with existing tools. Thus, my research contributions enable AEC decision stakeholders to make quick and informed decisions.

3.1 REQUIREMENTS OF AEC DECISION-SUPPORT TOOLS AND METHODS

Decision-support tools with good management of AEC decision information enable users to stay informed, to handle the decision information flexibly, to resume information management at any point with minimal rework, and to perform the decision-enabling tasks quickly. This requires decision-support tools and methods to effectively handle decision information and the decision-making process in response to their heterogeneous and evolutionary nature.

Corresponding to the heterogeneous nature of AEC decision making and decision information, good decision-support tools for AEC decision making ought to distinguish the basic types of decision information, such that decision stakeholders can put them into context. The tools should inform the stakeholders about the states of decision information, which helps decision stakeholders to realize what the choices are and what the current

solutions entail. The tools should be able to handle a variety of information forms contributed by different professional disciplines and, thus, ensure informativeness across multiple perspectives within the overall decision context.

To support the evolutionary nature of AEC decision making and decision information, good AEC decision-support tools ought to provide stakeholders the flexibility to incorporate new information, change and re-assemble existing information, and access and evaluate cross-disciplinary decision information. The tools should allow stakeholders to preserve candidate choices and document the decision rationale, because subsequent evolution of the decision process may call for re-consideration of such seemingly invalid information. Furthermore, the tools should support quick iteration and refinement of decision information with minimal rework and thus, ensure a fluid decision process. These requirements set up the basis of my validation metrics (section 3.5).

3.2 INTUITION

The limitations and impacts of the current management of decision information have motivated my doctoral research. As I began my research, I wondered why current practice compromised the decision basis and the decision quality. I asked the following questions:

- Why is professional's decision information (e.g., decision rationale, predictions, quantitative details, assumptions, etc.) so difficult to access?
- Why do decision makers spend the majority of their time uncovering and debating a topic that has only a minor impact on the decision?
- Why do decision facilitators have to spend their precious time, when being with the decision makers, on bringing the decision makers to the same understanding of the basic decision choices and their interrelationships?
- Are the limitations of current practice simply caused by the lack of decision-support tools and computer applications for the AEC industry?
- Or are they due to a lack of theories?

Based on my observations, the decision information that is needed to perform decision-enabling tasks is available and possessed by individual professionals and the facilitators. Then, I asked,

- Why is it difficult for generic decision-support tools and methods to manage (e.g., access, evaluate, and adjust) existing decision information?

To answer these questions, I balanced my observation from AEC industry cases with an investigation in the underlying theories. In my background literature research (sections 4.1, 5.1, and 6.1), I found that there are theories that promote the importance of generating multiple and creative alternatives, balancing heterogeneous types of predictions against criteria, leveraging the value of decision making during early project phases to capitalize on life-cycle benefits, and delaying the coupling of project options (e.g., Ballard 2000, Barrett and Stanley 1999, Dell'Isola 1982, Fischer and Kam 2002, and Paulson 1976). While existing literature addresses the objectives of AEC decision making, they do not specify the means and methods to support the management of AEC decision information during the decision-making process. My intuition was that my research contributions should establish the theoretical basis for AEC decision information, a focus area that would fill the gap between Decision Analysis and AEC theories (e.g., Virtual Design and Construction, Project Management, etc.). To better dissect this research problem, I revisited the information-people-process analysis that I presented in section 1.1. Specifically, I broke up the problem into three subsuming parts: representation (focus on decision information), methodology (focus on people's interaction with the decision information), and framework (focus on people's interaction with the decision information at different points in a decision-making process). Given heterogeneous sets of decision information and the number of disciplines and issues that are present in AEC decision making, a more formal and relevant representation of AEC decision information and its interrelationships is needed for decision stakeholders and computers to represent and manage decision information (e.g., provide a distinction between choices and criteria). Given the evolutionary nature of decision information, my intuition was that a formal methodology is needed to support a dynamic interaction with the decision information. Last, there was a need to replace ad hoc information management practices with a formal information management framework throughout the decision-making process. These observations, analyses, intuitions, and

questions led to my formal research questions and contributions that I introduce in section 3.4, and further detail in Chapters 4, 5, and 6.

3.3 RESEARCH METHODOLOGY

My doctoral research follows the methodology as outlined by Fischer and Kunz (2001, Figure 9). The methodology strives to balance between practice and theory, while making a contribution to knowledge with validation results that demonstrate power and generality. In Chapter 2, I have motivated the needs of conducting ethnographic research to document the current state of AEC decision making. I also explained that problem observation has played a critical role in my research because existing literature lacks the documentation and assessment of the AEC decision-making process, the roles of AEC decision stakeholders, the decision-enabling tasks, the decision-support tools and methods, as well as the representation of AEC decision information.

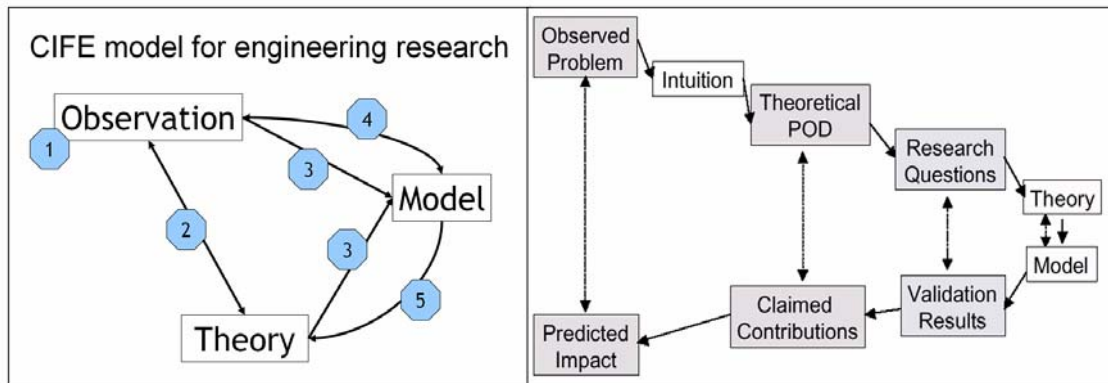


Figure 9. Fischer and Kunz (2001) outline the CIFE research model.

My literature review confirms that such limitations correspond to the shortcomings of existing theories, and do not merely result from a lack of development or implementation of existing theories. Because my contribution of a Dynamic Decision Breakdown Structure involves a new information management strategy beyond the scope and methods supported by traditional Decision Analysis, Virtual Design and Construction, Architecture-Engineering-Construction, and Project Management theories, I have developed a computer software prototype to make the contribution of my research more concrete to comprehend and validate.

Validation provides evidence on the power and generality of my research contributions. My research has four validation studies (sections 4.3, 5.3, 6.3, and 6.4), all of which focus on the scenarios from the six industry test cases (Chapter 2). In essence, my documentation of the status quo performance across all six industry test cases supplies a powerful, general, and detailed account of the information basis and information management methodology from current practice. This rich set of data and evidence serves as a benchmark for comparison against the performance evidence gathered with Decision Dashboard-based models of the test cases built with the ontology, supported by the Dynamic DBS methodologies, and carried out with the formal framework. Based on the analysis, I have established five metrics—(i) reconstructability, (ii) informativeness, (iii) flexibility, (iv) resumability, and (v) quickness. Consequently, my four validation studies allow me to develop comparative analyses to validate my research contributions against the evidence from current practice assessing their power with the five metrics and testing their generality across the six industry test cases.

My six industry test cases and four validation studies can be sorted into three categories of evidence for the power and generality of my research contributions. The first category of evidence includes Test Cases #1, #2, #3, and #4 in Validation Studies #1, #2, and #3 (sections 4.3, 5.3, and 6.3). This category of evidence is based on the most in-depth decision scenarios covering certain phases of the decision-making process. Because this category of evidence involves large-scale industry projects, my evidence is based on comparison of detailed documentation of current practice with a retrospective application of the Dynamic DBS for comparative analysis against five metrics. The second category of evidence entails Test Cases #5 and #6 in Validation Study #3 (section 6.3). Four project team members from these two test cases and I employed the Decision Dashboard prototype in support of specific decision-enabling tasks in specific information management phases, providing prospective metrics-based evidence during two half-day workshops. Finally, the third category of evidence refers to Test Case #1 in Validation Study #4 (section 6.4). To engage a diverse group of experts to validate the power and generality of the dynamic Decision Breakdown Structure, I condensed the rich set of decision information in TC#1 into a simplified version with a few discrete decision topics, criteria, options, and alternatives. This case abstraction allowed all participants to comprehend the decision scenario, the limitations of current practice, and the concepts of the Dynamic DBS during the two-hour demonstration meetings. Thus, I was able to collect both quantitative and qualitative data on the performance of the

DBS and interpret them as evidence for the power and generality of my contributions from twenty-one industry and research experts after these demonstration meetings.

In the following paragraphs, I explain my journey through problem observation, intuition, theoretical points of departure, research questions, theory, model, validation, claimed contribution, and predicted impacts.

In parallel to my undergraduate and graduate education, I have been actively involved in the building industry by practicing in an architectural firm, a biotech project team, an international project team, and a public owner. My industry involvement in the past eight years has provided me with a valuable opportunity to establish and maintain direct relationships with building owners, architects, structural engineers, MEP designers, general contractors, and subcontractors. The experience has allowed me to generalize my observations, analyze the current state of decision making in the AEC industry, and test my research concepts.

In June 2003, I took the general qualifying examination (GQE) and developed a dissertation proposal. Focusing on what has become TC#4, I generalized the limitations of current practice by conducting a literature research in preparation for the GQE. Based on my analyses of practice and theory, I formulated a set of research questions and proposed my research plan to develop a Decision Dashboard (“DD” in short, section 1.3.6). After successful completion of the GQE, my research switched gears to focus on prototype implementation. I developed the Decision Dashboard using Protégé^{xii}—a free and open source ontology development tool developed by Stanford Medical Informatics^{xiii}. To generalize the design of the ontology and methodology, I iterated the development of the DD using additional sets of case studies (i.e., TC#1, TC#2, and TC#3) that cover a variety of different decision-making scenarios, information types, forms, and states. I designed and implemented the ontology that makes up the DBS, and was assisted in the implementation by two research assistants, Nayana Samaranayake and Priyank Patel, on a part-time basis for

^{xii} <http://protege.stanford.edu>

^{xiii} <http://smi.stanford.edu>

a total of three quarters. Nayana and Priyank assisted me in programming the DMM-based methodology that I designed. As discussed in section 6.4, I held four demonstration sessions in June 2004. Over twenty industry professionals and researchers from around the U.S. and abroad attended the demonstrations and provided feedback and assessment on the value of my research contributions. Based on this feedback, I focused on improving the scalability of the AEC Decision Ontology. Subsequently, I validated my test cases with the DD while continuing to test my research contributions against additional test cases (i.e., TC#5 and TC#6) with actual industry cases and professionals.

The value and impact of my validation studies (and interventions in some cases) are further detailed in sections 3.5, 4.3, 5.3, 6.3, 6.4, and summarized in section 7.1. Having collected evidence for power and generality, I revisited my theoretical and practical points of departure, detailed my research contributions, documented my validation evidence, and completed this doctoral dissertation. Motivated to further my contributions in the area of AEC decision making and information management, the conclusions from this dissertation will form a pertinent foundation for my post-doctoral career (section 7.4).

3.4 RESEARCH QUESTIONS, CONTRIBUTIONS, AND VALIDATION STUDIES

Assessing the current state of practice introduced and analyzed in prior sections, I generalize the limitations of current practice into three main areas—representation, methodology, and framework (Figure 10), all of which I explain further in the following sections. My research goal is to contribute to the formalization of the representation, to the means and methods, and to the framework of managing (i.e., generating, enriching, organizing, querying, changing, evaluating, and archiving, etc.) decision information. My goal has led to three research questions:

- (1) How to formalize AEC decision information and its interrelationships with a computer representation?
- (2) What computer-based reasoning methods can utilize formally represented decision information to support AEC decision-enabling tasks?

- (3) How to formalize the management of decision information during the AEC decision-making process?

The three research questions correspond to the three contributions that make up a Framework for a Dynamic Decision Breakdown Structure. The first contribution is a Decision Breakdown Structure (DBS). In this contribution, I formalize an AEC Decision Ontology for the representation and organization of heterogeneous decision information. The second contribution offers dynamic methodology to the DBS. I formalize a Decision Method Model (DMM) in support of decision-enabling tasks. The third contribution provides an application framework for the application of the Dynamic DBS. I formalize a framework with information management phases and requirements for the application of the Dynamic DBS.

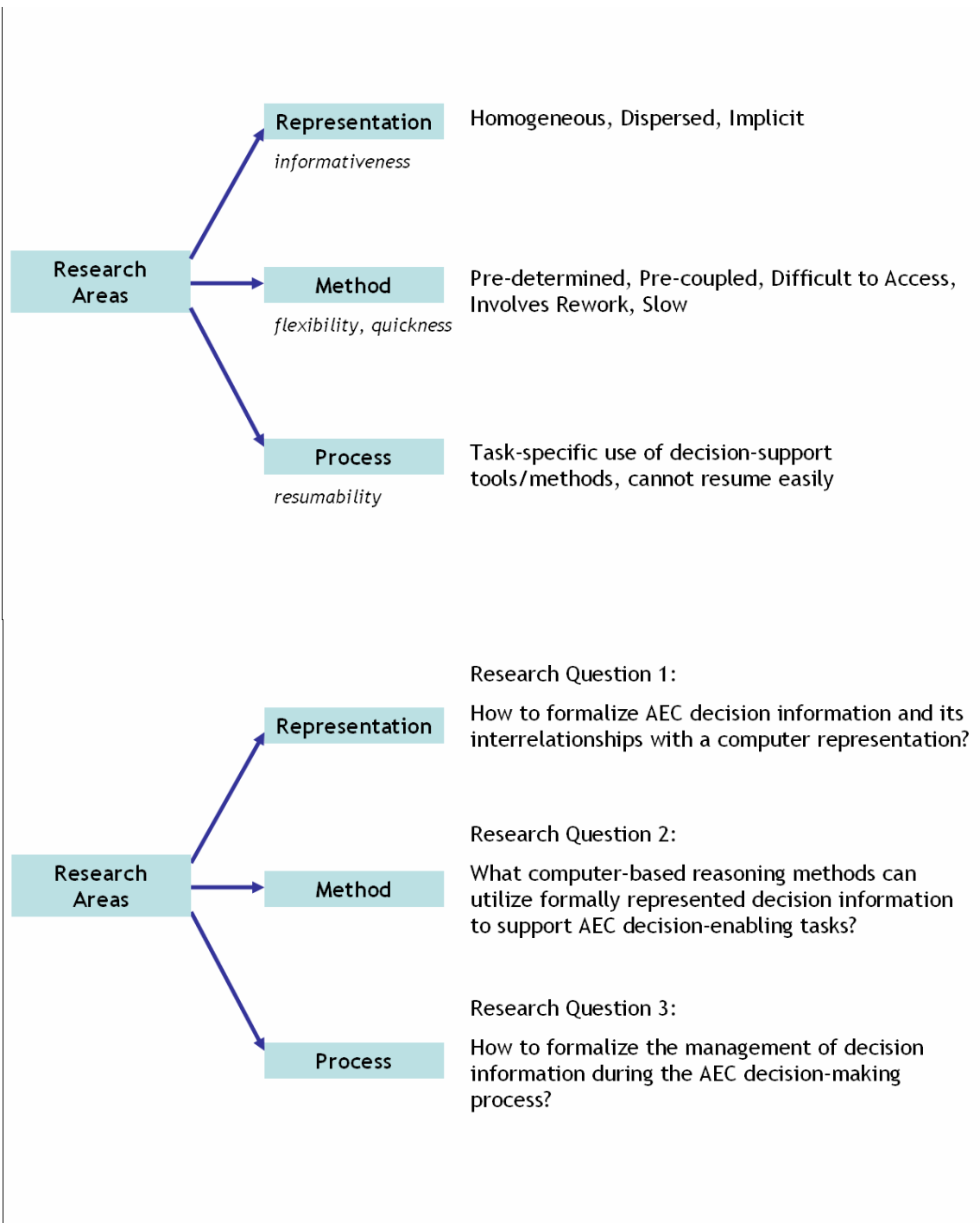


Figure 10. This doctoral research is organized into three main areas, which address the performance and current limitations of representation, method, and process (top) and their corresponding research questions (bottom).

3.4.1 RESEARCH QUESTION #1: HOW TO FORMALIZE AEC DECISION INFORMATION AND ITS INTERRELATIONSHIPS WITH A COMPUTER REPRESENTATION?

Decision information is made up of fragmented and heterogeneous pieces of information contributed by a number of decision stakeholders, their teams, and individual team members. Thus, it is imperative for theory and practice to address the integration need of representing fragmented decision information, to properly represent and distinguish decision information corresponding to its types, forms, and states, and to explicitly document the interrelationships (e.g., ripple consequences) among the fragmented elements of decision information. Current practice and theory are not addressing these areas, resulting in information dispersal across fragmented decision-support tools. They also result in homogenized representation of decision information and implicit representation of interrelationships among items of decision information. Although computer representations and breakdowns of specific product, organization, and process components exist in AEC theories, there are no formal common vocabulary for decision stakeholders or computer systems alike to describe or distinguish the many characteristics (section 1.2.2) of AEC decision information and its interrelationships.

Therefore, my first research question concerns the representation of AEC decision information and its interrelationships, specifically:

How to formalize AEC decision information and its interrelationships with a computer representation?

I devote Chapter 4 to this research question. As a preview, I investigate the theoretical points of departure (i.e., decision analysis and virtual design and construction theories) and explain why existing theories are limited in representing the heterogeneous and evolutionary nature of AEC decision information, its associated knowledge, and its interrelationships (section 4.1). I explain my first contribution of a Decision Breakdown Structure, which formalizes an AEC Decision Ontology that provides a vocabulary for both decision stakeholders and computer systems (e.g., the Decision Dashboard) to communicate and structure decision information. This contribution establishes the ontology elements, relationships, and attributes, which constitute a decision-scenario-based Decision Breakdown Structure (section 4.2). The ontology mitigates information dispersal by integrating and referencing decision information. It also addresses the homogenized and

implicit representation of decision information by establishing an explicit Decision Breakdown Structure of ontology elements, relationships, and attributes. To validate this contribution, the metric of re-constructability (section 3.6.1) was applied in Validation Study #1 (section 4.3). The validation involves my using the Decision Dashboard to re-construct the representation of decision information that was represented by an array of different decision-support tools used by practitioners in the test cases. The Validation Study provides evidence for assessing whether the AEC Decision Ontology is capable of representing and relating decision information with power (one DD versus an array of different decision-support tools from different test cases in current practice) and generality (the ability of the DD to handle the breadth of decision information types, forms, and levels of details). The scope of the validation focuses on the reconstruction of decision information that is necessary to support the completion of the decision-enabling tasks outlined in Chapter 2.

3.4.2 RESEARCH QUESTION #2: WHAT COMPUTER-BASED REASONING METHODS CAN UTILIZE FORMALLY REPRESENTED DECISION INFORMATION TO SUPPORT AEC DECISION-ENABLING TASKS?

While research question #1 addresses the heterogeneous nature of AEC decision information, this research question focuses on its evolutionary nature from the perspective of decision-enabling tasks. AEC decision information is evolutionary in nature because in building design and construction, the decision making process is also about development of new solutions and the uncovering and balancing of cross-disciplinary impacts (section 3.1). Consequently, different subsets of decision information pertaining to the decision makers' criteria, professionals' domain-specific options and predictions, and facilitators' coupling of options into alternatives are changing constantly. Therefore, it is crucial for decision stakeholders to manage decision information dynamically in response to its evolutionary nature. Decision-support tools are most valuable if they are informative about the changing information and flexible for changing evaluation and coupling needs; they shall also support what-if queries and studies, work rapidly (in seconds or minutes rather than days or weeks) in supporting a dynamic management (i.e., informative, flexible, and resumable) of AEC decision information. However, current theory and practice are limited in addressing the evolutionary nature of AEC decision information. They do not offer dynamic interaction methods for AEC stakeholders to manage decision information. Static management of evolutionary decision information with pre-mature coupling of options, pre-determined evaluation tables, and limited access to decision information across different domain-specific

representations adversely affect the decision facilitators' ability to complete decision-enabling tasks in an informative, flexible, resumable, and fast manner.

My second research question concerns the methods to utilize the formally represented decision information, specifically:

What computer-based reasoning methods can utilize formally represented decision information to support AEC decision-enabling tasks?

In Chapter 5, I go through the corresponding theoretical points of departure (section 5.1), my second research contribution (section 5.2), and its corresponding validation (section 5.3) in detail. My second contribution is the formalization of a Decision Method Model (DMM), which complements the AEC Decision Ontology with a dynamic methodology to manage evolutionary decision information. The DMM is composed of a set of base methods, which are combinable to form different composite methods that are needed to complete specific decision-enabling tasks. This formalization establishes the methods and procedures to distinguish the states of decision information, relate and reference digital information, couple, de-couple, and re-couple options, maintain dynamic access to and evaluation of embedded decision information, etc. (section 5.2). Made possible by the formal representation of decision information using the AEC Decision Ontology, the DMM contributes to dynamic information management. My second validation follows eight specific decision-enabling tasks (section 5.3) from the test cases. Examples of such decision-enabling tasks include impromptu access to decision information and the testing of a what-if scenario. The metrics of informativeness, flexibility, resumability, and quickness (sections 3.6.2-3.6.5) validate the contribution of my Decision Method Model with respect to the performance of current methods.

3.4.3 RESEARCH QUESTION #3: HOW TO FORMALIZE THE MANAGEMENT OF DECISION INFORMATION DURING THE AEC DECISION-MAKING PROCESS?

The first two research questions address the representation of heterogeneous decision information as well as a methodology for managing evolutionary decision information. Research question #3 relates the contributions of these two prior research questions to examine how they affect the continuity and quality of the decision-making process. Since

AEC decision making involves different levels of interaction among different stakeholders at different points of the decision process, there should be a formal information management approach or strategy to correspond to the changing requirements and circumstances throughout the decision process. Decision-support methods and tools used in current practice often support only specific decision-enabling tasks during a particular phase of the decision process. However, this narrow perspective often limits the access, evaluation, and adjustment (or in general, management) of decision information later in the decision process as requirements and circumstances change. As detailed in Chapter 6, there is a lack of distinction between the different information management activities and their corresponding requirements in a decision process. Ad hoc current practice and use of decision-support tools may serve the short-term tasks, but do not support information management needs at later points in the decision process under different circumstances. To maintain a good decision basis in current practice in spite of the lack of informativeness, flexibility, resumability, and quickness, decision stakeholders have to invest in extra rework effort and time to complete decision-enabling tasks.

My third research question is:

How to formalize the management of decision information during the AEC decision-making process?

In section 6.1, I explain why existing theories do not appropriately address the heterogeneous and evolutionary nature and challenges associated with AEC decision making. As a preview, virtual design and construction theories offer a framework to evaluate the quality of meetings and the value of visualization (Liston 2000 and Garcia et. al. 2003), but existing theories do not specify the information management aspects that influence the quality and visualization of decision information in meetings. My third contribution is a formal framework for managing decision information with a categorization of five information management phases in the decision-making process. The formal framework integrates both decision ontology and methodology to specify information management strategies that pertain to the five phases in the framework—definition, formulation, evaluation, iteration, and decision phases. This contribution lays down the principles and their corresponding means and methods that are required for the DBS to add value to different decision-enabling tasks in AEC decision making. The formal framework specifies

how stakeholders can rely on the Dynamic DBS to continually complete an array of different decision-enabling tasks across different phases of the decision process. It guides decision stakeholders to build ontology-based decision models and apply DMM-based methods, both of which lead to a decision-support framework that promotes informativeness, flexibility, resumability, and quickness in managing decision information. My third validation study analyzes the application of the Dynamic DBS Framework across the five information management phases and their corresponding evidence examples from all six industry test cases, based on the metrics of informativeness, flexibility, resumability, and quickness (section 6.3). Meanwhile, my fourth validation (section 6.4) complements the other three metric-based validations with a broader analysis (i.e., beyond the five metrics and beyond my personal fact-based analyses) of my research contributions. It captures the qualitative feedback from a group of twenty-one industry and research experts, who attended one of my four demonstration sessions. The sessions focused the experts' attention on the motivating case example in Chapter 1. I went through the same decision-making scenarios with current practice decision-support tools and the decision dashboard. The expert participants comprehended, evaluated, rated, and commented on the Dynamic DBS Framework.

3.5 METRICS OVERVIEW

Validation provides evidence of the power and generality of my research contributions. To set up a foundation for validating the value of information management in AEC decision making, I offer five metrics—(1) reconstructability, (2) quickness, (3) informativeness, (4) flexibility, and (5) resumability—based on my analyses of current practice (sections 1.2.2 and 2.8) and the requirements of AEC decision-support tools and methods (section 3.1). The performance of current decision-support tools and methods, in association with these metrics, was documented in Chapter 2. These metrics are proxy variables for the quality of managing AEC decision information, referring to the extent that the information basis of the decision is re-constructable, informative, flexible, resumable, and quick. In particular, reconstructability measures whether the decision information supported by an array of current decision-support tools can be reconstructed with one decision-support tool (i.e., the DD). The other metrics measure whether the means and methods to represent and manage the decision information are flexible and resumable and quick, such that stakeholders can complete decision-enabling tasks informatively. I use these five metrics in three of my four validation studies (sections 4.3, 5.3, and 6.3). These three validation studies aid in my

analysis of the applicability of my Decision Breakdown Structure (i.e., ontology), Decision Method Model (i.e., methodology, also known as “the Dynamic DBS”), and the formal framework contributions.

3.5.1 RE-CONSTRUCTABILITY

Re-constructability focuses on re-constructing pertinent decision information and its associated knowledge that are of relevance to the decision-making process (e.g., Level-1, to be discussed in section 4.1). This metric measures the ability of decision-support tools to regenerate existing decision information along with its associated knowledge across different decision-support tools. This knowledge covers both implicit and explicit understanding of the interrelationships, assumptions, and ripple consequences in the decision information.

3.5.2 QUICKNESS

In my research validation, quickness measures the efficient completion of decision-enabling tasks without compromising the quality required by the following three metrics. For instance, how quickly can decision stakeholders get an informative response (related to the metric of informativeness) perform evaluative and re-formulative tasks (related to the metrics of flexibility and resumability).

3.5.3 INFORMATIVENESS

Informativeness measures the accessibility to explicit and relevant data, information, predictions, and knowledge to enhance the decision basis of the stakeholders. For instance, a decision method would support informative decision making if it allowed stakeholders to comprehend the composition, different levels of detail, total picture, constraints, predicted impacts, choices, and ripple consequences associated with the decision under consideration. Rather than counting on subjective comprehension through an individual’s memory or skills, this metric specifically focuses on the presence of explicit information. In addition, informativeness is also associated with the access to information. If decision stakeholders cannot access existing information due to limitations of decision-support tools or methods, informative decision making is compromised.

3.5.4 FLEXIBILITY

Flexibility measures the capability for change in the management of decision information. For instance, one can analyze the flexibility of a decision method to shift the focus to specific decision issues across different levels of detail. Changes arise when different couplings of project options occur; when new states of decision information require different evaluation foci; or when the latest preferences prompt for different formulations of project plans. A flexible method or framework is capable of adjusting (e.g., by de-coupling, re-focusing, re-formulating, re-coupling, re-evaluating, etc.) the representation and evaluation of decision information under new states of preferences, foci, knowledge, and impromptu questions. This metric allows the analysis of respective capabilities of both current and Decision Dashboard methods to support flexible management of decision information.

3.5.5 RESUMABILITY

Resumability is the ability to resume an existing process. The smaller the amount of rework in reconstructing the decision information, the better the resumability in the decision-making process. Measuring beyond re-constructability, this metric allows one to analyze situations when decision information or its display formats need to change. In such instances, what process do the stakeholders follow to carry out the changes? Can they resume, i.e., pick up from where they left off, the information management process? Or do they need to reconstruct the underlying data before applying the change? How do different tools and methods affect the resumability of the decision-making process? The ideal quality of having a resumable management of decision information is that one can continue the process with minimal, or no, additional reconstruction and manual rework.

I further motivate the importance of these metrics pertaining to the specific validation needs in sections 4.3, 5.3, and 6.3. In addition to these five metrics, validation study #4 (introduced in section 3.5.3 and detailed in 6.4) complements my other three metric-based validations with a broader (i.e., beyond the five metrics and beyond my personal fact-based analyses) analysis of my research contributions based on experts' feedback.

CHAPTER 4—AEC DECISION ONTOLOGY

AEC Decision information is heterogeneous in nature because it is made up of fragmented contributions by a number of stakeholders. Existing decision-support tools and methods do not represent heterogeneous decision information in the evolutionary decision-making process in a way that is informative, flexible, resumable, and quick. There are needs to categorize the many types and structure the many interrelationships of AEC decision information that respond to its heterogeneous and evolutionary nature, while providing a basis for computer-based information management methods to enhance the completion of decision-enabling tasks.

Existing theories promote planning/design/construction analyses by multiple disciplines and the incorporation of choices in the establishment of an informative decision basis. However, existing theories are limited in addressing the integration need of representing fragmented decision information, to properly represent and distinguish decision information corresponding to its types, forms, and states, and to explicitly document the interrelationships (e.g., ripple consequences) among items of decision information (section 3.1.1). As a result, the use of generic (i.e., non-AEC context specific) decision-support tools and methods by AEC decision stakeholders leads to information dispersal, homogenized representation of decision information, and implicit interrelationships among items of decision information. The dispersal and ineffective representation of decision information adversely impact the management of AEC decision information to support decision-enabling tasks (Chapter 5). Hence, a good representation of AEC decision information ought to support the explicit representation, organization, integration, and referencing of heterogeneous information and its associated knowledge and thereby enable decision stakeholders to complete decision-enabling tasks more effectively.

This chapter presents my first contribution in this research—the formalization of an AEC Decision Ontology. Building upon the concept of alternative generation from Decision Analysis, the distinction of Function-Form-Behavior in design theory, the notion of levels of detail in Virtual Design and Construction, the concept of breakdown structures from project management, and the opportunities associated with ontology development, the AEC Decision Ontology provides a vocabulary to communicate and structure decision information (choices in particular), its associated knowledge, and its interrelationships. This vocabulary serves as a common

language for humans and computer systems to categorize heterogeneous decision information and structure its interrelationships. It allows decision stakeholders to integrate or reference heterogeneous decision information and hence, offers a solution to reduce information dispersal and enhance information retrieval given the number of AEC stakeholders involved in AEC decision making. The ontology is made up of conceptual elements, relationships, and attributes. They are the granular elements by which decision stakeholders represent, distinguish, and organize decision information, so that the information representation supports effective manipulation to support the completion of decision-enabling tasks. Using the AEC Decision Ontology, decision facilitators can formulate a Decision Breakdown Structure—a descriptive hierarchy of decision information that becomes the foundation for the application of a formal methodology (Chapter 5) and framework (Chapter 6) in support of decision-enabling tasks through different information management phases in AEC decision making. As introduced in section 3.5.1 and as I detail in section 4.3, the validation of my AEC Decision Ontology involves my using the Decision Dashboard to re-construct the representation of decision information that was represented by an array of different decision-support tools used by practitioners in the test cases. In each of these cases, I take the same base set of decision information from practice and build a Decision Breakdown Structure in the Decision Dashboard using the AEC Decision Ontology. Thus, it provides evidence for assessing whether the AEC Decision Ontology is capable of representing and relating decision information with power (e.g., the ability of the ontology to represent different sets of decision information currently represented by a number of decision-support tools used in practice) and generality (e.g., the ability to apply the ontology across varying decision contexts and project types).

4.1 POINTS OF DEPARTURE

Theories in Decision Analysis and Virtual Design and Construction establish the foundation for representing information pertinent to the AEC decision-making process. Guided by my first research question (section 3.5.1), my research investigates these theories and concludes that existing theories are limited in supporting the representation of choices and their interrelationships that are unique to the AEC decision-making processes.

In Decision Analysis theory, choice is an integral part of the decision basis (Howard 1988). The practice of architectural design, engineering modeling, and construction simulation offers choices for decision makers to consider before committing to major resource

allocation. However, current theories in Virtual Design and Construction (e.g., Form-Function-Behavior) and AEC project management (e.g., work breakdown structure) primarily focus on the representation of the decision composition (i.e., what the decision entails, such as the forms, functions, and/or behaviors of the product, processes, and/or the organization of a particular design/construction alternative). These theories are limited in representing decision choices and their interrelationships (e.g., choices in form, function, behavior), which are the focus of my AEC Decision Ontology.

Choice is an important Decision Analysis concept that is underrepresented in AEC and VDC theories. While building upon the representation of choice becomes a core foundation of my research, my research analysis concludes that merely using Decision Analysis representation alone is not sufficient to represent the heterogeneous and evolutionary nature of AEC decision information. Because AEC information involves different levels of detail based on fragmented and iterative contributions by many professional teams, there is a need to further break down choice into the distinctive types of AEC decision information (i.e., criteria, topics, options, and alternatives). In the following subsections, I also submit that the binary decision-tree based representation that is core to the DA approach does not fit well in the dynamic and evolutionary AEC decision-making process. In place of a binary representation, I will discuss various breakdown structures that are widely adopted by project management theories. I will explain the applicability of an ontology-based breakdown structure for the representation of AEC decision information, its choices and interrelationships.

4.1.1 REPRESENTATION IN DECISION ANALYSIS

This section assesses the information representation in Decision Analysis and presents my analysis that DA theory does not fully address the unique needs associated with representation of AEC decision information.

Decision Analysis establishes choice, information, and preferences as the three integral parts of the decision basis. Specifically, Howard (1988) details that choice is made up of alternatives the decision maker faces; information refers to models that include probability assignments to characterize uncertainty; whereas preferences are the value, time preference, and risk preference of the decision makers. He suggests that framing (i.e., presenting a problem), creating alternatives, and the elicitation of information and preferences are pre-

requisite of a logical evaluation of the decision basis. The formal representation of choices—in form of alternatives—in Decision Analysis are extensible points of departure for my research in formalizing the representation of choices in the AEC context.

However, specific representations of choices, information, and preferences differ across phases in the context of Decision Analysis. In particular, Howard (1988) recommends the use of a Strategy-Generation Table to create alternatives, an influence diagram to elicit the decision basis, and a Decision Tree to conduct logical evaluation. The sequential and separate treatments of alternative-generation and evaluation are not tailored for evolutionary AEC decision information. Furthermore, the representation of alternatives does not give the flexibility to AEC stakeholders to distinguish between choices at different levels of detail (i.e., options versus alternatives).

The Strategy-Generation Table (Figure 11) “enables people to discuss a few significantly different strategies rather than a combinatorially exhaustive and exhausting list” (Howard 1988). In essence, it provides a layout for decision stakeholders to list all the possible strategies (i.e., options) pertaining to different sets of themes (i.e., topics). By marking one strategy under every theme, one can generate an alternative based on one’s preferences. As Howard assesses, “you find that not all combinations make sense, that a certain decision in one area implies or at least indicates particular decisions in other areas.” However, the ability of a corporate executive to fully comprehend all these interrelationships among particular options may not translate to the many heterogeneous AEC stakeholders, who need to comprehend the interrelationships among a number of AEC technical disciplines (e.g., the decision makers in TC#1). This also exposes the limitation of the Strategy-Generation Table to incorporate finer levels of detail and specifically, option choices, associated with a particular strategy. In other words, there may be specific options within a strategy (i.e., alternative) that turn the strategy to be more attractive or less competitive than another strategy. This informativeness and flexibility cannot be achieved with the representation of a strategy-generation table.

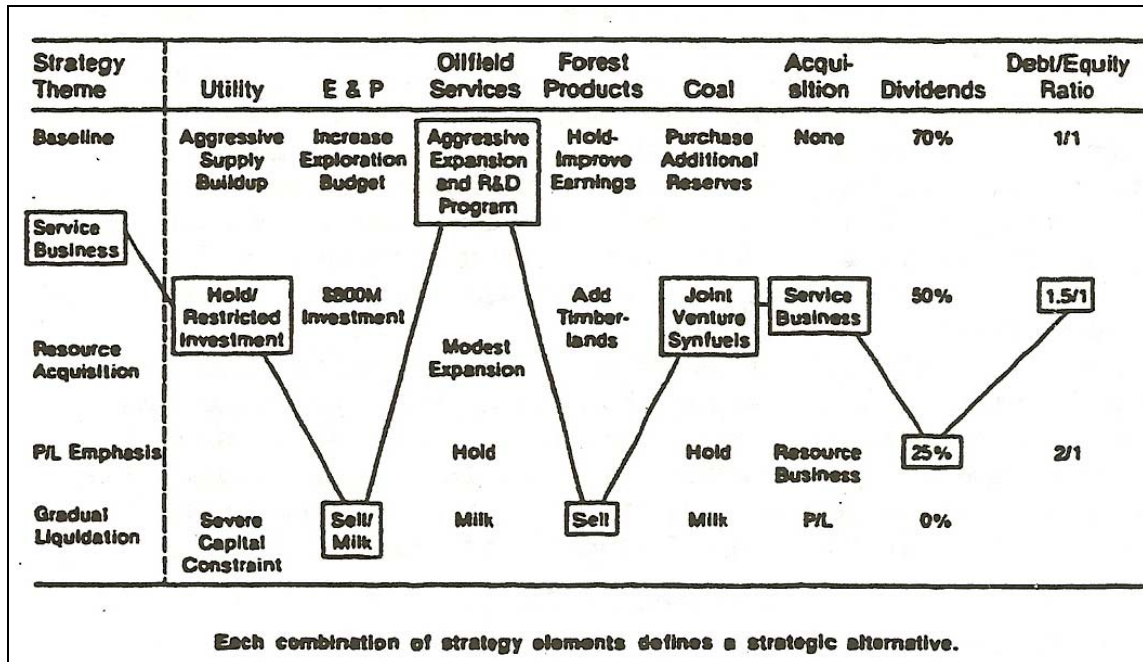


Figure 11. Howard (1998) gives an example of a Strategy-Generation Table.

While the Strategy-Generation Table allows one to represent the elements that constitute an alternative, the Influence Diagram contributes to the representation of decisions, uncertainty, and value, and their relevance (Howard 1990). Howard suggests that the term “relevance” is more accurate a definition than “influence” because the relationship should be a two-way relevance. As Lawrence Phillips (a reviewer of Howard 1990) discusses, an Influence Diagram is an aid for communicating about uncertainty during the initial formulation of decision problems; however, the most serious disadvantage is the difficulty Influence Diagrams, or “mutual-shaping systems” have with asymmetrical decision trees (Howard 1990) that are common in AEC decisions.

My analysis is that the Influence Diagram is a valuable representation to document the knowledge about general design and construction rules, e.g., the relevance between structural design and mechanical distribution in building design. It is also a useful tool to help assign risk preference. However, the representation in Influence Diagrams is too vague, general, and inflexible for specific project-based AEC decision making. Influence Diagrams focus on the interrelationships between decision topics, their uncertainties and value; but not the specific alternatives, options, and their interrelationships, e.g., the specific “relevance” or interrelationships among the options of concrete structure, steel structure, raised floor

distribution, and overhead ductwork. Furthermore, Influence Diagrams do not provide the flexibility for AEC stakeholders to specify, evaluate, or adjust alternatives or options at different levels of detail. As my research focuses on a dynamic set of options and their coupling into alternatives, the Influence Diagram is not an extensible point of departure for me to represent and organize AEC options, alternatives, and their corresponding interrelationships.

In addition to Strategy-Generation Tables and Influence Diagrams, representation in Decision Analysis often involves a decision tree. The decision tree provides a basis for the decision makers to assign probability values at each “decision node” and “chance node” (Lilien and Rangaswamy, 2001). The decision tree is a binomial representation of the decision prospects in a hierarchical tree branch format. The hierarchy requires a sequential relationship or an independent relationship between its parent node and the children nodes. Once all the decision outcomes are identified along with their specific course of actions (i.e., the decision prospects that may be generated from a Strategy-Generation Table), the decision makers can incorporate their subjective probabilities or probability distributions to the decision trees. With statistical computations and analyses, one can rationally identify the most optimal course of action based on one’s prescribed preference and criteria. A decision tree does not convey the evolutionary and interrelated information in the AEC context well. As the following example illustrates, the application of stochastic and decision tree approaches has been less popular in the AEC industry than in the fields of medicine, management science, and operations research.

CIFE researchers assess the feasibility and benefits of applying decision analysis techniques for both strategic and operational decisions (Blum et. al. 1994). They analyze the adoption of new or proven technology using a decision diagram and variables that are subject to the probabilities assigned based on the particular company in question. In particular, Blum et. al. investigate a general contractor’s decision regarding the selection of a computerized estimating system as well as the evaluation of a CAD system for a new package sorting facility. The authors conclude that the process proved to be “useful for framing the decision, identifying the key alternatives while eliminating others, and determining the value of gathering certain information” (Blum et. al. 1994). Based on these application examples in their research, one should notice the limitations of a binomial decision tree approach. The substantive decision alternatives in these three cases are limited to two (e.g., adoption vs. no

adoption, estimating system A vs. estimating system B, and CAD system A vs. CAD system B). Even though there are 19 variables that affect the final measure (i.e., metric or criterion), their effects are limited to the probability assignment. Furthermore, the relationships among these variables are pre-determined in that they are either sequential or isolated (e.g., state of economy leading to market demand). Meanwhile, decision stakeholders can only use a single dimension of measure (e.g., expected return or profit) to evaluate the respective decision prospects.

AEC decision options often relate to one another concurrently and dependently; both conditions are excluded or abstracted in a binomial hierarchy. Hence, to fit a complex and evolutionary AEC scenario into a decision tree, one is required to isolate these interrelated conditions, identify all the decision prospects in advance, and restructure the interdependent variables redundantly to fit a binomial representation. Thus, the representation and methodology of a binary decision tree does not provide the flexibility to manage evolutionary decision information, whose options, coupling of options, and their interrelationships are frequently in a state of flux and development. A binomial representation does not natively support highly interdependent, concurrent, and evolutionary relationships of decision information within a complex AEC project.

Furthermore, the binomial representation requires the decision facilitator to fix all the relationships within an alternative, hence, it is not flexible with process choices, which are important in the AEC context (e.g., the relationship between retail steel and parking can be sequential or concurrent in TC#4). In addition, the alternatives are fixed and hence, the decision is limited to a few predetermined courses of actions. In the AEC context, the options and alternatives in a complex project can include well over several dozen courses of actions. Hence, it does not allow decision stakeholders to resume the evaluation process easily when the representation of decision information needs to be adjusted. Last but not least, AEC decision criteria involve multiple dimensions (e.g., cost and time), and they are very often dictated by conflicting criteria and changing contexts, rather than a logical set of preferences and probability assignments.

Choice, strategy generation, and logical evaluation from Decision Analysis are valuable concepts for the AEC context. They provide a theoretical basis for AEC decision making to build upon. However, specific representation approaches such as Strategy-Generation Table,

Influence Diagram, and the Decision Tree are more tailored for general decision making, in which one or a few executives or analysts can master the interrelationships, general relevance diagrammatic notations are sufficient to abstract the problem, and prospective courses of action can be isolated in advance and assigned with probabilities. The DA representation has been applied in AEC decision making, but its applications are limited because explicit and option-specific documentation of interrelationships is necessary for the many AEC stakeholders and because AEC decision-making involves evolutionary information. Therefore, my research builds upon the conceptual basis of Decision Analysis but uses a different representation and information management strategy (sections 4.2 and 5.2) to focus specifically on the nature of AEC decision information and decision making.

4.1.2 REPRESENTATION OF DECISION INFORMATION IN VIRTUAL DESIGN AND CONSTRUCTION

While section 4.1.1 assesses the representation of choices in DA and its applicability in AEC decision making, this section focuses on Virtual Design and Construction (VDC) and design theories within the AEC context. Analyzing these existing theories, my finding is that there is a need to extend these theories to incorporate the formal representation of AEC choices and their interrelationships.

Virtual Design and Construction (VDC) is the use of integrated multidisciplinary performance models of design and construction projects to support explicit and public business objectives (Kunz and Fischer 2005). VDC embodies the concept of representing decision information virtually in the computer. Gero (1990) suggests that design representations can be categorized as function, behavior, and structure. Clayton et. al. (1995) have developed a computer-based Semantic Modeling Extension (SME) that links specific Function, Form^{xiv}, and Behavior (FFB) objects, which are formally represented in the computer, for specific design objectives. Meanwhile, Kunz et. al. (1996) extend the tradition of concurrent engineering and discuss the integrated use of symbolic and simulation models to cover product design, manufacturing process, manufacturing facility, and the design and management of organizations. Building upon these theoretical bases, Kunz and Fischer

^{xiv} Clayton et. al. use the term “form” in a way similar to Gero’s using the term “structure.”

(2005) suggest that a VDC project model should emphasize product, organization, and process (POP) in an integrated manner. In other words, an integrated POP model should represent the function, form, and behavior of a project product, organization, and process. They also define that a level-1 POP model represents Product, Organization, and Process elements that each incur about 10% of the project cost, design-construction effort, or schedule duration, whereas level-2 and level-3 models represent elements at finer levels of detail. The benefits of VDC and its representation allow AEC stakeholders to improve communication with visual models, to improve coordination and data sharing with integrated models, and to improve productivity [of design and construction tasks] dramatically with automated models (Fischer 2005).

VDC representations of AEC decision information establish the basis for stakeholders to specify POP functions, design POP forms, and predict their corresponding behaviors. Therefore, a choice in AEC can also be categorized as P, P, or O and F, F, or B. However, choices, their relationships, and their impacts (or ripple consequences) on POP-FFB are missing in current and the aforementioned VDC literature. Existing VDC theories do not support an explicit and integrated representation of competing functions, alternate forms, and multiple sets of behavior predictions. There are no formal representations of choices that pertain to a particular element or multiple elements in POP-FFB (e.g., how to represent multiple sets of behavior predictions associated with a particular form of a particular product?) In TC#2, the “product” of a new headquarters building has a “form” choice of an atrium with three different “predictions” of absenteeism improvement. Current VDC theories do not support a formal representation of these competing predictions.). There are no distinctions between options, i.e., discrete choices within a specific F, F, or B in P, O, or P. In TC#4 for instance, the “process” of construction phasing included two “form” options—“sequential” or “concurrent”. But there was no formal means to describe, explain, and differentiate this choice. The same is true for alternatives (i.e., the coupling of multiple FFB-POP options). In TC#1 for instance, there were two alternatives but there was no formal means to describe which options they share or do not share). Furthermore, there are no formal representations of the interrelationships among the options, alternatives, and other POP-FFB elements. Consequently, AEC stakeholders need to create alternate POP-FFB representations that are interrelated by implicit or ad hoc relationships whenever they introduce new options or alternatives. This requires a redundant representation of all the

unchanged portions and thus, adversely affects the management of AEC decision information (as I further address in Chapter 5).

The absence of choices in POP representations is further evidenced by the functionalities supported by state-of-the-art project planning and design tools that are used in the test cases. For instance, in AutoDesk Architectural Desktop (ADT), one has to start a new “drawing” to record a design alternative; similarly in Microsoft Project (MSP), even though one can track an as-planned versus as-built project schedule, one must restart a new schedule file to incorporate process or relationship alternatives. Cost estimation is another discipline-specific application. For Microsoft Excel to include a new cost estimate, one has to start a new worksheet. Options and alternatives are dispersed and excluded from a single model representation, whereas the rationale for the generation of options and alternatives is not formally documented or organized. While individual domain-specific applications do not handle choices among themselves, this limitation also extends to integration models and data representations that are illustrated in the following paragraph.

Similarly, other AEC representation models such as the Industry Foundation Classes (IFC), aec-XML (Extensible Markup Language) schema, the Work Breakdown Structure (WBS), the Organization Breakdown Structure (OBS), and the model server approach (e.g., ePM, Enterprise) do not provide clear bases for AEC stakeholders to represent choices when dealing with different FFB-POP information. For instance, the Project Management Institute defines the Work Breakdown Structure (WBS) as a key planning tool that defines a project in terms of its deliverables and establishes a foundation for other elements of the formal project plan including the project’s resource plan, budget, organizational plan (OBS) and master schedule^{xv}. Tsao et al. (2004) discuss the integration between a WBS and an OBS. However, in any one of these examples, the representation focuses on outcomes and deliverables, without any formal considerations or representations of work and organization choices. Beyond the AEC context, Kunz and Rittel (1979) outline an Issue-Based Information Systems (IBIS) and suggest that the categorization of “issues” can become the elements of information systems to support coordination and planning of political decision

^{xv} http://www.pmi.org/info/PP_PracStdForWBSUpdate.asp

processes. Kunz and Rittel's IBIS, as well as other project management breakdown structures identified in this paragraph, illustrate the needs to categorize and organize information while offering different solutions for such categorization and organization. Hence, the concepts of categorization and organization are extensible points of departure for my research.

In this section, I have assessed various AEC and VDC theories and their representation of AEC decision information. While these theories support AEC stakeholders to categorize a large set of AEC decision information by finer breakdowns of character (POP-FFB) or levels of detail, there is no formal representation of choices and the interrelationships of decision information. Hence, I take these AEC and VDC theories as extensible points of departure and complement them with explicit representation of choices, which will be applicable at different levels of detail across different types of characters. As evidenced in my six industry cases, AEC decision information is predominantly represented digitally in the computer. Therefore, one logical point of departure for my research is to analyze the possibility of constructing a semantic language to representation and interrelate AEC decision information (choices in particular). This led to my investigation of a computer ontology for AEC decision information.

4.1.3 COMPUTER ONTOLOGY

A computer ontology provides a vocabulary for describing information to both computers and humans. Gruber (1993) explains that the development of an ontology is an explicit formal specification of the terms in a domain and relations among them; he also explains that the term "ontology" is borrowed from philosophy, where an ontology is a systematic account of existence. Noy and McGuinness (2001) observe that ontologies have become common in the internet, which contributes to its "moving from the realm of Artificial Intelligence laboratories to the desktops of domain experts," such as ontologies in defense, medicine, and general sales, products, and services.

There are also precedents of ontology developments in the AEC domain. For instance, O'Brien et. al. (2003) describe a subcontractor process ontology; whereas Staub-French (2002) has developed an ontology that represents cost estimators' rationale as well as a feature ontology to formalize the impact of the features on cost estimating. In addition to

these research efforts, the Omniclass Construction Classification System^{xvi} (OCCS) is a “common language that classifies and identifies very discrete objects of the built environment”; it is currently being developed by a group of volunteers from organizations and firms representing a broad cross section of the AEC industry. In spite of its broad coverage of construction disciplines, services, elements, entities by form and function, facilities, information, and properties, etc. in its 15 tables, the OCCS does not provide a common language for the building industry to differentiate choices, options, alternatives, and their interrelationships pertaining to AEC decision information. Although a computer ontology is not available for AEC decision making, the concept of a common vocabulary for both computers and humans serves as another point of departure for my research.

4.2 CONTRIBUTION #1—AEC DECISION ONTOLOGY

My first contribution builds upon DA’s concept of alternative generation, the distinction of Function-Form-Behavior in design theory, the notion of levels of detail in VDC, the concept of breakdown structures, and the opportunities associated with ontology development. This contribution provides a vocabulary for decision stakeholders and computer systems (i.e., the Decision Dashboard) to represent and structure heterogeneous decision information and its associated knowledge. While existing AEC theories primarily focus on representing certain subsets of decision information (e.g., the representation of a certain process alternative or a certain product option), my research categorizes these types of information subsets (as ontology elements) and relationships between them (as ontology relationships). In other words, my research conceptualizes the different information types within the heterogeneous AEC decision information found in the industry test cases. My work offers a core set of information and relationship types. My hypothesis is that the ability to distinguish these information and relationship types will aid in the representation and management of AEC decision information to improve the completion of decision-enabling tasks.

To support the representation of discrete items of decision information, their interrelationships and associated details, my contribution of an AEC Decision Ontology

^{xvi} <http://www.occsnet.org>

offers three ontology parts—elements, relationships, and attributes (Figure 12). These three ontology parts are abstract and conceptual; they rely on symbolic representations to explicitly represent relevant decision information and its associated knowledge from the perspectives of the decision stakeholders. Ontology elements include decision topics, criteria, alternatives, and options. Ontology relationships relate and organize ontology elements. Ontology attributes supplement elements and relationships with placeholders to store relevant textual and numeric information in the Decision Dashboard. Following the rules and definitions outlined in the following sections, AEC decision facilitators can build a Decision Breakdown Structure to support decision-making processes using these three ontology parts.

The AEC Decision Ontology presented in the following subsections is semantically appropriate rather than being a generalization of the decision information present in the industry test cases. In other words, the ontology is designed to hold a greater set of decision information than the information sets identified in the test cases. For instance, even though the industry examples do not involve any competing sets (or choices of) requirements (e.g., aggressive project schedule and higher budget vs. baseline schedule and tighter budget), my ontology still provides a formal structure for representing, structuring, and interrelating such sets of decision information. The following subsections describe the three parts of the AEC Decision Ontology: elements, relationships, and attributes.

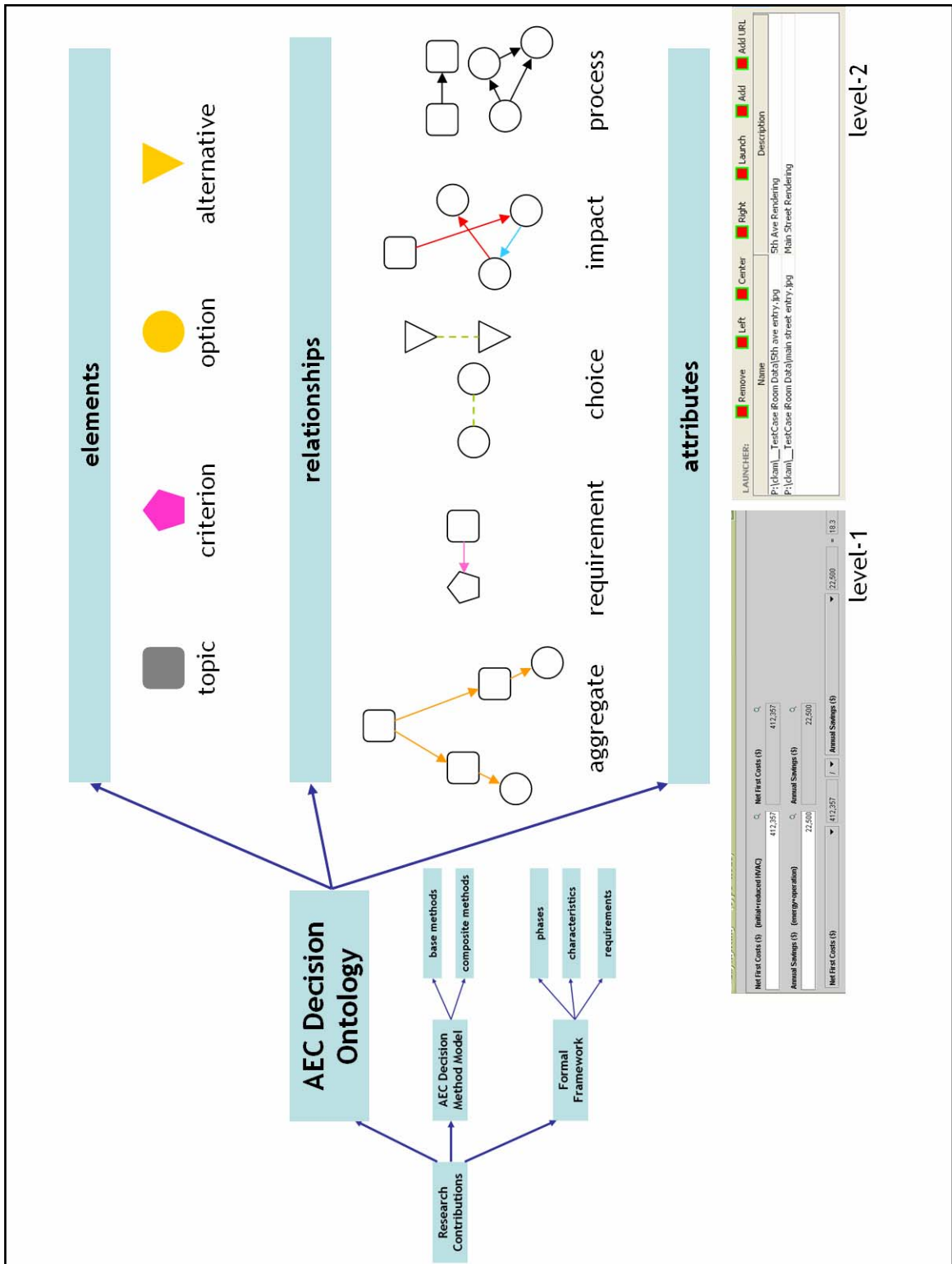


Figure 12. Elements, relationships, and attributes are the three parts of the AEC Decision Ontology, with which decision facilitators can represent decision information (e.g., choices) and its interrelationships in their formulation of a Decision Breakdown Structure.

4.2.1 ONTOLOGY ELEMENTS

Building upon and generalizing the concepts of issue (Kunz and Rittel 1979), requirement (Kiviniemi 2005), choice (Howard 1966), coupling (Barrett and Stanley 1999), and breakdown (e.g., Tsao et al. 2004), I have formalized topic, criterion, option, and alternative as the four ontology elements of the AEC Decision Ontology to represent the heterogeneous nature of AEC decision information. These ontology elements allow AEC decision stakeholders to categorize different forms and types of fragmented items of decision information into topics, criteria, options, and alternatives.

4.2.1.1 DECISION TOPICS

Represented as gray boxes in the DD, decision topics build upon the concepts of issue (Kunz and Rittel 1979) and breakdown structures (section 5.1) to become the indexes or metadata that are part of a decision breakdown structure. They allow the grouping and structuring of decision needs across different levels of detail. They categorize product, organization, process, and resource topics (e.g., in the motivating case example, entry location is a product decision topic; whereas Department H transition is an organization decision topic). Decision topics offer hierarchy and branching functions to organize and represent the topics of decisions to be addressed in the Decision Dashboard.

4.2.1.2 DECISION CRITERIA

Represented as pink pentagons in the DD, criteria are public and explicit requirements established in association with the decision topics. Building upon the concepts of client requirements (Kamara et. al. 2002) and requirements modeling (Kiviniemi 2005), decision criteria may be high-level (e.g., program requirements of the headquarters in the motivating case example) or finer-detail-level criteria (e.g., specific area requirements of the common program) depending on their specific attachments, represented in the form of “required by” relationships, to the appropriate “decision topic” nodes. Criteria allow decision makers to evaluate decision choices (options or alternatives) or a decision chain (i.e., branch of a decision breakdown structure with certain selection of options and alternatives) against explicit functional requirements in an absolute context (section 5.2.1).

4.2.1.3 DECISION OPTIONS

The concept of choice is core to the theories in Decision Analysis but has not been formally represented in VDC or project management theories in AEC (section 5.1). As my contribution builds upon DA's representation of choice, I have also identified the need to represent discrete decision choices with a formal distinction between options (following paragraph) and alternatives (following subsection):

Represented as circles in the DD in either active/selected state that is being recommended (orange) or idle/candidate state that is under consideration (blue, see section 5.2.2), options are discrete decision choices in the most detailed form. Options allow decision makers to represent competing choices, be they product, organization, process, or resource in nature. They become discrete information entities, which allow decision facilitators to treat them as part of a selection, preserve seemingly invalid solutions, specifically relate inter-disciplinary impacts, and make relative evaluations, etc. (with appropriate methods that are described in section 5.2). Examples of decision options that are associated with the decision topic of entry location in the motivating case example include entry at Main Street, entry at Fifth Avenue, and corner entry.

4.2.1.4 DECISION ALTERNATIVES

Represented as inverted triangles in the DD in either active/selected (orange) or idle/candidate (blue) states (section 5.2.2), alternatives embody an aggregated selection of options. Rather than listing every single possible coupling of options (as in binary representations), the ontology captures selective couplings of options (i.e., alternatives) deemed considerable. Examples of decision alternatives are the two alternative schemes in the motivating case example (section 1.3.1.3) that were presented to the decision makers during the decision review meeting, each of these alternatives involved a particular mix of selected options that were coupled by the decision facilitator to become an alternative scheme.

4.2.2 ONTOLOGY RELATIONSHIPS

As illustrated in the industry test cases, the lack of explicit representation of interrelationships among decision information undermines the ability of the decision

stakeholders to complete decision-enabling tasks. In light of the limitation of existing theories in addressing the representation of interrelationships among choices and across different levels of detail, I have formalized aggregate, choice, requirement, impact, and process relationships as the ontology relationships in the AEC Decision Ontology. Together, they become the formal links to represent the interrelationships among decision information represented with the ontology elements.

4.2.2.1 AGGREGATE RELATIONSHIP

Represented as orange unidirectional arrows in the Decision Dashboard, aggregate relationships connect an actively selected (i.e., recommended) set of decision elements. They formalize the representations of information entities that are coupled together. Aggregation may relate the following ontology elements:

(1) Decision Topics:

Different decision topics can be connected with one another hierarchically by aggregate relationships. Such hierarchical organization of decision topics contributes to a top-down structure with each tier of aggregated decision topics forming a finer level of detail, resulting in the core of a decision breakdown structure. For instance, aggregate relationships connect the decision topic “renovation plans” to the decision topics “entry location” and “amenity location” in TC#1 (Figure 15), forming a hierarchical structure with “renovation plans” at the top level of detail and the two location topics at the second level of detail.

(2) Decision Topics and Decision Options:

Aggregate relationships connect each decision topic to its selected choices of options. For instance, an aggregate relationship connects the decision topic “entry location” to the location option “Main Street” under the decision scenario illustrated in TC#1 illustrated in Figure 15.

(3) Decision Topics and Decision Alternatives:

An aggregate relationship connects a decision topic to its selected alternative (i.e., a particular combination of selected options) that is under recommendation (e.g., “Alternative 2” in TC#1 in Figure 15).

(4) Decision Alternatives and Other Ontology Elements (i.e., topics, criteria, alternatives, and options)

Originating from a decision alternative, aggregate relationships may connect to other decision topics, criteria, alternatives, and options that are coupled as an alternative under consideration (section 5.2). The aggregate relationships connecting “Alternative 2” in TC#1 to “Main Street,” “On Penthouse,” “On East Roof,” “Dept. H Stays,” “Begin with East Demolition,” “Use Existing Basement Plant,” and “Suggested Sequence” are examples of such aggregate relationships (Figure 15).

4.2.2.2 CHOICE RELATIONSHIP

Represented as green bidirectional arrows, choice relationships connect competing and non-competing choices under consideration within a specific decision issue. The elements that are connected by choice relationships may all be alternatives (which gives stakeholders a set of alternative choices), may all be options (a set of option choices), or a combination of options and decision topics, which can then be broken down into options and alternatives. In TC#1, the decision options “Main Street,” “Fifth Avenue,” and “Corner Entry” are connected by choice relationships; likewise the decision alternatives “Alternative 1” and “Alternative 2” are also related with a choice relationship.

4.2.2.3 REQUIREMENT RELATIONSHIP

Represented as pink unidirectional arrows, requirement relationships can occur at different levels in the DBS (section 4.2.4). They connect decision topics (e.g., swing space in TC#1) to their respective decision criteria (e.g., space area requirements for the swing space).

4.2.2.4 IMPACT RELATIONSHIP

Represented as cyan (positive impact) or red (negative impact) bidirectional arrows, impact relationships document the ripple effects among decision topics, alternatives, and options.

(1) positive impact relationships, such as that between the decision options to “begin with east wing demolition” and to “use existing basement plants” in TC#1, are synergistic if they are selected at the same time.

(2) negative impact relationships, such as the conflict between the decision options to locate the MEP plant on the rooftop and the decision to assign the common program to the penthouse in the motivating case example, have problematic effects on the decision scenarios if they are selected to go with one another.

4.2.2.5 PROCESS RELATIONSHIP

Represented as black unidirectional arrows, process relationships depict the temporal dependencies of decision topics. Precedence relationships denote the precedent-successor relationships between decision topics, where the finish dates of the precedent decision topics become the start dates of the successor decision topics (e.g., “Phase 1A Demo” must take place before “Phase 1B Utility,” which is followed by “Phase 1C Superstructure” in TC#1, see Figure 15). Precedence relationships possess a “lag duration” attribute to represent a time buffer between predecessor and successor activities. When there are multiple process relationships for a decision topic, the attributes (refer to the following section) embedded in the succeeding decision topic inherits the latest start date among all its predecessor decision topics.

4.2.3 ONTOLOGY ATTRIBUTES

All ontology elements (i.e., decision topics, criteria, options, and alternatives) and all ontology relationships (i.e., aggregate, choice, requirement, impact, and process relationships) can have attributes. The Decision Dashboard supports different forms of ontology attributes, such as text, numeric values, and predetermined choices. To support the representation of the decision information from the six test cases, I have created a library of over 30 attributes in the DD (Figure 13). DD users can reuse these attributes or create new attributes to capture pertinent decision parameters associated with specific decision content or relationships.

Within the ontology attributes, I have defined two types of decision information—Level-1 decision information and Level-2 decision information. Level-1 decision information is information that is embedded in the DD (e.g., numeric value, text, decision rationale, etc.) that supports live manipulation with the Decision Method Model (section 5.2). Level-2 decision information refers to existing electronic

information (in computer applications or databases) that is being referenced explicitly from the DD (see section 5.2 for its specific enabling method).

- | | |
|---|---|
| Alternative Activator | Cumulative Payback (Type 2) |
| Alternative Duplicator | Cumulative Score (Aesthetic) |
| Calculation Operator | Cumulative Score (Sustainability) |
| Calculator Operator (field by field) | Dashboard Evaluation Table (Requirement) |
| Component Area (Type 1) | Date (Anticipated Start) |
| Component Area (Type 2) | Date (Overall Finish) (part of Cumulative Duration) |
| Component Area (Type 3) | Date (Overall Start) (part of Cumulative Duration) |
| Component Cost (Type 1) | Date (Predicted Completion) |
| Component Cost (Type 2=First Cost) | Evaluation Table (Requirement) |
| Component Cost (Type 3=Annual Savings) | Evaluation Table (Sibling) |
| Component Cost (Type 4=Productivity Gains) | Improvement in Absenteeism (%) |
| Component Cost (Type 5=Absenteeism Gains) | Improvement in Productivity (%) |
| Component Duration | iRoom Launcher |
| Component Payback (Type 1) | isOption |
| Component Payback (Type 2) | isSelOption |
| Component Score (Aesthetic) | Lag (Days) |
| Component Score (Sustainability) | Network Relationship Types |
| Cons | Network Slot |
| Control Panel | Parent-Alternative |
| Cumulative Area (Type 1) | Pros |
| Cumulative Area (Type 2) | Referenced Application & File |
| Cumulative Area (Type 3) | Required Area |
| Cumulative Cost (Type 1) | Required Budget |
| Cumulative Cost (Type 2=First Cost) | Required Duration |
| Cumulative Cost (Type 3=Annual Savings) | Required Milestone |
| Cumulative Cost (Type 4=Productivity Gains) | Required Performance Specification |
| Cumulative Cost (Type 5=Absenteeism Gains) | Required Score (Aesthetic) |
| Cumulative Duration | Required Score (Sustainability) |
| Cumulative Payback (Type 1) | |

Figure 13. A list of the ontology attributes present in the Decision Dashboard prototype.

4.2.4 DECISION BREAKDOWN STRUCTURE—THE INTEGRATION OF ONTOLOGY ELEMENTS, RELATIONSHIPS, AND ATTRIBUTES

All together, the ontology elements, relationships, and attributes enable decision stakeholders, and in particular decision facilitators, to create project-specific Decision Breakdown Structures. The ontology enables the DBS to become an integrated and hierarchical structure for decision stakeholders from multiple disciplines to view and manage the heterogeneous and evolutionary decision information. Similar to the

importance of defining the meaning of human languages through words and grammar, semantics play an important role in establishing the meaning of the AEC Decision Ontology. To further explain the semantics of the DBS, I summarize the applicable ontology relationships between different combinations of ontology elements in Table 5.

From \ To	Topic 	Criterion 	Option 	Alternative 
Topic 	"Aggregate" "Process" "Choice" "Impact"	"Requirement"	"Aggregate" "Choice" "Impact"	"Aggregate"
Criterion 	Not Allowed	"Choice"	Not Allowed	Not Allowed
Option 	"Choice" "Impact"	Now Allowed	"Choice" "Impact"	"Impact"
Alternative 	"Aggregate"	"Aggregate"	"Aggregate"	"Choice" "Aggregate"

Table 5. A table summarizing the ontology relationships between different ontology element combinations in the AEC Decision Ontology.

Table 5 reinforces the conceptual formalization of the DBS in that:

- The DBS is hierarchically organized around the “topic” element and “aggregate” relationship (unidirectional). They form the *core structure of a DBS* (Figure 14). As evidenced in the first row in Table 5, there are aggregate relationships between the ontology element “topic” and the elements “topic,” “option,” and “alternative.”

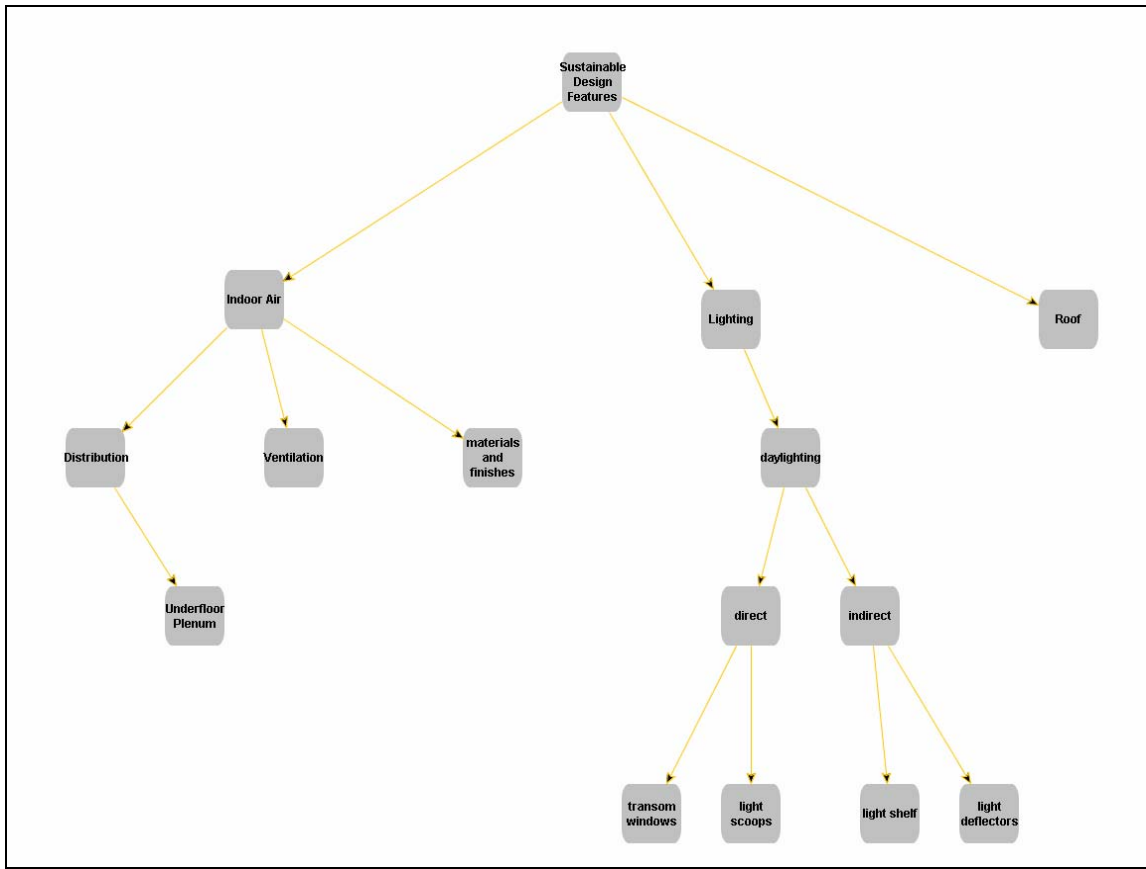


Figure 14. The core structure of the DBS in TC#2 has 5 levels of detail, as evidenced by the number of “topic” tiers that are interconnected by “aggregate” ontology relationships.

- Each DBS must have a “topic” as the top-most anchorage, which is the parent (i.e., originator of aggregate relationships) of other topics, alternatives, and/or options. The DBS is scalable because it allows decision stakeholders to represent and organize decision information with multiple *levels of detail*. While the top-most anchor topic always serves as the first level of detail in the DBS, each parallel set of “topics” connected by their parent “topics” through “aggregate” relationships form a finer level of detail. Whether or not the ontology elements “criterion,” “alternative,” and “option” are connected to the elements “topic” does not affect the levels of detail in a DBS, the same applies to “topics” connecting to other “topics” through “process,” “choice,” and/or “impact” relationships. Taking TC#2 as an example, the DBS in Figure 14 has 5 levels of detail.

- The DBS enables the explicit documentation of coupling through its ontology element “alternative” and relationship “aggregate”. An example is the presence of “aggregate” relationships (e.g., see Figure 15 for coupling from “Alternative 1” and “Alternative 2”) across the bottom row of Table 5.
- The DBS allows the attachment of criteria to decision topics at different levels of detail, through the unidirectional relationship “requirement” that connects a “topic” to a “criterion.” The characteristic of this unidirectional relationship designed specifically to constrain a “topic” by a “criterion” also leads to four null entries in Table 5. These “Not Allowed” table entries between the ontology elements “criterion” and “topic,” “option,” and “alternative” are in violation with the DBS semantics presented in this bullet.
- The DBS supports the incorporation of choices across all four types of decision information (i.e., topic, criterion, option, and alternative). An example is the presence of the ontology relationship “choice” between all peer elements (i.e., from topic to topic, criterion to criterion, etc.) along the diagonal table cells in Table 5.
- In addition to choices among different instances of the same elements (e.g., entry option “Main Street” and entry option “Fifth Ave” in TC#1), the DBS allows the incorporation of choices at a hybrid level of detail (e.g., option “conventional distribution” and topic “underfloor distribution” in TC#2, see Figure 16). This is evidenced by the presence of ontology relationship “choice” in the table cell corresponding to “From Option To Topic” in the second column of Table 5.

Table 5 also aids in my validation study #1 to gain insight into the number of distinctive elements and relationships that are either implicit or represented in a homogenized manner in current practice. The ontology also paves the way for my formalization and application of a Decision Method Model (Chapter 5) and Framework for the application of a Dynamic DBS (Chapter 6).

4.3 VALIDATION STUDY #1—RECONSTRUCTABLE ONTOLOGY

My first validation study presents reconstructability evidence from the Decision Dashboard approach based on existing decision information from the test cases. By reconstructability, this validation evaluates whether the Decision Breakdown Structure and its AEC Decision Ontology have the power and generality to represent and organize decision information and its associated knowledge (i.e., interrelationships) found in practice. The validation focuses on reconstructing four existing sets of information (i.e., Test Cases #1, #2, #3, and #4) with the Decision Ontology, by making an explicit representation and distinction of decision information as well as the many interrelationships between the information. While current decision-support tools in practice vary among their representation strategies when dealing with decision information (e.g., computer slide show in TC#1, paper-based report in TC#2, etc.), this validation study uses the DD as the only decision-support tool for all four test cases. In each of these cases, I take the same base set of decision information from practice and build a Decision Breakdown Structure in the Decision Dashboard using the AEC Decision Ontology.

The following subsections analyze the extent to which the ontology-based Decision Dashboard, in comparison to current decision-support tools, supports an explicit representation, organization, integration, and referencing of decision information and its associated knowledge across the four test cases. As Chapters 5 and 6 explain, such an explicit representation provides the basis for a Dynamic DBS to the completion of decision-enabling tasks, which outperforms current practice based on a homogenized representation of decision information. Thus, this validation study also contributes to the effective and efficient completion of decision-enabling tasks in the AEC decision-making process. Meanwhile, the evidence for re-constructability includes power (i.e., the ability to use one set of AEC Decision Ontology, in comparison to a variety of current decision-support tools and methods, to represent decision information) and generality (i.e., breadth—across multidisciplinary perspectives with respect to different sets of decision information across different test cases) of the Decision Breakdown Structure.

4.3.1 TEST CASE #1: HEADQUARTERS RENOVATION—SCHEMATIC DESIGN

In section 2.1, I provided the observation that centers around the decision information used by the decision facilitators in a series of design review meetings between the owners and the

professionals in TC#1. In my reconstruction of TC#1 with the AEC Decision Ontology in the Decision Dashboard (Figure 15), I focus on the matching of level-1 decision information with the decision information that MS PowerPoint represented, organized, integrated, and referenced in the slide set. In addition to the MS PowerPoint-based decision information, I incorporate other level-1 information and associated knowledge that were required to complete the decision-enabling tasks. Such information and associated knowledge were implicit, they were only available through the architects' verbal account of the decision information during the review meeting. To represent the decision information for TC#1, I use ontology elements to represent 3 instances of decision criterion, 14 instances of decision topic, 13 instances of option, and 4 instances of alternative across 5 levels of detail. The organization of and inter-linkages between these element instances require 50 instances of ontology relationships, which include aggregate, choice, requirement, impact, and process relationships. The reconstruction has integrated 15 attributes, such as component and cumulative cost, component and cumulative area, start date, and budget, etc. One of these attributes provides references to non DD-based digital files and their native applications. There are 10 instances of such referential attribute, providing explicit and direct linkages to specific schedule files, 3D renderings, spreadsheets, and requirement documents associated with specific element instances.

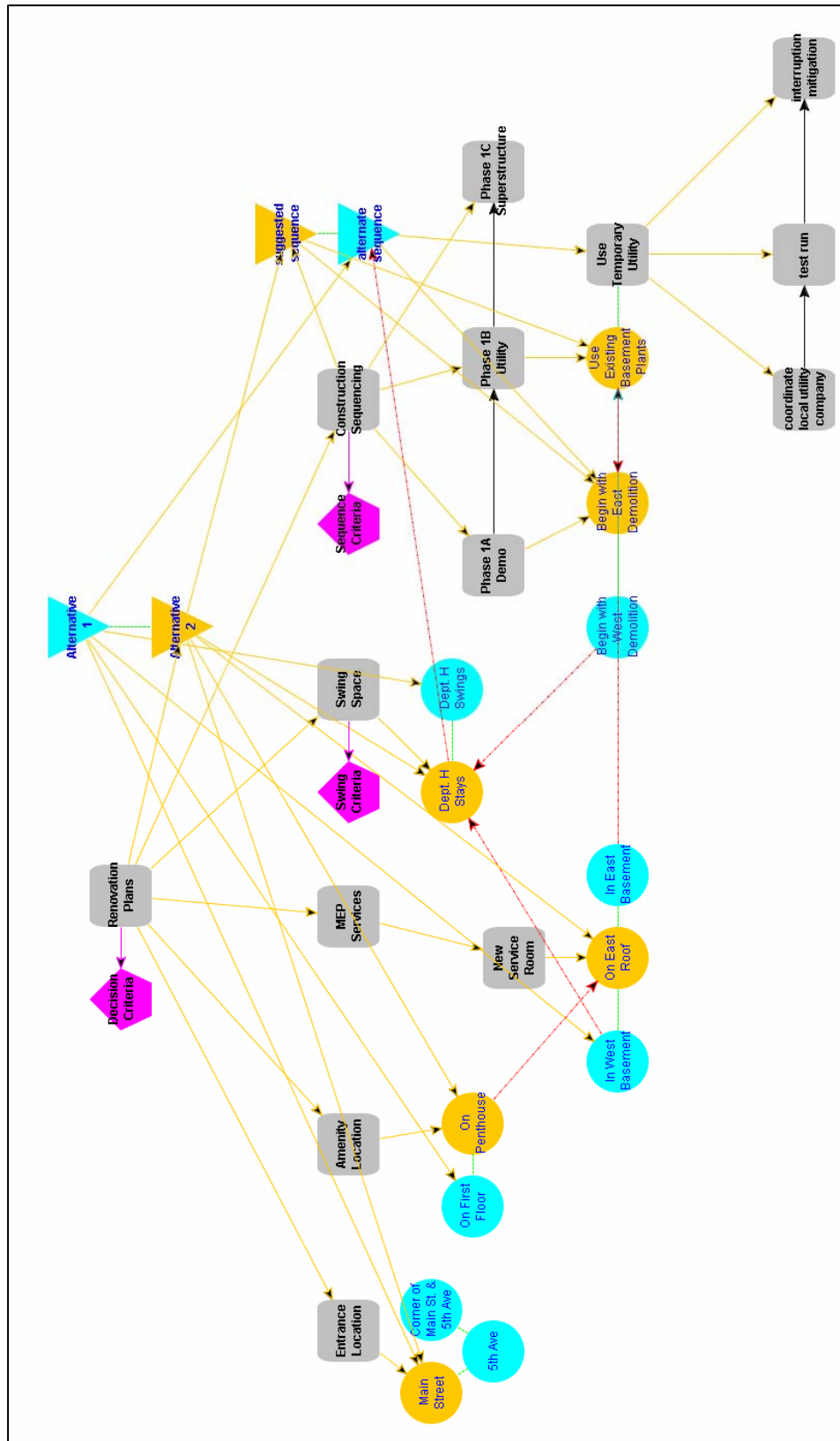


Figure 15. A screenshot of the Decision Breakdown Structure built in the Decision Dashboard based on the existing decision information in TC#1.

Note that all test cases in this dissertation follow the same DBS layout convention, i.e., top-down layout of DBS where decision topics are structured hierarchically. Decision topics are placed by a layout convention such that decision criteria are placed vertically to their left, alternatives are placed vertically to their right, whereas options are placed horizontally to their bottom.

4.3.2 TEST CASE #2: NEW CAMPUS HEADQUARTERS

Section 2.2 presented this test case that focuses on the decision information that the designers submitted to the owners as a cost-benefit analysis of various sustainable features for a campus headquarters project. In my reconstruction of TC#2 with the AEC Decision Ontology in the Decision Dashboard (Figure 16), I focus on the data that supports the 8 key evaluation tables in the paper-based report that served as the decision basis for TC#2. The ontology-based DBS represents the design strategies of roof, indoor air, and lighting as decision topics, under which proposed solutions such as green roof, underfloor air, and natural daylight are represented as the preferred options. Based on the printed report, I have reconstructed 16 instances of decision topic, 14 instances of option, 3 instances of alternative, and 4 instances of criterion (the criterion instances are placeholders because no specific criteria were available).

The Decision Breakdown Structure is organized into 5 levels of detail. There are 42 instances of ontology relationships that include aggregate, choice, and requirement relationships. No impact or process relationships are employed because the printed document did not report cross-option or process dependencies. Rather than modeling the productivity data as a separate decision topic (which is how the professionals treated the issue in the report—putting it under a new section), I integrate the productivity data with its corresponding design features (i.e., underfloor plenum and natural daylighting). To be explicit about the professionals' assumptions about the likelihood of productivity improvement, I instantiate 3 mutually exclusive options (i.e., best, most likely, and worst cases) and associate them with their corresponding design features. As a result, numeric assumptions and predictions are integrated in the Decision Dashboard, with specific relationships to the particular features and scenarios they belong to. Furthermore, I use aggregate relationships to couple all the sub-feature scenarios into an overall scenario (best,

most likely, and worst). Thus, my reconstruction resembles the different levels of coupling (between features and sub-features) present in both the executive summary and individual sections of the printed report in current practice.

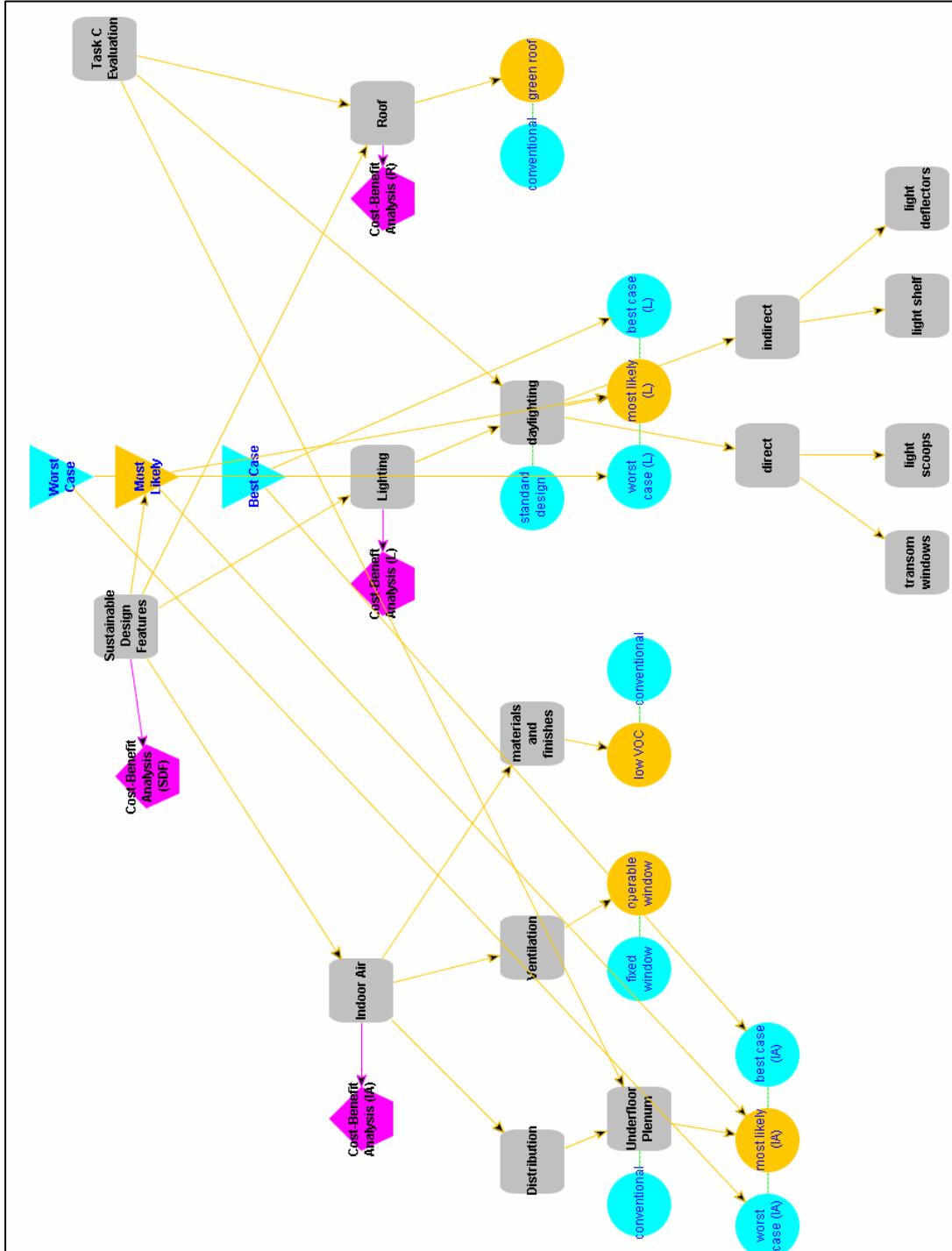


Figure 16. A screenshot of the Decision Breakdown Structured built in the Decision Dashboard based on the existing decision information in TC#2.

4.3.3 TEST CASE #3: HEADQUARTERS RENOVATION—PROGRAMMING

Section 2.3 presented the decision information that the lead designer submitted in the form of a Program Development Study (PDS) to the owner of TC#3. My ontology-based decision dashboard models level-1 decision topics and options. I obtained these level-1 decision topics by reading through the PDS report, and capturing the main bullets under narratives about options from each of the 16 subsections. In total, there are 39 instances of decision topic and 58 instances of option identified in the resultant Decision Breakdown Structure (Figure 17 and 18). In terms of organization, the ontology elements are connected by aggregate, choice, and impact relationships. All together, there are 103 instances of these relationships, making up 6 levels of detail present in the reconstructed DBS.

The impact relationships within the DBS serve to connect interrelated options across different subsections in the report. In current practice, the designers describe such ripple consequences in different parts of the PDS report without cross-referencing the consequences. For example, the description of zoning effects on additional floor construction is only available in the section about site. If one only refers to the structural section or the cost estimate section without reading the site section, one would not notice the constraints imposed by the zoning ordinance. In my Decision Dashboard reconstruction, impact relationships are documented bi-directionally (e.g., there are mutual impacts between zoning and additional floor decisions). Therefore, stakeholders can get a more complete comprehension of the many interrelationships originating from or targeting particular ontology elements.

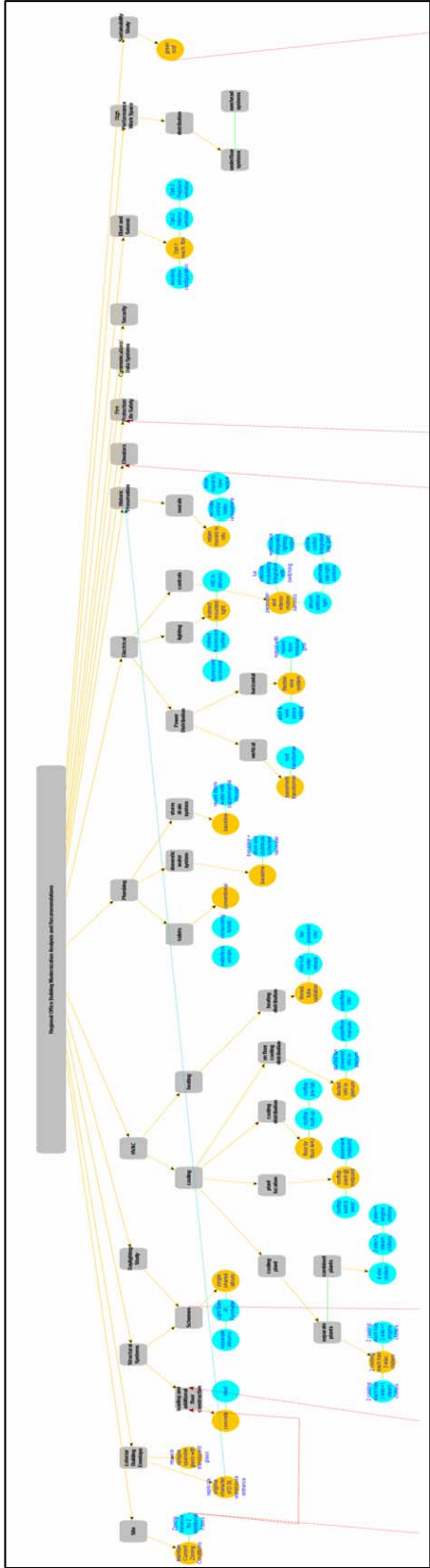


Figure 17. A screenshot of the overall Decision Breakdown Structure built in the Decision Dashboard based on the existing decision information in TC#3.

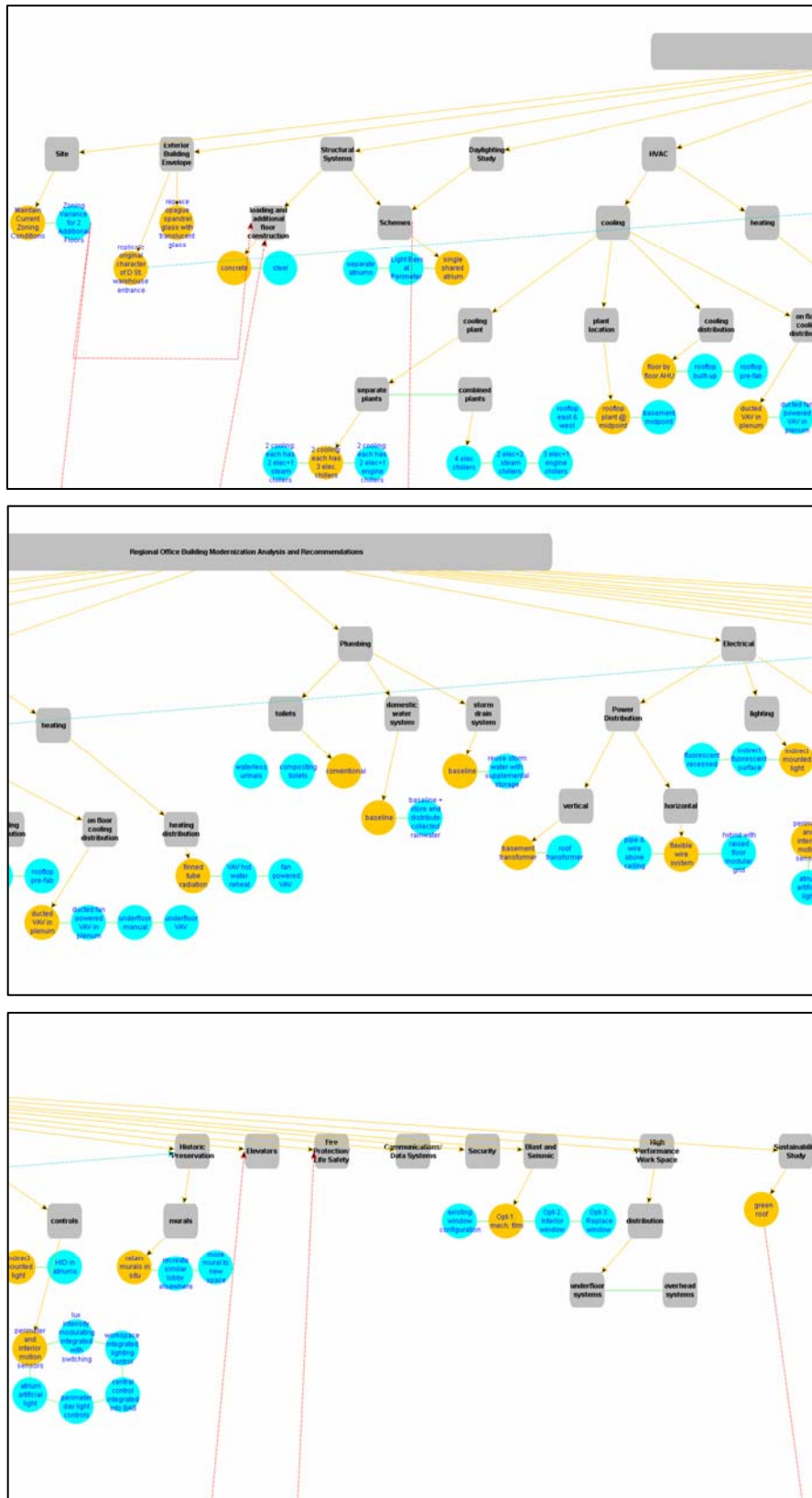


Figure 18. The overall DBS in Figure 17 is broken into three screenshots (top, middle, and bottom screenshots of Fig. 18 correspond to the left, middle, and right, respectively, of Fig. 17).

4.3.4 TEST CASE #4: NEW RETAIL COMPLEX

The decision information brought together by the decision facilitators in TC#4 was presented in section 2.4. The meeting focused on the mitigation strategies to alleviate the impact of an unexpected delay in the construction project. My reconstruction of TC#4 focuses on the relationships among the acceleration options, while explaining how these options combine into different alternatives. The reconstruction is made up of 9 instances of decision topic and 11 instances of decision option, which combine into 4 different instances of acceleration alternatives (Figure 19). These 24 instances of ontology elements require 38 instances of ontology relationships, including aggregate, choice, process, and impact relationships. As attributes embedded in the ontology elements, linkages to iRoom applications and specific POP models are available in the Decision Dashboard.

While current practice combines PowerPoint and individuals' mental correlations, the AEC Decision Ontology enables DD users to understand the acceleration choices under the decision topics of product, organization, process, and resources. DD users can query specific attributes that include reference information to POP models, which pertain to particular options or topics, in the CIFE iRoom. Furthermore, users can adjust evaluation foci (in terms of topics and/or attributes and/or criteria, see section 5.2) in real-time and comprehend the cross-option impacts among the many decision choices. Hence, they are informed of the opportunities and limitations associated with the reformulation process (section 5.3, Decision-Enabling Task #1), during which professionals mix and match options to come up with different alternatives.

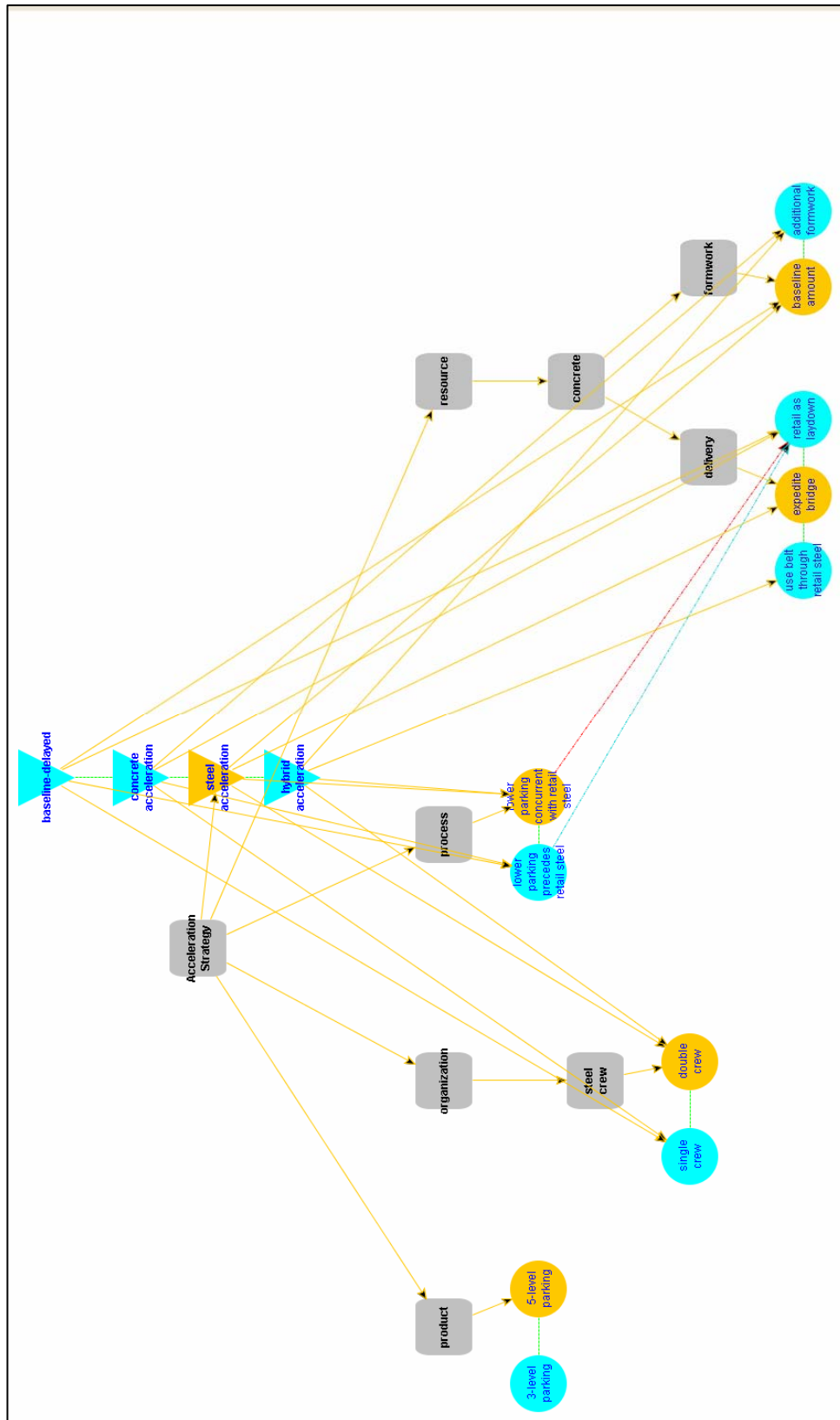


Figure 19. A screenshot of the Decision Breakdown Structured built in the Decision Dashboard based on the existing decision information in TC#4.

4.3.5 INTEGRATED ANALYSIS

The data in Validation Study #1 provides the evidence that the AEC Decision Ontology is sufficient and capable of representing, organizing, integrating, and referencing decision information to support the decision making objectives and processes undertaken by the decision stakeholders in Test Cases #1 through #4. Using the framework established in Table 5, Table 6 summarizes the collective use of the ontology elements and relationships for the four test cases. The numbers along the first column of Table 6 denote the number of instances of ontology elements present in the 4 DBS's (i.e., 78 instances of topic, 7 instances of criterion, 96 instances of option, and 11 instances of alternatives); the numbers in the other columns (i.e., second through the fifth) represent the number of instances of ontology relationships (e.g., 77 instances of ontology relationships from topic to topic, 7 from topic to criterion, 37 from topic to option, and 4 from topic to alternative, etc.). The result is significant because the DBS formalizes the explicit representation of heterogeneous decision information with its ontology elements and relationships. As Validation Study #2 (section 5.3) illustrates, the Dynamic DBS methods rely on such formal representation and categorization to manage heterogeneous and evolutionary decision information to improve the ways facilitators complete decision-enabling tasks. There are two "no instances" cells reported in Table 6. They refer to the absence of relationship instances between the elements "alternative" and "criterion," as well as "criterion" and "criterion". As explained in section 4.2, the design of the DBS is semantically appropriate as it covers a more comprehensive set of decision information and interrelationship than that identified from industry test cases. Hence, the two entries of "No Instance" signal that the AEC Decision Ontology is capable of handling additional types of decision information than those that are present in the four cases. For instance, the cases do not involve competing sets of decision criteria (e.g., one set of criteria may include an aggressive construction completion milestone and a high construction budget, whereas its competing set of criteria may include a later milestone and a lower construction budget) present in any of the four test cases reconstructed in this Validation Study. Similarly, the table shows that the alternatives present in the test cases do not involve any coupling with decision criteria, in spite of the capability of the DBS to incorporate such decision scenarios.

In terms of implications on practice, the validation study shows the severity of homogenized representation, implicit relationships, and inflexible methods on the management of AEC decision information in current practice. First, the DBS's of the industry cases include

explicit representations and categorizations of 192 instances of ontology elements (adding the total number of element instances in column 1 in Table 6) and 233 instances of ontology relationships (adding the total number of relationship instances in columns 2 through 5 in Table 6). As illustrated in the specific decision-enabling tasks in Chapter 2 (e.g., task #7 in TC#3), the implicit management of such information types and relationships often adversely impacts the completion of AEC decision-enabling tasks. Second, 11 alternatives and 96 options are identified based on the reconstruction of the 4 industry cases. Hence, the inflexibility of current decision-support tools limits decision stakeholders to decisions based on 11 alternatives, rather than a richer access and manipulation of 96 options. Third, the drastic difference between the number of topic instances (78) and criterion instances (7) signals the lack of criteria (and furthermore, competing criteria choices) corresponding to the decision topics. As illustrated in decision-enabling task #2 in TC#1 (section 2.1), the inability to retrieve decision criteria poses challenges for decision makers to make informed decisions in a timely manner. By formalizing the categorization of information types, the AEC Decision Ontology promotes the recognition, and hence mitigation, of such imbalance treatments between topics and criteria.

From \ To	Topic 	Criterion 	Option 	Alternative 
Topic  78	77	7	37	4
Criterion  7	Not allowed	No instance	Not allowed	Not allowed
Option  96	7	Not allowed	64	1
Alternative  11	1	No instance	33	2

Table 6. Table summarizing the number of ontology elements and relationships that are explicitly represented and distinguished based on the decision information used on the four test cases. The left-most column presents the number of ontology elements present in the test cases (e.g., 78 instances of ontology element “Topic”); the second-left through the right-most columns present the number of relationships between different elements (e.g., 77 instances of ontology relationships between ontology elements “Topic” and “Topic”).

4.4 CHAPTER CONCLUSION

In this chapter, I have presented the concept of a Decision Breakdown Structure that is constituted of different AEC Decision Ontology parts (i.e., elements, relationships, and attributes). Existing theories do not address the representation of choices and their interrelationships in the AEC context. Building upon the theories in Decision Analysis, the DBS extends representations in VDC and AEC theories and enables the formal representation of AEC decision information. Validation Study #1 demonstrates that the ontology-based reconstruction has the power and generality to represent, organize, integrate, and reference decision information and its associated knowledge that are involved in the four industry test cases. The ontology-based DBS is general, because (1) it represents decision information that is traditionally represented with an array of current decision-support means and methods; and (2) it supports the representation of different sets of decision information and interrelationships through different project phases and across different types of building projects. It is powerful as it contributes to an explicit categorization of the heterogeneous decision information and its interrelationships, which are not present in the homogenized representation of decision information in current practice. These distinctions of elements and relationships play an important role in enabling decision facilitators to manage the decision information with a DBS, a dynamic methodology, and a continuous process. With the categorization of decision information corresponding to its information type (through ontology element) and interrelationships (through ontology relationships), the DBS lays the foundation for the management of formally represented decision information (Chapter 5) throughout the many phases in the AEC decision-making process (Chapter 6). In the validation studies in the following two chapters, I analyze the value of DD's integrated and referenced information management method for better completion of decision-enabling tasks.

CHAPTER 5—AEC DECISION METHOD MODEL

Given the evolutionary nature of AEC decision information, different subsets of decision information pertaining to the decision makers' criteria, professionals' domain-specific options and predictions, and facilitators' coupling of options into alternatives are changing frequently (section 3.5.2). Therefore, it is crucial for decision stakeholders to manage decision information dynamically. Decision-support tools shall keep decision stakeholders informed about the changing information, they shall be flexible for the changing evaluation and coupling needs, they shall enable facilitators to resume decision-enabling tasks under impromptu and what-if scenarios, while they shall be fast in supporting a dynamic management (i.e., informative, flexible, and resumable) of AEC decision information. However, current theory and practice provide few methods that address the evolutionary nature of AEC decision information and maintain a good decision information basis. They do not offer dynamic interaction methods for AEC stakeholders to manage decision information. Static management of evolutionary decision information with pre-mature coupling of options, pre-determined evaluation tables, and limited access to decision information across different domain-specific representations results in the completion of decision-enabling tasks that is not informative, inflexible, not resumable, and slow.

My second contribution is the formalization of a Decision Method Model (DMM), which complements the ontology-based Decision Breakdown Structure with a dynamic methodology to manage evolutionary decision information. The DMM is composed of a set of base methods, which are combinable to form different composite methods that support specific decision-enabling tasks. Made possible by the formal representation of decision information using the AEC Decision Ontology, the DMM contributes to dynamic information management. The base and composite methods developed in this doctoral research respond to the information management needs based on the decision-enabling tasks from the industry test cases (sections 2.1 through 2.4). This formalization establishes the methods and procedures to distinguish the states of decision information, relate and reference digital information, couple, de-couple, and re-couple options, maintain dynamic access to and evaluation of embedded decision information, etc. (section 5.2). The current set of methods are not meant to cover every single decision need exhaustively, but to demonstrate that computer reasoning methods built upon the AEC Decision

Ontology may be formalized, pre-packaged, and reused to assist decision stakeholders in completing an array of decision-enabling tasks.

My second validation study shows the value of the DMM for 8 specific decision-enabling tasks from the test cases (sections 2.1 through 2.6 and 5.3). Examples of such decision-enabling tasks include impromptu access of decision information, the testing of a what-if scenario, etc. The metrics of informativeness, flexibility, resumability, and quickness (sections 3.5.2-3.5.5) validate the contribution of my Decision Method Model with respect to the performance of current practice.

5.1 POINTS OF DEPARTURE

Having a formal computer representation of decision information presents opportunities for decision facilitators to process (e.g., access, evaluate, modify, re-combine, add, etc.) AEC decision information and its interrelationships to complete decision-enabling tasks. To uncover the limiting factors affecting conventional decision-support methods used in current practice, I examine the theories that lay out the foundation for managing decision information in both AEC and non-AEC contexts.

Decision Analysis (DA) employs a formal stochastic methodology to analyze and evaluate information, choice, and preferences that need to be properly framed and synthesized by the decision analysts. However, I submit that the heterogeneous and evolutionary nature of AEC decision information makes it difficult to apply this stochastic methodology to solve AEC decision problems (section 5.1.1). Within the building industry, computer-based reasoning methods and non-computer-based methods exist to leverage formal representations in support of planning, design, and construction tasks (e.g., Critical Path Method, time-cost tradeoff, information visualization, requirements management, etc.). However, there are no formal methods in VDC or AEC theories (section 5.1.2) that detail the distinction of choices, their interrelationships, their coupling and decoupling, and other aspects. To determine the relevance and limitations of current theories with respect to my research motivation and questions (section 3.4), I examine different DA, VDC, and AEC methods in the following subsections.

5.1.1 DECISION ANALYSIS METHODS

The Decision Analysis concepts of a Strategy-Generation Table, Influence Diagrams, Decision Basis, and Decision Tree were introduced in section 4.1.1. In this section, I discuss the methods to process and reason about these DA representations, and explain why these methodologies are not readily extensible to support the scope of my research.

Howard (1988) suggests that a Strategy-Generation Table (an example is shown in section 4.1.1) is the most important idea in creating alternatives, in that a total strategy can be specified by selecting among decisions in each of specific theme areas and linking them to form an alternative. Based on my assessment, the Strategy-Generation Table is valuable for laying out options in support of AEC decision-enabling tasks. However, it should be elaborated to detail the interrelationships between the options, provide additional information pertaining to the options and allow additional breakdown of choices (e.g., a set of options within an option). A strategy-Generation Table can bypass these elaborations in decision scenarios where an analyst or a decision maker can master all these interrelationships by oneself. But this is rarely the case in AEC decision making. First, the knowledge about interrelationships between particular options is often dispersed among the many AEC professionals. Second, this knowledge often cannot be documented and pre-determined all at once. Therefore, an explicit elaboration will allow more stakeholders to understand the interrelationships among the stakeholders at different points of the decision process. Meanwhile, all the decisions (which are options in the terminology of my research) that make up an alternative in the Strategy-Generation Table are either peers or are not related to one another. In decision analysis, choices are only available at the alternative level; there is no distinction between options and alternatives. In other words, there is only one tier (or level) of detail (e.g., four dividend options, figure 11 in section 4.1.1). This does not support the many levels of detail and hierarchies needed to break down an AEC decision scenario (e.g., the DBS of TC#2 as illustrated in Figure 15 in section 4.3). For instance, in one hierarchy, a structural designer offers the options between structural steel and concrete; in a secondary level of detail, he/she can choose between precast concrete or cast-in-place concrete; under another hierarchy, an architect may also specify different material choices, that will also lead the decision towards precast or cast-in-place concrete. Therefore in the AEC context, a Strategy-Generation Table is not informative or flexible enough to support stakeholders in completing AEC decision-enabling tasks.

Another key factor limiting the applicability of DA methods in AEC is the separation between the generation and evaluation of alternatives. In DA, alternatives must be identified and represented in a binomial decision tree before a stochastic evaluation method can be applied. However, in AEC decision making, alternatives are seldom ready for fixation and the same applies to its many criteria, options, and coupling of options. Given the heterogeneous and evolutionary nature of AEC decision making, it is difficult to clearly frame a set of alternatives for selection. There are often additional ideas to be incorporated, better design and construction plans that may generate a ripple consequence to other decision information. Therefore a more integrated method is needed to bridge the generation and evaluation of alternatives to support the dynamic and evolutionary nature of AEC decision making. Furthermore, my assessment is that offering a method to better manage decision information will assist the AEC stakeholders more than introducing them with another variable—probability.

Probability encoding is the process of extracting and quantifying individual judgment about uncertain quantities (Spetzler and von Holstein, 1972). It transforms a decision maker's (or a group of decision makers') attitude towards risk (or risk preference) into the assignment of subjective values to possible outcomes. Through judgment and interviews, the process of probability encoding generates a series of probability distributions to represent each of the many decision variables. The goal of this statistical (i.e., stochastic) approach is to allow decision analysts to evaluate the decision objectively and determine the optimal course of action based on the decision makers' subjective set of value judgments. However, psychology research shows that decision makers are not necessarily fluent in communicating their risk preference values through a normative procedure of probability assignments. The stochastic approach is subject to human biases and heuristics under uncertainty (Tversky and Kahneman 1974). Howard (1983) notes that the mistakes of assigning probabilistic logic become almost unavoidable when the problem is complex. Decision analysis theorists use influence diagrams to assess the relevance and influence in conducting logic checks. However, as I discussed in section 4.1.1, influence diagrams are valuable in communicating knowledge ideas, but are not specific enough to inform about AEC decision information and its interrelationships.

Since the decision context in the AEC industry is more normative, an explicit documentation of decision information may amend the limitations associated with a relatively more

subjective probabilistic approach. In other words, a dynamic management of an explicit representation of decision information may be more effective in promoting AEC decision making than incorporating another dimension of variable (i.e., probability assignment) into the problem. Rather than extending the stochastic method in formal Decision Analysis, my research promotes the methods that allow stakeholders to complete decision-enabling tasks in ways that are informative, flexible, resumable and fast (e.g., focus on managing the decision information available to them, uncovering the missing information or interrelationships, improve the options and their coupling into alternatives, and integrating the generation and evaluation of alternatives, etc.).

The discussion about the inflexibility and limitations of formal Decision Analysis was exemplified by Popper et. al. (2005) in a recent article in *Scientific American*. The authors suggest that formal methods of decision analysis that use mathematical models and statistical methods to determine optimal courses of action do not provide the flexibility and broad perspective that is needed to deal with the world's most pressing environmental, health, and social problems. The criticism that the models "force people to select one among many plausible, competing views of the future" also matches the criticism by Barrett et. al. (1999)'s about a "decision cage" in the building industry. Popper et. al. suggest that "the computers have to be used differently" and strive for a flexibility to work around traditional predict-then-act methods. My research aligns with their theme as I strive to offer an alternative-generation and evaluation method that combines prediction and action in parallel with the dynamic and evolutionary AEC decision process.

While established methods in Decision Analysis are not fully tailored for the heterogeneous and evolutionary nature of AEC decision making, section 5.1.2 explores the point of departure associated with computer methods in Virtual Design and Construction.

5.1.2 VIRTUAL DESIGN AND CONSTRUCTION-BASED COMPUTER METHODS

Since VDC theory offers methods to generate, integrate, and manage heterogeneous decision information, it serves as another logical point of departure for my research. However, these methods contribute to the homogenization of decision information (section 2.8), adversely limiting the capability of decision support tools to manage decision choices in the completion of decision-enabling tasks. Consequently, decision-enabling tasks such as

evaluation and re-formulation of alternatives must be conducted sequentially with VDC methods.

Section 4.1.2 presents that representations of decision information in virtual design and construction take place within the native formats of domain-specific applications (e.g., AutoDesk Architectural Desktop for product representations and Microsoft Project for process representations), which can be translated for representations in cross-disciplinary data models and standards (e.g., the IFC, xml, and CIS/2). While these representation models do not support the formal representation of choices (section 4.1.2), the same limitation applies to the integration methods in current VDC approaches. Integration methods focus on integrating discipline-specific P, O, or P models into integrated product-process or process-organization models. However, these methods do not offer formal solutions for managing options or alternatives in support of decision-enabling tasks.

State-of-the-art virtual design and construction (VDC) integration methods treat each alternative as a set of pre-coupled options by interlinking information views from different disciplines (e.g., integrated product and process view such as a 4D model). Such linkages have the potential to contribute to a balanced representation (e.g., balancing the emphasis on P, O, and P views) and thus comprehension of a particular decision alternative, e.g., in the Interactive Workspace environment (which I discuss in the following paragraph).

Examples of interdisciplinary visualization or simulation applications include Common Point 4D (CP4D), which integrates product and process models, and ePM SimVision (SimVision), which integrates process and organization models. Given alternative POP models from discipline-specific applications, CP4D has to create new 4D models for new alternatives while SimVision has to start new cases. The implication of these dispersed and isolated formulations of alternatives lies in the completion of decision-enabling tasks during the evaluation and iteration phases of AEC decision making (see section 6.2.3 and 6.2.4). The dispersal of decision alternatives and their lack of integration make it difficult for one to query, explain, evaluate, and mix and match alternatives in an evolutionary decision process. Decision makers and facilitators conduct evaluation of alternatives with a macro (i.e., high-level) focus at the alternative level, through tables and spreadsheets that neither communicate the interdependency of the decision options and alternatives well, nor allow a hierarchical investigation into the details or performance predictions at the option (i.e., micro

detail focus) level. Similarly in the case of SimVision’s “executive dashboard”, the evaluation table only provides data for the aggregated alternatives at a macro level.

As multiple POP models are becoming more readily available, the need to balance multi-stakeholder views and automate the inter-linkages of cross-disciplinary information has led to the iRoom research. Prior research in the interactive workspace (iRoom) by Johanson et. al. (2002), Fischer et. al. (2002), Schreyer et. el. (2002), and Kam and Fischer (2003) demonstrate that decision makers and technical consultants can leverage the advancement of information visualization methods to balance POP views across various disciplines (Figure 20). This enables decision facilitators to complete decision-enabling tasks that contribute to decision briefing, but not iteration. As a later validation case study demonstrates, there is still a need to build a formal method that organizes multiple POP models and views to help explain and retrieve information in the iRoom (see decision-enabling task #8 in section 5.3).

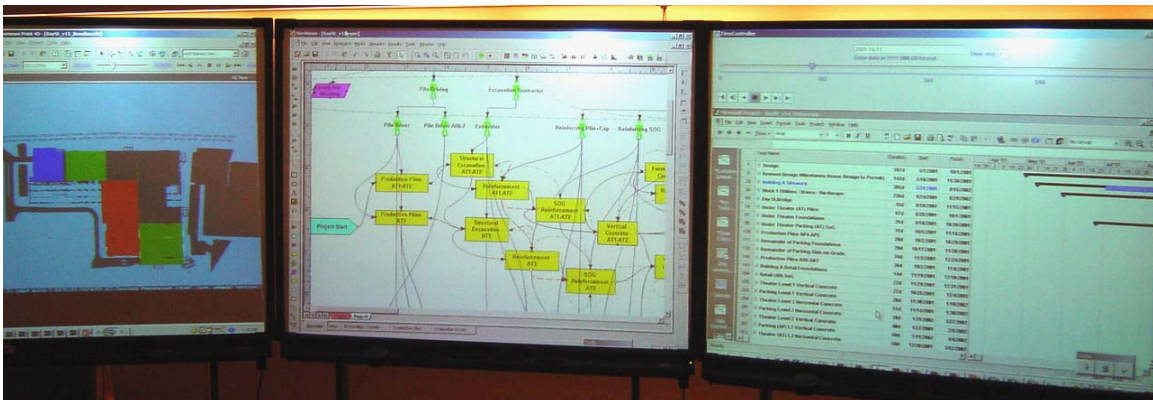


Figure 20. Product, Organization, and Process (POP) models are displayed in the left (product), middle (organization and process), and right (process) screens in the CIFE iRoom, which supports the automatic cross-referencing of decision information across different screens by a common set of names and date format.

Kunz and Fischer (2005) introduce a method for building an integrated project model—the POP model—that integrates the formal representations of the function, form, and behavior (FFB) of the project product, organization, and process (POP). They describe that the objectives of the POP model are to identify the POP resources that will require the greatest cost, effort, or schedule early in the design process and to enable consistent modeling of the POP elements in the associated POP models. They advocate that the integrated model should balance its P, O, and P levels of detail, such that Level-1 and Level-2 models (section

4.1.2) can be defined in early project phases. Because this approach contributes to the consistency in breaking down the P, O, P, into Product Breakdown Structures, Organization Breakdown Structures, and Work Breakdown Structures, the value of the POP model lies in its definition and coordination of the shared data across these PBS, OBS, and WBS. Kunz and Fischer suggest that methods such as consistent naming, referencing, and explicit representation in a shared data model (e.g., a spreadsheet) are keys to the development of an integrated POP model.

My research supports the concept of an integrated FFB-POP project model while I am injecting a set of methods to formally incorporate and manage FFB choices in POP. Existing methods and theories do not explicitly explain how a POP model can incorporate different functions (e.g., different budget and milestone combinations), different forms (e.g., different product designs, organization compositions, etc.), and different behaviors (e.g., different predictions pertaining to the life-cycle cost or productivity impacts of a particular design). In addition, my assessment of the industry test cases is that in AEC decision scenarios, choices often involve POP breakdown across different levels of detail (e.g., a decision scenario such as Test Case #1 in which the breakdown of Product decision topics requires a finer level of detail than that of its Organization decision topics). Hence, my formalization of a dynamic methodology supports the building of a Decision Breakdown Structure for the purpose of incorporating hybrid levels of detail that are needed to represent and manage a specific decision scenario. Meanwhile, my research also further formalizes the association of different POP elements. While the POP model relies on consistent names and the modeler's discipline to make references in the data model (Kunz and Fischer 2005), my research offers a set of specific and explicit relationships that enable the linkages of POP elements as well as their choices.

In a nutshell, existing VDC methods focus on the generation, integration, and maintenance of P, O, P, F, F, and B, but not their choices. Choices are not formally supported by the methods in all three types of VDC modeling that I described in this section: (1) discipline-specific product, organization, and process modeling, (2) inter-disciplinary product-process and process-organization modeling, as well as (3) integrated project model, i.e., the POP model. Existing theories do not detail the methodology to manage decision information and its interrelationships in support of AEC decision-enabling tasks. Whether a decision alternative only involves changing a particular option of form or changing a number of

options in form, function, or behavior, current methods still require one to re-create a new POP-FFB representation to describe the new alternative. Existing theories do not provide a formal solution to decouple an alternative, to mix and match, and to evaluate different options. As a result, decision-enabling tasks such as evaluation and re-formulation of alternatives are conducted sequentially. This adversely affects the availability of a good information basis and the ability of the decision makers to make quick and informed decisions.

5.1.3 OTHER AEC-BASED COMPUTER METHODS

In addition to DA and VDC methods, other AEC-based methods also focus on the generation, integration, and management of P, O, P, F, F, and B. Hence, they serve as another point of departure for my assessment of applicable computer reasoning methods in managing AEC decision information. As in the case of VDC, these theories do not specify how choices can be formally incorporated. However, their methodologies (e.g., object-oriented modeling, critical path methods, etc.) to manage and process AEC information with computer-based methods are additional and extensible points of departure for my research.

The Critical Path Method is based upon a diagrammatic network, a graphical project model that represents the job activities and their mutual time dependencies (Clough et. al. 2000). As in the cases of other intra-disciplinary applications (e.g., design or cost), a schedule represents the best thinking and knowledge about the criteria of the decision makers available at the particular time of planning. In formulating a CPM schedule, one can iteratively correct, refine, and improve the project plan (Clough et. al. 2000). Moreover, one can be uncertain about an activity by introducing slack or probability distribution (e.g., the Program Evaluation Review and Technique procedure). Based on my literature review, project planning literature does not support any formal inclusion of project alternatives in the same model. However, the method to propagate schedule information such as dates and durations based on CPM relationships is an extensible point of departure for managing the AEC Decision Ontology (e.g., to propagate attributes across different ontology elements based on their connecting ontology relationships).

Similar to the probabilistic phase of Decision Analysis, there is an extensive list of both automated and manual problem-solving optimization research in the field of AEC and

beyond, such as neural network modeling (Lu 2002), linear programming and integer programming (Burns et. al. 1996), pairing and weighted ranking approach (Kamara et. al. 2002), and the Analytic Hierarchy Process (Saaty 1990). These approaches focus on a particular area—the analysis phase (i.e., evaluation, see section 6.2) of AEC decision making. They offer to optimize the generation or selection of the best alternative given predetermined sets of parameters, options, alternatives, relationships, and criteria. There has been less research on detailing or formalizing the flexible and fast definition, formulation, and iteration of such sets of parameters, options, alternatives, relationships, and criteria, all of which are prerequisites for optimization. Therefore, my research acknowledges this body of existing work (in stochastic modeling, optimization, pairing, ranking, etc.) but focuses on the dynamic management of decision information that is often assumed to be pre-determined in existing research. Because there is a potential contribution to bridge my research in managing decision information and such existing work, I list potential bridges as a topic for future research in Chapter 7,

Froese (1992) experiments with object-oriented data models to support the representation and communication of project management data. Using basic object characteristics such as attributes, hierarchies, and inheritance, the data model becomes the foundation for Froese's general domain model and project model for project management and construction. The domain model is equivalent to a schema or ontology, which specifies the hierarchy and relationships among product models, process models, resource models, and organization models. Froese's work demonstrates the value of object-oriented modeling in the representation, structuring, and manipulation of project management data. Decision information and project management data are both similar in their heterogeneity, specifically, the need to process heterogeneous project management information (e.g., time, cost, product, process, organization, and resource, etc.) is similar to the need to handle heterogeneous decision information (e.g., topic, option, alternative, criterion, attribute, etc.) in AEC decision making. Hence, the object-oriented modeling approach is an extensible point of departure for my research. It contributes to a formal and flexible method to represent and manage heterogeneous decision information in ways that are more powerful, repeatable, and consistent than with current practice.

Concluding the three subsections in section 5.1, existing theories (e.g., Decision Analysis, optimization, pairing, and analytic hierarchy process, etc.) isolate information between

decision formulation and evaluation, which relies on logical stochastic modeling or pairing to come up with decision recommendations. Based on my observations of the characteristics of AEC decision making gathered from the industry test cases, these methods do not fit well in solving the information management needs in AEC decision making. Although AEC methods (e.g., VDC, CPM, etc.) do not address the management of choices and their interrelationships, their computer-based reasoning methods (e.g., object-oriented modeling) offer points of departure for my formalization of dynamic methods in supporting the completion of AEC decision-enabling tasks.

5.2 CONTRIBUTION #2—DECISION METHOD MODEL (DYNAMIC DBS FOR DECISION-ENABLING TASKS)

Based on AEC computer-based reasoning methodology, my second contribution is a Decision Method Model (DMM). The DMM is a set of methods that formalize an array of computer-based reasoning methods to process information that are formally represented by the AEC Decision Ontology. Targeting the decision-enabling tasks identified from the industry test cases (sections 2.1-2.4), the DMM developed in this doctoral research is not meant to cover every single decision need exhaustively. The key of the contribution is to establish a proof-of-concept that formalizing a set of dynamic methods, which tailor to the characteristics of AEC decision information and the AEC decision-making process, can empower AEC stakeholders to manage decision information in ways that are more consistent and valuable (i.e., flexible, fast, more informative, and resumable) than generic decision-support methods.

Per the aforementioned scope, the DMM is composed of 6 base methods and 4 composite methods (Figure 21). While my first contribution defines the basic types of decision information and interrelationships that can be combined to form a DBS; this contribution illustrates that there are certain discrete methods (i.e., base methods, which define the reasoning mechanisms and processes to apply the AEC Decision Ontology) needed to perform a particular decision-enabling task. This contribution also presents the concept that even though specific decision-enabling tasks may involve different decision needs (section 5.3), decision facilitators only need to apply different combinations (i.e., composite methods) of the same pool of base methods when completing these tasks under the Dynamic DBS approach.

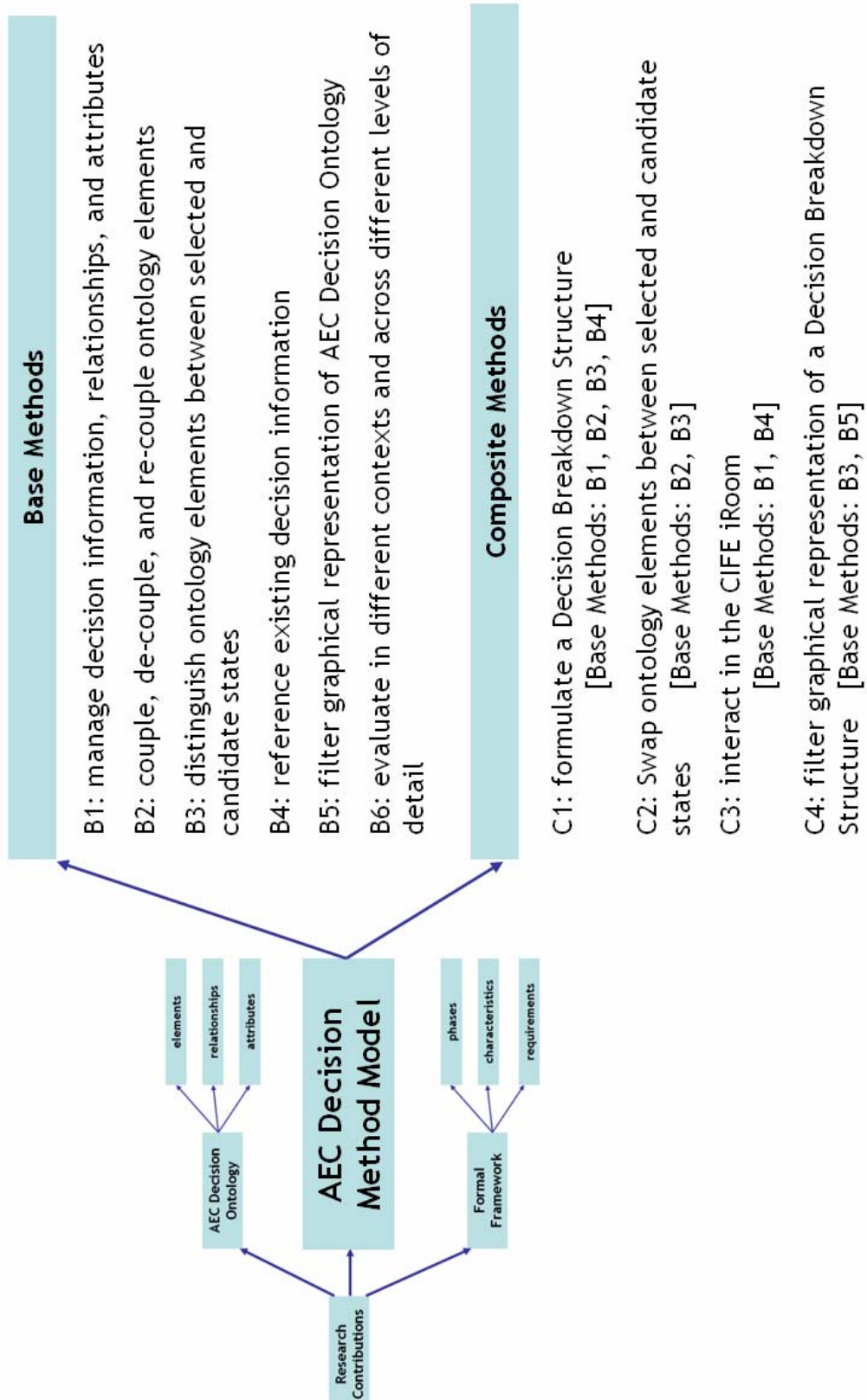


Figure 21. The AEC Decision Method Model provides a dynamic methodology for AEC decision facilitators to perform decision-enabling tasks with the AEC Decision Ontology.

I have developed the DMM upon the AEC Decision Ontology and have implemented it in the Decision Dashboard prototype. In the following sections, I present the 6 base methods and 4 composite methods in the current DMM, along with their associated method features. Method features are the unique functional characteristics pertaining to each of the base and composite methods in the DMM. They are the functional and performance objectives (e.g., to propagate interdependent decision information or to evaluate competing choices); I have formalized ontology-based computer reasoning methods to accomplish them. In other words, a method feature aligns a particular information management need (arisen from a decision-enabling task) with an ontology-based reasoning method.

5.2.1 BASE METHODS

B1: MANAGE DECISION INFORMATION, RELATIONSHIPS, AND ATTRIBUTES

Method Overview

My analysis of current practice (sections 1.3, 2.7, and 2.8) explains the needs to properly represent decision information and categorize its types and relationships. This base method includes a number of method features that allow decision stakeholders (e.g., owners, professionals, etc.) to manage—that is, to generate, assign, populate, organize, propagate, query, edit, reorganize, duplicate, archive, and/or delete—AEC Decision Ontology elements, relationships, and attributes with the DD (Figure 22). The following subsections explain how these method features support the realization of the AEC Decision Ontology in a computer environment. In essence, this base method facilitates an explicit representation and organization of level-1 decision information and its associated knowledge (e.g., knowledge of ripple consequences among options). Its method features (e.g., populate, propagate, reorganize) provide an object-oriented computer modeling foundation for other reasoning methods in the DMM.

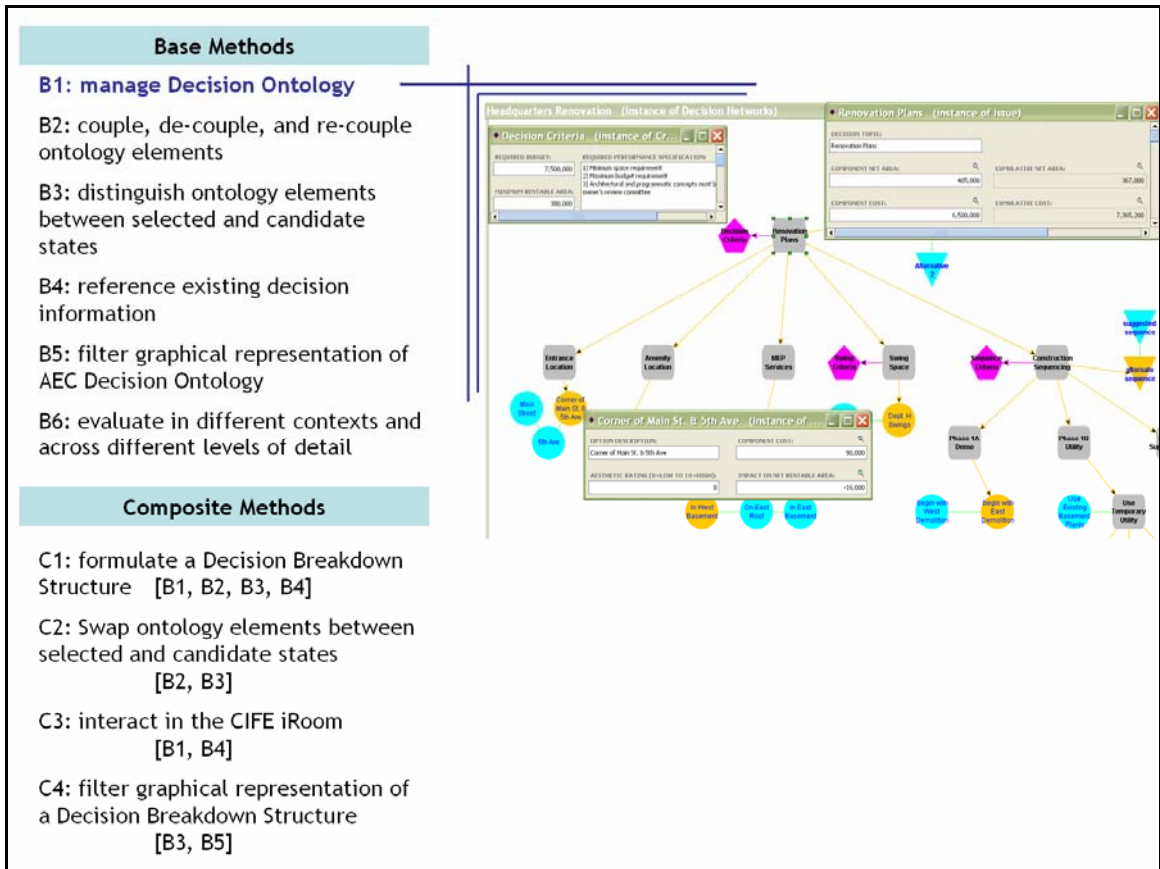


Figure 22. DMM Base Method B1 enables decision facilitators to create and populate instances of ontology elements and relationships, while associating them with Level-1 decision information that can be propagated within the Decision Breakdown Structure.

Method Feature—Generate (elements, relationships, attributes)

The ontology elements and relationships (section 4.2) are incorporated as the core components in the DD prototype. Based on the decision information present in the four industry test cases, I have generated over 30 AEC-specific Level-1 attributes in the DD (section 4.2.3). Such attributes can be assigned to ontology elements or relationships, both of which are discrete objects within the object-oriented computer environment of the DD. When DD users find it necessary to generate new attributes for one or multiple elements or relationships (i.e., computer objects), they can use the method feature “generate” to create new attributes in the DD, assign them with appropriate forms (e.g., text field, integer, etc.), and associate these attributes with the relevant ontology elements or relationships.

Method Feature—Populate (element) and Organize (relationships)

Once DD users have generated and configured their desired attributes in association with the relevant ontology elements or relationships, they can populate (i.e., instantiate) specific element instances in the DD to represent particular topics, criteria, options, and/or alternatives. For each ontology element (e.g., topic), DD users can populate as many instances as necessary to build a DBS. Once DD users have populated instances of ontology elements in the DD, they can organize the element instances with ontology relationships. When populating instances of an ontology relationship (e.g., aggregate, choice, etc.), DD users have to follow the semantics of the DBS (section 4.2) and ensure that each relationship instance is connecting two ontology elements. The DD recognizes the originating as well as the target instances and allows users to select the type of relationship (e.g., aggregate, choice, etc.) that goes between the instances. Within the DD prototype, each element or relationship instance is its own computer object. Though different instances may inherit the same ontology behaviors (as defined by the “Generate” method feature), each instance may carry its unique set of attributes (e.g., topic names, cost, etc.). In essence, this method feature allows DD users to populate as many instances of ontology element and relationship as necessary to formally represent the decision information pertaining to a decision scenario.

Method Feature—Modify (elements and relationships)

Once DD users have populated ontology elements or relationships, they may modify those instances from one element/relationship type to another (e.g., modify an element instance from decision topic to an option, modify a relationship instance from aggregate to choice, etc.).

Method Feature—Assign (attributes)

I noted that the DD test cases had over 30 AEC-specific attributes to support the test cases in my research (section 4.2.3). DD users can generate new attributes as necessary for a decision scenario. Whether DD users adopt existing attributes or generate new attributes, they may assign attributes to any ontology element or relationship. An attribute may be assigned to one or multiple element(s) and/or relationship(s); an ontology element or relationship may hold one or multiple attributes. This flexibility

allows DD users to customize the association of attributes with an ontology element or relationship, so as to enhance the information management capability of the DBS.

Method Feature—Query, Edit, and Operate (attributes)

To query or edit the current value of an instance’s attributes, DD users can use the “Edit” method feature in the Dashboard Panel to bring up the attribute form, read the attribute values, and make necessary changes. In addition, the “Operate” method feature allows DD users to perform basic calculations within an instance (e.g., an instance holds an attribute with area information, DD users can enter a rental income per area value to calculate the rental income). Based on the industry test cases and their particular decision-enabling tasks, the DD offers two types of calculations in its current form. First, an attribute can operate (add, subtract, multiply, and divide) with a floating number that DD users can define (e.g., projected rent per square foot). Second, an attribute can operate with another attribute within the same instance (e.g., divide attribute “increased first cost” by attribute “annual savings” to obtain the simple payback).

Method Feature—Propagate (attributes)

To overcome the risk of data re-entry and to automate recurring needs of information processing as observed from the industry test cases (e.g., when dealing with ripple consequences), this method feature automates basic propagation of attribute values across a specific set of ontology elements that are appropriate for the DBS. I have designed the following three propagation method features, which propagate attribute values across particular chains of ontology relationships:

(1) Propagation of attribute values of elements connected by aggregate relationships

The DD has component and cumulative attributes. Component and cumulative attributes must be numerical (integer or float); examples include cost, area, rental income, savings, payback, and productivity gains, etc. When two ontology elements are connected by an aggregate relationship, all attributes that have labels beginning with the text “component” (e.g., component cost) in the “aggregated” element are propagated to the target “aggregating” element. The “aggregating” element has “cumulative”

attributes, which sum up all the “component” attributes from itself and from its “aggregated” elements sharing the same attribute names. The propagation will be automatically updated whenever an “aggregated” attribute is updated. Hence, DD users can query an “aggregating” element and remain informed about the cumulative impacts from the “aggregated” elements.

In TC#1 for instance, if the “building modernization” topic is connected to the “system upgrade” topic by an aggregate relationship, then “building modernization” is the aggregating ontology element and “system upgrade” is the aggregated element. When the “component cost” attribute in “system upgrade” is updated, the “cumulative cost” in “building modernization” will be automatically updated with this propagate method feature.

(2) Propagation among elements connected by impact relationships (Quantitative Ripple Effects)

This feature takes into account the affects of impact relationships on specific pairs of element instances. In an impact relationship, attributes with labels beginning with the text “component” (e.g., component cost) may have influence on the “cumulative” attributes in its target element instance. However, the influence would only come into effect when the originating and target element instances are in selected states (see DMM Base Method B3 in the upcoming subsection). Depending on the nature of the influence, this impact value may be positive or negative, and in turn, the impact would affect the value of the target attributes accordingly.

(3) Propagation among elements connected by precedence relationships

Similar to the above method feature (2) on propagation, this feature applies to process relationship instances to support basic Critical Path Method (CPM) calculations. Specifically, this is a temporal propagation of date and duration attributes across element instances connected by precedence relationships. Similar to the two aforementioned propagation concepts, there are “component” and “cumulative” attributes for dates and durations. The “component” attributes of start date, finish date, and duration capture the temporal information from a specific element instance (e.g., decision topic instance, option instance, etc.). When this particular element instance is connected to another element instance through a precedence relationship instance, the

“component” start date of the successor element instance is computed by adding the lag (which may be positive or negative and is an attribute unique to the precedence relationship, see section 4.2.2.5) to the finish date of the predecessor element instance.

In addition, this propagation feature enables the DD to incorporate the concept of a Hammock Activity in the CPM (Clough et. al. 2000). When a chain of such precedent instances are present to connect a series of ontology elements, the overall (i.e., cumulative) start date of these instances’ parent decision topic is the “component” start date of the first element instance in the chain. The parent decision topic takes the “component” finish date of the last element instance in the chain as its overall (cumulative) finish date. The DD calculates the overall duration attribute in this parent decision topic by finding the difference between the latest finish and earliest start dates. If there are multiple precedence elements connecting to a successor element, the successor element’s instance takes the critical path propagation as the basis of its “component” start date.

Method Feature—Duplicate and Archive (elements)

In DD’s Dashboard Panel, there is a function to duplicate a user-selected element instance. This duplication method feature also allows DD users to archive element instances, in which decision rationales, history, and assumptions, etc. can be archived together as attributes of the instances.

B2: COUPLE, DE-COUPLE, AND RE-COUPLE DECISION INFORMATION

Method Overview

My analysis of current practice (sections 1.3, 2.7, and 2.8) explains the need for decision facilitators to couple and decouple decision information across different levels of detail with flexibility (e.g., area information in TC#1). My literature review identifies project management theories that support the coupling, but not de-coupling or re-coupling, of decision information. By formalizing a method to manage the states and types of decision information based on its ontology elements and relationships, this base method allows decision stakeholders to couple (i.e., to combine independent

decision information as an integrated combination), de-couple, and re-couple instances of ontology elements.

Method Feature—Couple

Coupling can only originate from decision topics (Figure 23 Left) or alternatives (Figure 23 Right). In either case, coupling offers a top-down order to couple the targeted elements (e.g., topic, criterion, alternative, option, to which the coupling is targeted) as the coupled children of a topic or alternative (from which the coupling is originated). Meanwhile, the DD propagates instances' attributes from the bottom up through the coupling chain. Utilizing the “aggregate” relationship in the AEC Decision Ontology, DD users can achieve coupling, de-coupling, and re-coupling method features with element instances. Decision information (or specific ontology elements such as decision topics, alternatives, and options) that is connected by “aggregate” relationships represents a hierarchical coupling relationship within the information. A chain of “aggregate” connections represents an active state of a recommended information set.

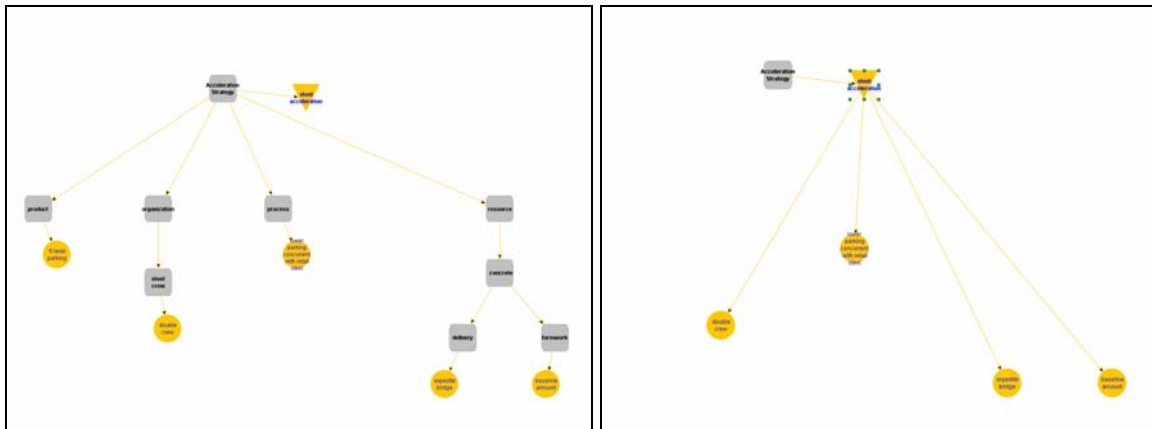


Figure 23. Examples of coupled decision information from the DBS in TC#4. Left: coupling originates from decision topics that help form a hierarchical DBS. Right: coupling originates from alternative that explains what micro decisions (i.e., option selection) are entailed in an alternative.

Method Feature—Decouple

A coupled chain of ontology elements (e.g., topic “Entrance Location” and option “Fifth Ave” that are coupled by an aggregate relationship) can be decoupled either by discarding the aggregate relationship connecting the subject element instances or by changing the target of an aggregate relationship to another ontology element instance (e.g., change the target of the aggregate relationship from the options “Fifth Ave” to “Main Street” and thus, forming a new coupling between “Entrance Location” and “Main Street.”). Depending on the states of the individual chain instances, the bottom-up propagation may or may not channel to the top-most decision topic. In the event that a parent decision topic or alternative instance in a chain is decoupled from its parent instance (i.e., no longer connected to its parent by an aggregate relationship), the bottom-up chain will turn idle and be isolated as a candidate chain from the current recommended decision structure.

B3: DISTINGUISH DECISION INFORMATION BETWEEN SELECTED AND CANDIDATE STATES

Method Overview

My analysis of current practice highlights the importance for decision makers to be informed about the decision choices and the needs to preserve seemingly invalid options (while differentiated from the recommended ones). My literature review explains that current AEC and VDC theories often equip stakeholders with methods (e.g., PERT) to consider the uncertainty associated with decision attributes (e.g., duration), but not discrete decision options (e.g., to build sequentially or concurrently). Hence, stakeholders often lock in to decision options and prematurely discard seemingly invalid options that may become valid again as the decision context evolves. In DA theories, the method to select among choices is strictly associated with the stochastic modeling and evaluation. This base method formalizes how facilitators manage and graphically distinguish the status of decision information throughout the decision-making process with the Decision Dashboard. My research specifies two states—selected and candidate—for all ontology elements (i.e., option, alternative, decision topic, and criteria). Each element is either in an active “selected” state or a dormant “candidate” state. This base method (Figure 24) allows decision stakeholders to distinguish ontology elements between their “selected” states (i.e., active,

recommended, and chosen element from the perspective of their immediate decision topic parent) and “candidate” states (i.e., inactive, not recommended, and not chosen element from the perspective of its immediate decision topic parent).

Method Feature—Distinguish

All ontology elements are either in “selected” or “candidate” states. In the DD implementation, the same ontology element in either state shares the same symbol shapes, attributes, and management properties. A key distinguishing factor between the two states is that elements in the “selected” state are connected to their parent elements by “aggregate” relationships, whereas “candidate” elements are connected to their peer elements by “choice relationships (“candidate” elements do not connect to any parent elements). Therefore, only the attributes in “selected” ontology elements propagate up the chain *per* the aforementioned propagation feature (i.e., propagation of attribute values of elements connected by aggregate relationships earlier in this section).

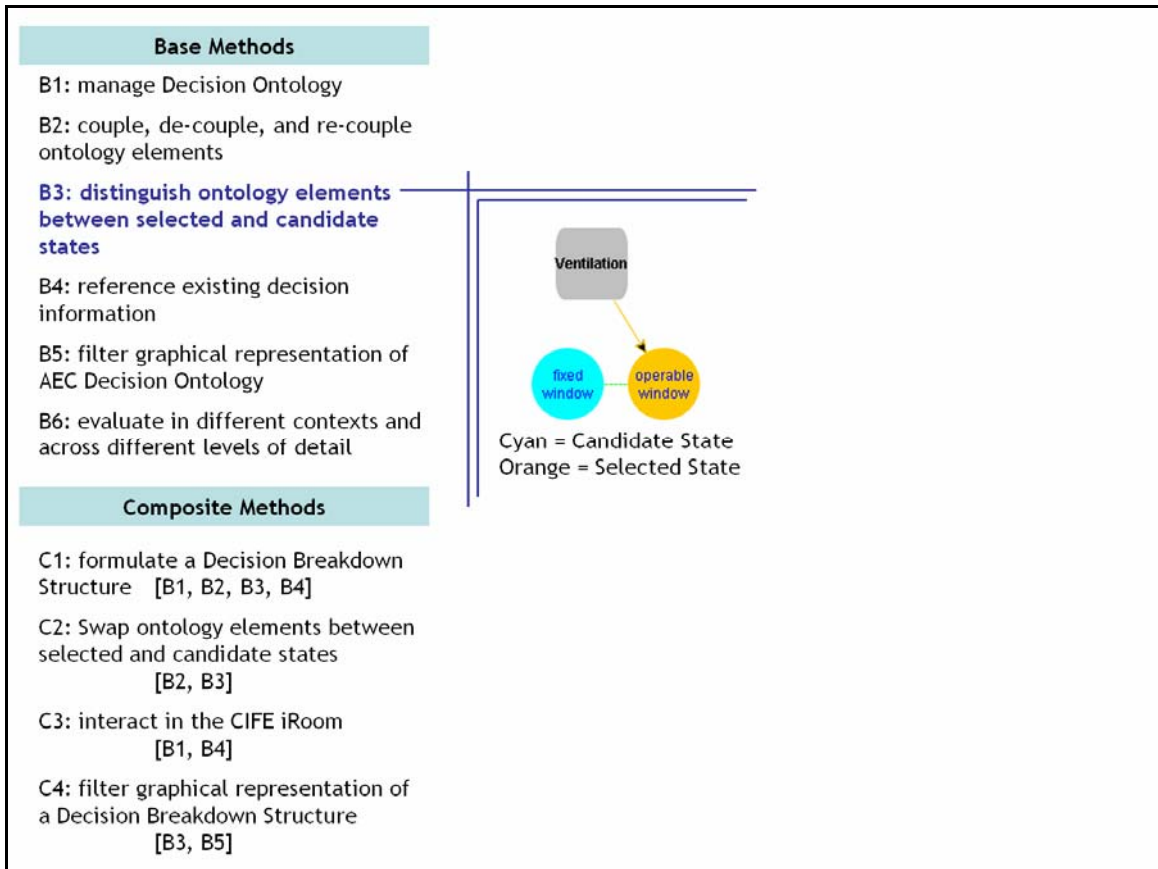


Figure 24. DMM Base Method B3 enables decision facilitators to distinguish ontology elements between their candidate (e.g., fixed window option in TC#2) and selected (e.g., operable window) states based on the ontology relationships connecting them (aggregate relationship between topic “ventilation” and option “operable window, and choice relationship between option “fixed window” and option “operable window”).

B4: REFERENCE EXTERNAL DECISION INFORMATION

Method Overview

My analysis of current practice highlights the importance of informative and fast decision-support as well as the challenge to access the detailed decision information with generic decision-support tools and methods (e.g., access particular product, organization, or process option in TC#4). Limited by their methods to manage decision information, generic decision-support tools in my industry test cases (Chapter 2) require decision stakeholders to replicate (TC#1 and TC#3), re-enter (TC#2), and mentally associate (TC#4) decision information. Such inability to directly reference (i.e., incorporate) and formally associate existing decision information have led to difficulty

when accessing decision information (TC#1 and TC#3), errors in data re-entry (TC#2), and inefficiency when associating decision information (TC#4). Taking the concepts of real-time information access from prior CIFE iRoom research as a point of departure, this base method allows decision stakeholders to make explicit and associative references from ontology elements and/or relationships to external (i.e., not within the DD prototype) digital information (i.e., information available on a personal computer or a computer network) and its native software applications. While decision stakeholders use base method B1 to embed decision information within the DD, they can reference digital decision information external to the DD with this base method.

Method Feature—Reference

In section 4.2, I mention that there are different forms of ontology attributes, which DD users can customize to suit the needs of a particular decision scenario. One of these predetermined attributes allows DD users to specify one or multiple digital reference(s), such as a 3D model file, cost estimate report, schedule file, 4D model file, image file, document, spreadsheet, internet hyperlink, etc. The digital references can point to content available on the same personal computer, within the same local area network, or on the internet. Once a DD user specifies the path of a digital reference, the path is stored as an attribute within the instance of the ontology element or relationship (Figure 25). DD users can apply the query, edit, or delete features (as described in DMM Base Method B1 earlier this section) to manage the reference paths.

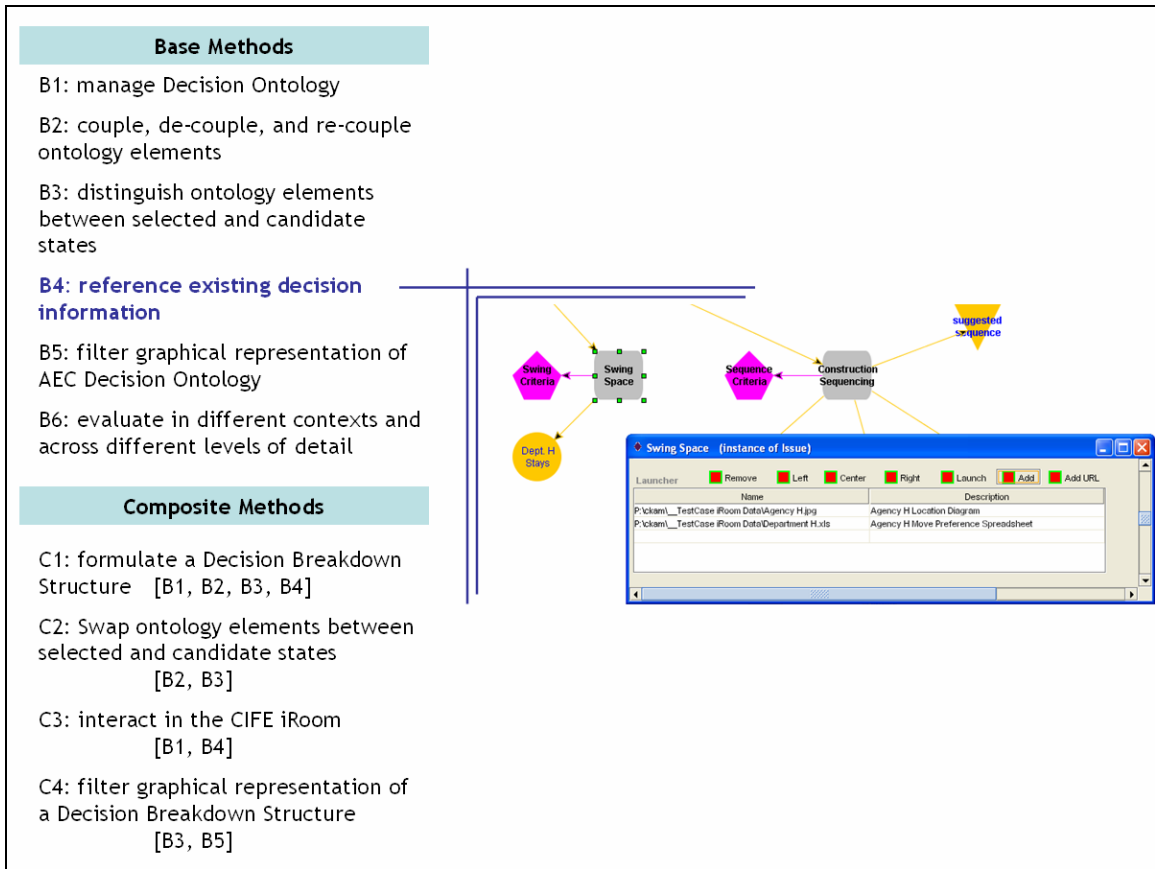


Figure 25. In TC#1, the decision topic "Swing Space" in the DBS references two digital files using the reference method (DMM Base Method B4). This method allows DD users to associate specific decision information with a particular ontology instance.

Method Feature—Launch

In addition to storing the paths of digital references, the DD also allows its users to associate a preferred computer software application with a digital reference. With this one-click launch feature, the DD automatically launches a software application (which has been installed on the same personal computer as the DD) and call up the relevant digital reference file. While DD users can incorporate any computer applications into this feature, the current DD supports automatic launching of the following applications: Microsoft Word, Microsoft PowerPoint, Microsoft Excel, Adobe Acrobat, Note Pad, Microsoft Internet Explorer, Microsoft Project, and Common Point 4D.

B5: FILTER GRAPHICAL REPRESENTATION OF AEC DECISION ONTOLOGY

Method Overview

My analysis of current practice illustrates the limitations of current practice in accessing specific decision information pertinent to an impromptu decision scenario (e.g., Decision-Enabling Task #7 in TC#3, section 2.3). The categorization of ontology elements and relationships in the DBS presents an opportunity for object-oriented computer methods to highlight, isolate, and query decision information in support of a shifting decision focus. This base method allows decision stakeholders to filter the graphical representations of the ontology's elements in the DD graphical window.

Method Feature—Show Elements by Types

When DD users place check mark(s) in one or multiple of the “All Decision Topics,” “Decision Criteria,” “Alternatives,” or “Options” checkboxes and press the “Refresh” button, the DD graphical window will only display the specific types of ontology elements that are being checked. The element instances (in selected and candidate states) appear as discrete symbolic shapes with no visible arrows (i.e., relationships) connecting them.

B6: EVALUATE IN DIFFERENT CONTEXTS AND ACROSS DIFFERENT LEVELS OF DETAIL

Method Overview

My analysis of current practice highlights the importance of dynamic evaluation supports for changing decision foci (e.g., TC#2). This base method allows decision stakeholders to evaluate conceptual elements in both absolute (i.e., with a specific set of criteria) and relative (i.e., among competing choices) contexts. It also allows decision stakeholders to evaluate (in absolute or relative contexts) ontology elements across different levels of detail.

The evaluation tables supported by the following method features are dynamic since they do not have any predetermined contents for their columns or rows. DD users have the discretion to interactively choose or change the contents (e.g., attributes) for evaluation in the three method features discussed below. Sharing this concept of an

evaluation table, the following three method features handle the evaluations across different types of ontology elements differently.

Method Feature—Evaluate Competing Choices (Relative Context)

This method feature applies to the “decision topic” ontology element, which has an attribute in the form of a dynamic and interactive evaluation table that is available in each decision topic instance (Figure 26). This evaluation table allows DD users to compare competing choices associated with a decision topic. Such choices may be competing options (e.g., entrance locations A and B), competing alternatives (e.g., renovation alternatives 1 and 2), or competing decision topics (but not a criterion, which is addressed in the following section); they may be in candidate or selected states.

Base Methods

- B1: manage Decision Ontology
- B2: couple, de-couple, and re-couple ontology elements
- B3: distinguish ontology elements between selected and candidate states
- B4: reference existing decision information
- B5: filter graphical representation of AEC Decision Ontology
- B6: evaluate in different contexts and across different levels of detail**

Composite Methods

- C1: formulate a Decision Breakdown Structure [B1, B2, B3, B4]
- C2: Swap ontology elements between selected and candidate states [B2, B3]
- C3: interact in the CIFE iRoom [B1, B4]
- C4: filter graphical representation of a Decision Breakdown Structure [B3, B5]

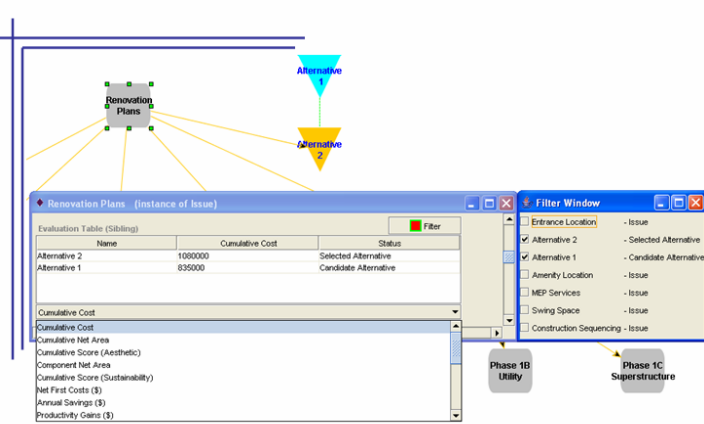


Figure 26. DD users can highlight a particular decision topic ("Renovation Plan" in this illustration) and evaluate its associated alternatives, topics, and/or options ("Alternative 1" and "Alternative 2" in this illustration) pertaining to a specific attribute performance ("cumulative cost" in this illustration).

To come up with the content for the rows in the evaluation table, this method feature follows the aggregate relationship to include the “aggregated” elements that are connected to the decision topic being considered. This method feature includes these directly connected “aggregated” elements as well as their sibling elements connected by “choice” relationships. Hence, DD users can evaluate all competing choices associated with a decision topic element. To better customize the content in the evaluation table, this method also provides a filter button for DD users to filter out particular ontology element types or instances. For instance, DD users can focus only on competing options and not competing decision topics under a particular decision topic element. Once DD users come up with the appropriate rows in the table, they can generate the column by choosing which attribute to show with a drop-down menu. DD users can customize each evaluation table differently from one decision topic instance to another instance. The customized table is saved by the DD and can be brought up in future queries. This method feature is significant because it allows decision facilitators to dynamically customize their desired view of decision information in real-time. Thus, this method feature supports flexible evaluation of competing choices during the evolutionary decision-making process.

Method Feature—Evaluate Functional Requirements (Absolute Context)

During synchronous decision review meetings (e.g., the design review meeting as part of the motivating case study in section 1.2), decision makers are often interested in validating the competing proposals (e.g., design alternatives of a building and options for a room) against the functional requirements (e.g., overall spatial program of a building and specific programmatic requirements of a room). Using static decision-support tools (e.g., a paper-based report with pre-determined table), facilitators often lack the means and methods to provide informative responses to decision makers (e.g., motivating case example in section 1.2). In the DMM, the Dashboard Panel offers a dynamic and interactive evaluation table for comparing choices against functional requirements. This evaluation table shares some method features with the evaluation table designed for the relative context explained above, such as filtering and bringing up “aggregated” and its competing choices. However, the difference is that this evaluation table, available in the Dashboard Panel in the DD, also incorporates the criterion element for consideration.

This method feature allows DD users to first select the attribute to be evaluated from the decision choices, followed by the selection of the criterion's attribute against which the first attribute is evaluated. In addition, DD users can specify one of three available constraints—larger than, equal to, or less than—to enforce the absolute requirement between the choices and the criterion. To graphically enhance the evaluation of the table, this method feature also assigns a green/red color status for evaluation content that satisfies/fails the constraint condition.

Method Feature—Evaluate Across Macro, Micro, and Hybrid Levels of Detail

Motivated by my observation from industry practice (decision-enabling task #6 in section 2.2.2) that it may be necessary to evaluate decision information across different levels of detail, I have formalized this method feature. This method feature complements the two evaluation method features above to provide additional flexibility for DD users to evaluate competing choices or functional requirements across different levels of detail in a dynamic manner. First, the Dashboard Panel's evaluation table for the absolute context updates the evaluation focus (upon the user's hitting the "refresh" button) by tracking the decision topic instance that the DD user highlights. Thus, DD users can dynamically adjust the focus of the evaluation table from macro decision alternatives and/or criteria to micro decision options and/or criteria throughout the decision-making process. Second, DD users can customize an evaluation table that spans hybrid levels of detail. By default, evaluation tables compare decision choices and criteria at the same level of detail. However, DD users can create a decision topic instance and initiate aggregate relationships targeting element instances in different levels of detail to customize an evaluation table with hybrid content (section 5.3, Decision-Enabling Task #6).

5.2.2 COMPOSITE METHODS

In the DMM, composite methods support the needs of decision-enabling tasks by combining different base methods and their method features. The following sections discuss how different combinations of base methods and their method features can generate four composite methods. The corresponding sets of method behaviors come with these pre-packaged composite methods. Together, the composite methods and their method features

make it easier for AEC stakeholders to leverage the capabilities of the AEC Decision Ontology and different DMM base methods when completing specific decision-enabling tasks.

C1: FORMULATE A DECISION BREAKDOWN STRUCTURE

Method Overview

DD users can use a number of DMM base methods to develop a DBS. This composite method formalizes the incremental and logical sequence DD users might use when developing a DBS. It allows decision stakeholders to formulate (i.e., to express according to specific terms or concepts) a DBS, which consists of decision information and its associated knowledge that are represented as elements, relationships, and attributes (Figure 27). This composite method combines the following base methods:

Base Method B1: Manage Decision Information, Relationships, and Attributes

Base Method B2: Couple, De-Couple, and Re-Couple Decision Information

Base Method B3: Distinguish Decision Information Between Selected and Candidate States

Base Method B4: Reference Existing Decision Information

Method Feature—Formulate a Decision Breakdown Structure

To formulate a DBS, decision stakeholders first lay out their decision needs, the constraints, and the solution ideas in the DD (Base Method B1). They populate instances of decision topic, criterion, and option in the DD graphical window. They label these element instances with appropriate descriptions and incorporate additional notes or ideas as attributes, while documenting the functional requirements as attributes in the criterion instance. Subsequently, the decision facilitators and the professionals (DD users) can group related decision topics and structure the decision topics hierarchically, establishing as many levels of detail (with topics) as necessary to model the decision scenario. At the same time, they can associate the decision criterion and selected (i.e., recommended) option instances with the appropriate decision topics, and thereby connect decision criteria and selected options to the decision breakdown structure as well. These procedures establish the core structure of the DBS.

Once the DD users have established a core structure of the DBS, they can incorporate competing decision criteria, topics, and/or options into the DBS. They can distinguish between these choices and the “selected” states and the “candidate” states (Base Method B3). They can make recommendations by coupling “selected” decision topics, criteria, and options into alternatives (Base Method B2). They can also use duplicate ontology elements for archiving purposes or for facilitating the generation of decision alternatives (Base Method B1).

Formulating a DBS is an iterative process that provides AEC stakeholders a valuable opportunity to document and test the facts and their ideas. Thus, the DD users may modify ontology and relationship instances continually to reflect their best interpretation of the decision scenario (Base Method B1). They can customize the attributes in the ontology elements and relationships, and configure ontology relationships to automate different attribute propagation needs within a DBS (Base Method B1). Once attribute settings are configured, DD users can either enter decision information as attribute values or link element instances to existing decision information external to the DD prototype (Base Method B4).

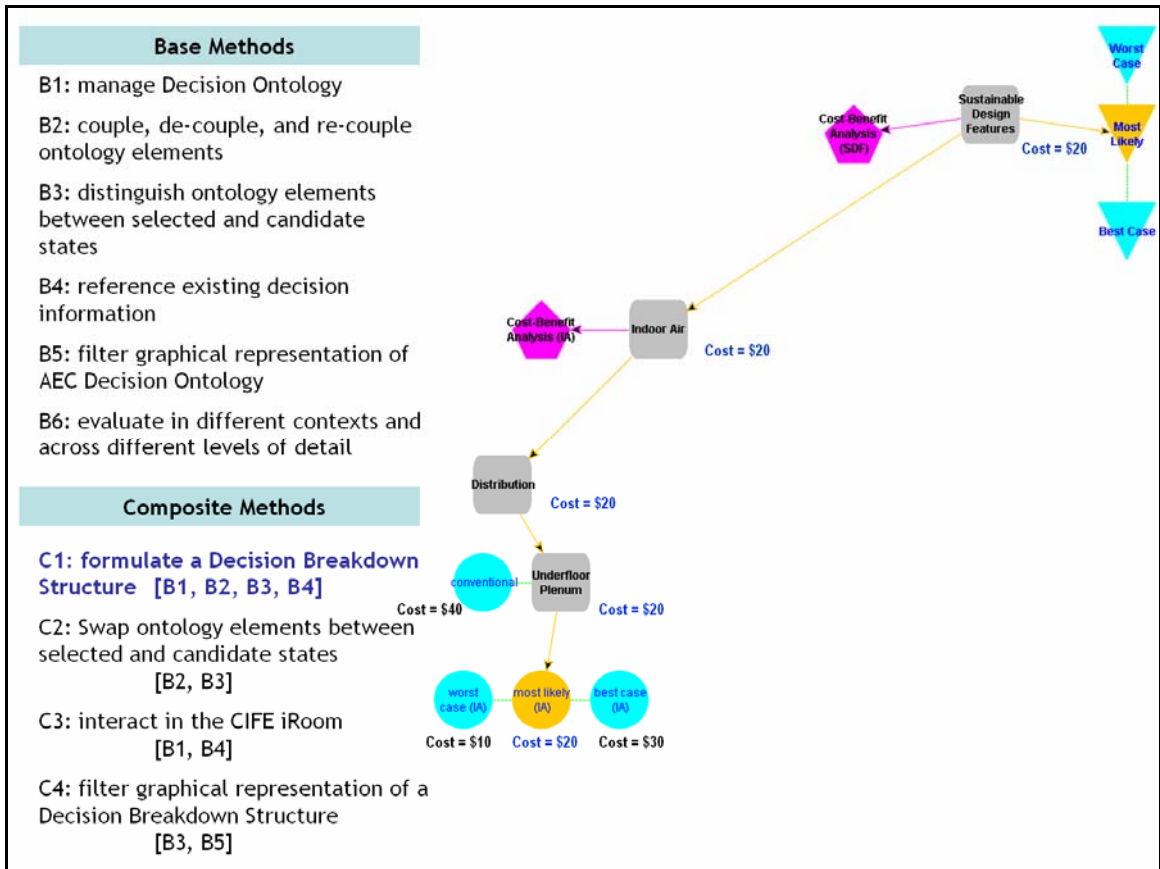


Figure 27. This figure illustrates a partial DBS in which there are 4 levels of details, as evidenced by the presence of four tiers of decision topics connected by unidirectional aggregate relationships. It also highlights the concepts of attribute propagation in the DBS. The attributes of a selected decision option (cost in this example) propagate across a chain of aggregate relationship in accordance to the semantics of the AEC Decision Ontology.

The DD users can enrich the DBS by documenting the ripple consequences and by specifying the temporal dependency among the ontology elements (Base Method B1). With DMM composite method C1, decision facilitators can manage existing and new decision information in form of a DBS in the DD. Decision topics, criteria, options, alternatives, and their interrelationships such as ripple consequences and temporal dependencies can be formally integrated in a DBS to support decision evaluation and iteration.

C2: SWAP DECISION INFORMATION BETWEEN SELECTED AND CANDIDATE STATES

Method Overview

The DMM needs to support quick and flexible changes to the DBS in respond to the evolutionary decision-making process. This composite method allows decision stakeholders to swap (i.e., to exchange the states reciprocally) decision information, in the form of ontology elements, between selected and candidate states in the Decision Dashboard. This composite method combines and automates the following base methods:

Base Method B2: Couple, De-Couple, and Re-Couple Decision Information

Base Method B3: Distinguish Decision Information Between Selected and Candidate States

Method Feature—Swap

The swap feature automates the reciprocal change of the states (between “selected” and “candidate” states) based on an user-initiated change of relationships (between “coupled” and “decoupled” relationships) among two competing ontology elements and their parent decision topic. When DD users change the target of an “aggregate” relationship from an originally “selected” element instance to another originally “candidate” element instance, this swap method feature automatically swaps the states between the two element instances. This swap method feature applies to all selected and candidate ontology elements (topics, criterion, option, and alternative). As a result, DD users do not need to manually change the ontology characteristic for each of the affected element instances because the swap method feature automates these changes when a change of relationship occurs.

C3: INTERACT IN THE IROOM ENVIRONMENT

Method Overview

Decision-support tools should provide decision stakeholders quick access to a high-level strategic decision view as well as a detail-level information view. While the DBS (as represented as a symbolic structure in the DD’s graphical window) provides a strategic decision view, the DD relies on linkages to external digital information for the

detailed view. In addition to DMM base method B4 (which automates the referencing and retrieval of digital information within the same personal computer or over the computer network), this composite method allows decision stakeholders to reference and launch decision information within the CIFE iRoom (interactive workspace) with the Decision Dashboard. This composite method combines and builds upon the following base methods:

Base Method B1: Manage Decision Information, Relationships, and Attributes

Base Method B4: Reference Existing Decision Information

Method Feature—Reference and Launch in the CIFE iRoom

In the CIFE iRoom, this method feature allows DD users to associate decision information with digital references from any one of the networked iRoom computers. Once such references are made, DD users have the discretion to launch this digital reference in any one of the three CIFE iRoom computers. All such references and launch method features are available as attributes that can be assigned to all ontology elements. As in the base method, this iRoom interaction is facilitated by the DD's internal knowledge about the correlation between digital files and their corresponding native applications. Therefore, DD users can make a one-click launch to bring up a relevant file with its native application to describe and explain the decision information concerning that element instance in the CIFE iRoom.

C4: FILTER GRAPHICAL REPRESENTATION OF A DECISION BREAKDOWN STRUCTURE

Method Overview

As decision facilitators continue to accrue a variety of decision information with a DBS in the DD, the need to flexibly and quickly focus on different pertinent subset of decision information also increases. This composite method (Figure 28) allows decision stakeholders to perform composite (i.e., combinable) filtering of the graphical representation of a Decision Breakdown Structure in the Decision Dashboard based on Base Method B5 (Show Elements By Types). Thus, DD users need to first make a base filter selection before applying one, two, or all of the following three composite filters. This composite method combines and builds upon the following base methods:

- Base Method B3: Distinguish Decision Information Between Selected and Candidate States
- Base Method B5: Filter Graphical Representation of AEC Decision Ontology

Base Methods

B1: manage Decision Ontology

B2: couple, de-couple, and re-couple ontology elements

B3: distinguish ontology elements between selected and candidate states

B4: reference existing decision information

B5: filter graphical representation of AEC Decision Ontology

B6: evaluate in different contexts and across different levels of detail

Composite Methods

C1: formulate a Decision Breakdown Structure [B1, B2, B3, B4]

C2: Swap ontology elements between selected and candidate states [B2, B3]

C3: interact in the CIFE iRoom [B1, B4]

C4: filter graphical representation of a Decision Breakdown Structure [B3, B5]

Refresh
Default DBS
Complete Network
Edit

<input type="checkbox"/> Decision Breakdown Structure	<input checked="" type="checkbox"/> Decision Status	<input type="checkbox"/> Relationships
<input type="checkbox"/> Highlighted Only	<input checked="" type="checkbox"/> Selected	<input checked="" type="checkbox"/> DBS Relationships
<input checked="" type="checkbox"/> All Decision Topics	<input type="checkbox"/> Candidates	<input checked="" type="checkbox"/> Sibling Relationships
<input checked="" type="checkbox"/> Parents		<input type="checkbox"/> Coupling Relationships
<input checked="" type="checkbox"/> Children		<input type="checkbox"/> Ripple Effects
<input checked="" type="checkbox"/> Decision Criteria		<input type="checkbox"/> Positive Impacts
<input checked="" type="checkbox"/> Alternatives		<input type="checkbox"/> Negative Impacts
<input checked="" type="checkbox"/> Options		<input type="checkbox"/> Temporal Relationships
		<input type="checkbox"/> Precedents
		<input type="checkbox"/> Successors

Figure 28. A screenshot of the graphical filter tool (DMM Composite Method C4) in the Decision Dashboard.

Method Feature—Filter Elements by States

This method feature offers two decision status checkboxes—“selected” and “candidate”. It enables DD users to filter the ontology elements by further distinguishing whether those element instances are the recommended set (i.e., “selected”) and/or the idle set under consideration (i.e., “candidate”). This composite filter applies to all ontology elements, that is, decision topics, criteria, alternatives, and options.

Method Feature—Filter Elements by Relationships

The aforementioned base and composite filters affect only the visibility of the element instances in the DD Graphical Window. This method feature focuses on the relationships (i.e., DD graphical arrows) connecting the elements (i.e., DD graphical shapes). It offers five checkboxes and four sub-checkboxes, allowing DD users the discretion to view the aggregate (from topics to other elements), choice, aggregate (from alternatives to other elements), impact, and process relationships. Meanwhile, the four sub-checkboxes qualify whether the ripple effects (i.e., impact relationships) generate positive versus negative impacts and whether the temporal (i.e., process) relationships should display the predecessor versus the successor elements.

Not only does this method feature turn relationships (i.e., arrows) visible, it also turns the arrow's targeting element visible. Hence, there may be scenarios in which the relationship would turn visible some elements that would otherwise be invisible based on the base selection. In this scenario, this method feature would override the results of the aforementioned base or composite methods. For example, assuming DD users check the decision topics and the options in the base selection (Base Method B5) and filter these elements by the "candidate" states (i.e., only checking the "selected" states). In this example, if DD users apply a filter to turn all choice relationships visible, then this relationship filter will override the state filter. Specifically, all decision topic instances' choices and all option instances' choices that are in candidate states will also be visible, along with the green arrows that denote the choice relationships. This example also demonstrates that since the base selection does not include alternatives or criteria, all selected and candidate instances of alternative or criteria elements will remain invisible in the DD Graphical Window.

Method Feature—Focus on a Highlighted Element

All aforementioned filters apply to all element and relationship instances in the DD model. This method feature allows DD users to apply the above filters to a particular element instance—be it decision topic, criterion, alternative, or option. As a result, DD users can apply this method feature to focus on a particular group or branch of decision information in the DD. When a DD user checks the "highlighted only" checkbox in addition to other element, status, and relationship checkboxes, the DD will track the

currently highlighted element instance in the DD graphical window and apply a filter pertaining to this particular selection. For instance, if a DD user highlights an option and checks on “highlighted only,” “all decision status,” and “choice relationships,” then the DD will only turn visible the immediate choices (i.e., option elements connected by choice relationships) of the highlighted option. Furthermore, this method feature also offers users the opportunity to focus only on the parent elements or only on the children elements of a highlighted element instance. Users can make this filter by checking the “parent” and/or the “children” checkbox(es).

5.2.3 CONCLUSION FROM CONTRIBUTION #2

In this section, I have presented 6 base methods, 4 composite methods, along with their 22 method features. I have built these methods upon the AEC Decision Ontology and have implemented them in the DD prototype. These methods are not meant to cover every single decision need exhaustively. However, as the subsequent sections and chapters show, these methods are adequate to solve an array of decision-enabling scenarios drawn from the industry test cases. In Chapter 7, I discuss how these base and composite methods form an important foundation for future work. In essence, researchers can build upon my contribution and define a method feature by identifying a generic information management objective (e.g., to couple decision information) necessary to complete certain decision-enabling tasks. Once a method feature has been defined, one can develop DBS ontology-based computer reasoning methods to turn this feature into a DMM-based solution. If the computer reasoning methods under development only serve a specific method feature (e.g., to distinguish whether decision information is in selected or candidate state), they will become base methods in the DMM. In cases where certain subsets of the computer reasoning methods under development can serve other method features, the methods are recognized as composite methods in the DMM (e.g., a subset of the method to bring up decision information in the iRoom can also serve the method feature of referencing existing decision information, therefore the method supporting iRoom information retrieval is a composite method).

The contribution of my base and composite methods resides in the concept of complementing the AEC Decision Ontology with a set of dynamic methodologies. These methods enhance the decision-support capabilities of the DD, allowing AEC stakeholders to

manage decision information in a DBS approach that is more consistent, effective, and efficient (i.e., flexible, fast, more informative, and resumable) than other current methods.

5.3 VALIDATION STUDY #2—INFORMATIVE, FLEXIBLE, RESUMABLE, AND QUICK

METHODOLOGY

My second validation study compares the completion of specific decision-enabling tasks between current practice (sections 2.1.2, 2.2.2, 2.3.2, and 2.4.2) and the Decision Method Model (the following subsections). Informativeness, flexibility, resumability, and quickness serve as the metrics in this comparison. This validation captures specific decision scenarios from all six industry test cases (Table 7). In these scenarios, the continuation of the decision-making process is dependent on the successful completion of certain decision-enabling tasks (DET) by the facilitators and professionals. In current practice, decision facilitators and AEC professionals in the four test cases applied an array of current means and methods to complete eight decision-enabling tasks, so as to enable all stakeholders to carry on the decision-making process with necessary formulation, evaluation, and re-formulation of decision information (sections 2.1-2.4). In this validation study, I explain how decision facilitators and AEC professionals can apply the DMM to different Decision Breakdown Structures, built with the AEC Decision Ontology in the DD, to manage the necessary information. In the following subsections, I describe the means and methods by the DMM-based DD in completing the decision-enabling tasks and analyze whether the DMM (when compared with conventional practice carried out by different industry professionals across different industry cases) is powerful (i.e., enhances the completion of the decision-enabling tasks with informativeness, flexibility, resumable continuation, and/or quickness) and general (i.e., across eight different types of decision-enabling tasks).

Task/ Case	Decision-Enabling Task and Metrics	Current Methods and Results	Enabling DMM Methods and Results (B=Base, C=Composite)
DET#1 TC#1	Decision-Enabling Task: to re- formulate a hybrid solution Metrics: resumability, flexibility, informativeness, and quickness	MS PowerPoint does not allow re-formulation in real time and updating of area and cost results. Result: inability to re-formulate during the time available in a meeting; 4 weeks spent in re- formulation and meeting re- scheduling	C1: Formulate a DBS C2: Swap decision information between selected and candidate states Result: the DD updates area and cost attributes instantaneously after the swap.

DET#2 TC#1	<p>Decision-Enabling Task: to respond to an impromptu query about decision information in a decoupled form</p> <p>Metrics: informativenss, flexibility, and quickness</p>	<p>MS PowerPoint only provides spatial information that is pre-defined prior to the evaluation.</p> <p>Result: uninformative verbal claims, defer response as a follow-up action</p>	<p>B1: Manage Decision Information, Relationships, and Attributes C1: Formulate a DBS C4: Filter Graphical Representation of a DBS</p> <p>Result: the DBS allows users to break down spatial information into its decoupled form or propagate and sum up spatial information in the coupling of different options.</p>
DET#3 TC#1	<p>Decision-Enabling Task: to respond to an impromptu evaluation between alternatives and criteria</p> <p>Metrics: informativenss, flexibility, and quickness</p>	<p>MS PowerPoint does not allow re-formulation in real time and updating of area and cost results.</p> <p>Result: uninformative with rough mental estimates, inflexible to shift the content focus of evaluation tables, defer response as a follow-up action</p>	<p>B6: Evaluate in Different Contexts and Across Different Levels of Detail C1: Formulate a DBS C4: Filter Graphical Representation of a DBS</p> <p>Result: the DD allows users to adjust the focus of decision information in evaluation tables. It provides a dynamic response to macro, micro, relative, or absolute evaluation needs.</p>
DET#4 TC#2	<p>Decision-Enabling Task: to explain prediction assumptions and make necessary corrections</p> <p>Metrics: informativeness, resumability</p>	<p>Paper-based report replicates decision information and leads to inconsistent reporting; it does not explain the assumption basis and does not allow stakeholders to make corrections easily.</p> <p>Result: multiple data re-entries led to a 26% variance and inconsistency in the reporting of the green roof option.</p>	<p>B1: Manage Decision Information, Relationships, and Attributes C1: Formulate a DBS</p> <p>Result: single data entry and data propagation across the DBS support quick correction and ensure consistent reporting of decision information.</p>
DET#5 TC#2	<p>Decision-Enabling Task: to evaluate macro and micro impacts among three case scenarios</p> <p>Metrics: informativess, flexibility</p>	<p>Pre-determined report does not explain the interrelationships between three predictive scenarios and specific design features, sub-features, and their choices. Assumptions have been pre-determined.</p> <p>Result: predetermined table report limits decision choices to three scenarios, without knowledge about specific inter-relationships between these cases and specific design features and choices.</p>	<p>B6: Evaluate in Different Contexts and Across Different Levels of Detail C1: Formulate a DBS C2: Swap decision information between selected and candidate states C4: Filter Graphical Representation of a DBS</p> <p>Result: The DBS informs stakeholders about choice relationships between peers and aggregate relationships across different levels of detail; the DMM enables stakeholders to mix and match predictive scenarios with various design choices.</p>

DET#6 TC#2	Decision-Enabling Task: to evaluate decision information in the executive summary Metrics: informativenss, flexibility, resumability, and quickness	The contents and the focus of the evaluation table in the executive summary was pre-determined. Result: Design features and sub-features were inconsistently reported in the executive table with no explanations, the table did not inform decision stakeholders about a shift in levels of detail among the comparison targets, which led to an unfair decision basis.	B6: Evaluate in Different Contexts and Across Different Result: The DMM provides dynamic evaluation tables for topics or choices at the same level of detail by default. DD users can customize what attributes should be evaluated. The DMM also supports quick evaluation across different levels of detail, should there be a need for it.
DET#7 TC#3	Decision-Enabling Task: to comprehend the ripple consequences of a specific decision option Metrics: informativenss and quickness	Binder report shows an option to add two additional floors at 12% of total budget with no detailed references to explain the ripple consequences this option has on other design decisions. Result: An owner representative had to spend several hours to go through the 283-page program report to look for the narrated descriptions dispersed across different sections in the report.	B1: Manage Decision Information, Relationships, and Attributes C1: Formulate a DBS C4: Filter Graphical Representation of a DBS Result: the DMM formalizes the documentation of ripple consequences with two-way relationships. DD users can isolate a particular option and query for the impact relationships leading to and from one specific option. In seconds, the DD can single out the ripple consequences among 97 instances of elements and 103 instances of relationships.
DET#8 TC#4	Decision-Enabling Task: to explain and comprehend different decision alternatives Metrics: informativenss and quickness	the CIFE iRoom supports cross-highlighting of decision information among competing or inter-related models. There were no formal tools or methods to support the explanation or retrieval of information. Result: the facilitator relied on his/her memory or personal notes to explain assumptions and differences among alternatives. He needed to memorize or create custom organization schemes of virtual design/construction models to facilitate the information retrieval process.	B1: Manage Decision Information, Relationships, and Attributes C1: Formulate a DBS C3: Interact in the iRoom Environment C4: Filter Graphical Representation of a DBS Result: the DBS immediately updates its graphical representation to aid in the explanation of scope, assumptions, and distinctions when users swap among alternatives. The DBS offers a structure for referencing information and documenting ripple consequences such that facilitators can shift the attention to other decision-enabling tasks.

Table 7. An overview of the eight decision-enabling tasks (DET) that form the validation basis of the dynamic Decision Method Model.

DECISION-ENABLING TASK #1: RE-FORMULATE A HYBRID SOLUTION

This decision-enabling task provides the performance results that support the metrics of resumability, flexibility, informativeness, and quickness from current and DD-based practices. The case demonstrates the value of the following composite methods in the Decision Method Model:

C1: Formulate a Decision Breakdown Structure

C2: Swap Decision Information Between Selected and Candidate States

DMM APPLICATION AND PERFORMANCE

The background and the performance results documented from current practice of decision-enabling task #1 was detailed in section 2.1. By swapping the aggregate relationships from “corner” to “5th avenue” (DMM Composite Method C2), the DD allows the design team to mix and match available decision choices. By adding another “aggregate” relationship originating from the decision topic of “entrance location” to “Main Street,” which is the second entrance that is recommended as a hybrid solution, the DD propagates the impact of dual entrances throughout the Decision Breakdown Structure instantaneously (DMM Composite Method C1). Hence, the DD updates its attributes, such as square footage calculations and cost differentials, and allows an immediate evaluation against the project criteria (e.g., minimum area requirement).

ANALYSIS

From a resumability perspective, the current methods require rework with the CAD, area, and cost authoring tools to adjust the values in the decision-support view. In contrast, the DD is capable of supporting the documentation of design choices, incorporating relevant level-1 parameters (e.g., cost and area) in the decision model, enabling the generation of a hybrid alternative, and providing feedback to a what-if question.

Besides resumability, the Dynamic DBS is more flexible, informative, and faster. The combination of methods C1 and C2 provides AEC professionals the flexibility to dynamically de-couple and re-couple design options, which are finer decision choices than design alternatives. In contrast, the flexibility of current decision-support tools is

limited to the pre-determined alternatives because individual alternatives have to be incorporated in advance of the decision review meeting.

The DMM also contributes to the metrics of informativeness and quickness. The presence and dynamic propagation of level-1 decision information (e.g., cost and area information pertaining to individual candidate options and overall design proposal) in the DBS shortens the latency of responses to an inquiry from 4 weeks to minutes, while improving the information basis of the decision stakeholders as they consider the hybrid design solution.

DECISION-ENABLING TASKS #2 AND #3

Decision-Enabling Task #2: Impromptu Query and

Decision-Enabling Task #3: Impromptu Evaluation

These two decision-enabling tasks provide the performance results for the metrics of informativeness, flexibility, and quickness from both current and DD-based practices. The tasks demonstrate the value of the following base and composite methods in the Decision Method Model:

B1: Manage Decision Information, Relationships, and Attributes

B6: Evaluate in Different Contexts and Across Different Levels of Detail

C1: Formulate a Decision Breakdown Structure

C4: Filter Graphical Representation of a Decision Breakdown Structure

The main limitation of the current method is that it does not allow informative, flexible, or quick access to the set of decision information from the formulation phase (section 6.2). Current practice only exposes decision makers to a subset of decision information, which is recommended by the decision facilitators (e.g., the design team) for the evaluation phase (section 6.2).

DMM APPLICATION AND PERFORMANCE

The background, as well as the performance results documented from current practice of decision-enabling tasks #2 and #3 were detailed in section 2.1. Using DMM

methods, DD users can associate area attributes with the corresponding decision options (DMM Base Method B1). These embedded attributes contribute to the formulation of a DBS, which then allows DD users to query for area information in coupled alternative form (e.g., total building space for the schemes) and the de-coupled option form (e.g., common space and MEP space). With DMM Base Method B1 and Composite Method C1, DD users can propagate the area information such that the component options (e.g., common space, mechanical space, office space, etc.) can be aggregated to become the parts of a cumulative decision topic (i.e., the total building). These methods allow DD users to dynamically retrieve the assumptions (e.g., the derivation of productivity improvements) and make-up of each scheme when presented with an impromptu question. Also, the DD allows explicit representation and differentiation of decision topics, criteria, options, and alternatives. Therefore, given an impromptu scenario, the DD users can quickly and informatively access such information along with its embedded or referenced attributes. Furthermore, DD users can quickly and flexibly adjust the focus of a predetermined evaluation table during the review meeting by dynamically customizing the evaluation content in the DD (e.g., alternatives, options, attributes, etc.). Hence, the DD supports decision facilitators to respond to a wider set of macro, micro, relative, or absolute evaluation needs than in current practice (DMM Base Method B6).

ANALYSIS

As these two decision-enabling tasks demonstrate, the decision stakeholders often have legitimate reasons that prompt them to query, access, and analyze information beyond the recommended set. However, current tools and methods do not allow easy access to a working set of information, they do not allow easy adjustment of a predetermined evaluation focus. In decision-enabling task #2 for example, by making verbal promises or approximating bay size dimensions, the designer's urge to expedite the decision process compromised the information basis of the decision makers. As the financial specialist was not satisfied with the responses, the lack of informativeness and flexibility then compromised quickness, because the specialist needed to wait for the follow-up effort by the design team. Not only does deferring take up additional time, but it also loses the attention of all the decision makers who are deprived of the opportunities to exchange analytical and evaluative thoughts in the same room at the

same time. In comparison, the dynamic interaction enabled by the DMM with a relatively more comprehensive set of information contained in a DBS (section 4.3.1) promotes informativeness, flexibility, and quickness in the same AEC decision scenario.

DECISION-ENABLING TASKS #4 AND #5

Decision-Enabling Task #4: Explain Assumptions & Make Necessary Corrections and

Decision-Enabling Task #5: Evaluate Macro and Micro Impacts Among Three Case Scenarios

These two decision-enabling tasks provide the performance results for the metrics of informativeness, flexibility, resumability, and quickness from current and DD-based practices. The tasks demonstrate the value of the following base and composite methods in the Decision Method Model:

B1: Manage Decision Information, Relationships, and Attributes

B6: Evaluate in Different Contexts and Across Different Levels of Detail

C1: Formulate a Decision Breakdown Structure

C2: Swap Decision Information Between Selected and Candidate States

C4: Filter Graphical Representation of a Decision Breakdown Structure

Paper-based reports only provide a static snapshot of a recommendation based on the state of information at the time. It requires a one-time, special preparation and synchronization with the sources of decision information. This synchronization needs to be redone whenever the decision scenario and information change. As this decision-enabling task demonstrates, paper-based reports cannot flexibly adjust this snapshot or the data during the evaluation process. Adjustments would require manual interventions or rework, both of which diminish the informativeness of the original paper-based report. Conversely, the DD allows a more explicit documentation of the assumed values, the formulas, and the propagation of values. This does not only reduce the need for data entry and associated risks of error, the DD also offers a more transparent solution for stakeholders to comprehend and adjust prior states of decision information. Thus, the DD is more informative and resumable than the paper-based report.

The test case also demonstrates that there is no formal representation of interrelationships between different decision choices in current practice. In other words, current practice does not provide a “big picture” of the problem areas that an attribute or a value influences. In contrast, the DBS provides an explicit view of the decision scenario, graphically connecting the interrelated options and alternatives, such that decision stakeholders are aware of the decision context and the available choices. Furthermore, the DD also offers more dynamic interaction capabilities to mix and match different scenarios, thus it is more flexible and quicker than current decision-support tools.

DMM APPLICATION AND PERFORMANCE

As introduced in section 4.3.2, the design features and their associated productivity predictions currently present in the paper-based report can be formally structured and organized with the Decision Breakdown Structure in the Decision Dashboard. The DBS allows DD users to integrate pertinent decision information (DMM Composite Method C1). In TC#2, the DD integrates information such as first costs, productivity improvement, absenteeism improvement as attributes in their corresponding options or topics (DMM Base Method B1). Thus, with the initial data entry, the propagation of attribute values and the formula calculation method feature of DMM Base Method B1 reduces the need to re-enter decision information. This method also keeps the assumptions and deriving formula explicit for decision stakeholders to understand the sources of numbers and refine the assumptions as required by the evolving decision process.

The DBS also offers an explicit structure of the design (product) choices and their interrelationships with the three productivity scenarios. DD users can formally associate the worst, most likely, and best cases with the topic of underfloor plenum. Hence, when DD users evaluate the decision information with the dynamic graphical filter (DMM Composite Method C4), they notice that the productivity improvement has no direct relationships with the ventilation, or material finishes, or other branches of the DBS. This is helpful because all attributes from the recommended selections (e.g., most likely productivity gains, operable window, low VOC, green roof, etc.) are integrated and propagated in the DBS. Thus, upon reviewing the evaluation table

(DMM Base Method B6), stakeholders can continually monitor the aggregated first cost, energy savings, and other pertinent criteria based on the recommended selection. Should the stakeholders be interested in testing other combinations of options and alternative scenarios, they can dynamically mix and match options and alternatives and get the updated predictions reported in the evaluation table (DMM Composite Method C4).

ANALYSIS

One may argue that a spreadsheet may also minimize data re-entry and ensure better consistency and accuracy when dealing with numeric values. In terms of calculation, the contribution of the DMM in terms of processing and propagating the attributes is the same as spreadsheet calculations. However, what is different in the DD is that the DBS recognizes whether an ontology element is in candidate or selected states, which in turn affects the propagation of the attribute values and hence, the evaluation table. Hence, the use of spreadsheets as decision-support tools does not offer the ontology-based capabilities that the DD offers with its integration of the DBS and the DMM.

DECISION-ENABLING TASK #6: EVALUATION CONTENT IN THE EXECUTIVE SUMMARY

This decision-enabling task from TC#2 provides the performance results for the metrics of resumability, flexibility, informativeness, and quickness from current and DD-based practices. The case demonstrates the value of the following base method in the Decision Method Model:

B6: Evaluate in Different Contexts and Across Different Levels of Detail

DMM APPLICATION AND PERFORMANCE

In contrast to the performance results in current practice (section 2.2), the decision makers can access and assess pre-determined and dynamically generated evaluation tables with the DD. By default, the DD provides live evaluation tables for topics or choices of the same level of detail, which correspond to the same tier of ontology elements in the DBS (DMM Base Method B6). The table for comparing the decision topics of “indoor air quality,” “daylighting,” and “green roof” packages can be evaluated at their parent decision instance—“sustainable design features.” By the same

token, different sub-features under indoor air quality package can be evaluated in a table form through the “Indoor Air” decision topic.

Should there be reason to compare different levels of details (e.g., packages against sub-feature in TC#2), the Decision Dashboard allows one to generate a custom evaluation table to come up with the same content and decision focus as the executive summary table in the conventional approach (DMM Base Method B6—Evaluate Across Hybrid Levels of Detail). By adding a decision topic with “aggregate” relationships directed towards the decision topics of green roof (2nd tier LOD in the DBS), underfloor plenum (3rd tier LOD in the DBS), and daylighting (2nd tier LOD in the DBS), the decision facilitator can generate an evaluation table that matches the conventional practice.

ANALYSIS

When compared to the limitation of pre-determined evaluation foci and contents as evidenced in the current methods, the DMM provides a more informative, flexible, resumable, and quick methodology for decision makers to conduct and adjust evaluative tasks during the decision-making processes. With the flexibility to shift the decision focus between macro and micro levels of detail, the DD enables a more proactive approach for evaluation. With dynamic propagation of attributes and generation of evaluation tables, DD users can obtain decision information much more quickly than in conventional practice.

The underfloor plenum line item in the “executive summary” in the status quo evidence was skewed by the pre-determined table to show a sub-feature within the package that had the best cost-benefit result among all sub-features, rather than showing the cost-benefit numbers averaging all the design features under the package of “indoor air quality.” With DD’s default evaluation of content across the same level of detail, DD users can obtain a fairer view. They can be more informed of the significance of the decision information and its interrelationships with other issues. DD users no longer need to mentally relate dispersed decision information to stay informed about the decision context. Should there be a real need to compare hybrid levels of detail, the DD provides a resumable solution that can quickly leverage existing data to generate a custom table.

**DECISION-ENABLING TASK #7: COMPREHENDING THE RIPPLE CONSEQUENCES OF BUILDING
ADDITIONAL FLOORS**

This decision-enabling task from TC #3 provides the performance results for the metrics of quickness and informativeness from both current and DD-based practices. The case demonstrates the value of the following base and composite methods in the Decision Method Model:

B1: Manage Decision Information, Relationships, and Attributes

C1: Formulate a Decision Breakdown Structure

C4: Filter Graphical Representation of a Decision Breakdown Structure

Under current practice as illustrated in TC#3, design professionals do not have any formal methods of documenting ripple consequences between pieces of decision information. The lack of 2-way references and the dispersed documentation of the ripple consequences adversely impact the uncovering process undertaken by the owner representative. Without a method to understand quickly the ripple consequences of accepting or rejecting the option to construct additional floors, the owner representative had to carefully read through the text narrative in 283 pages to look for the relevant information. Using the DD, the owner representative can instantaneously highlight and filter for the impact relationships. This quickness translates into better informed decision makers.

DMM APPLICATION AND PERFORMANCE

In contrast to the performance result of current practice described in section 2.3, DMM Base Method B1 and Composite Methods C1 and C4 allow consistent and explicit documentation of ripple consequences and thereby enable informative and fast uncovering of these interrelationships. With level-1 decision information and interrelationships reconstructed in the DD using Composite Method C1 (the scope of the re-construction was described in section 4.3.3), DD users can query for the “impact” relationships between a particular option and all other relevant decision information. Specifically, a DD user can highlight the option of “additional floors” in the DD Graphical Window and visually inspect all the ripple consequences (i.e., impact relationships) that are originating from and targeting to the highlighted option. A DD user can query those impact relationships (i.e., the arrows) and identify the rationale

documentation, the impact cost, and additional supporting references (all of which are presented as descriptive text in current practice) pertaining to the impact relationships and their connected element instances (DMM Base Method B1). In addition, a DD user can focus his/her evaluation by applying the graphical filters to turn particular element instances or relationships visible/invisible (DMM Composite Method C4). In seconds, the DD can single out a particular element instance and its ripple consequences among 97 instances of elements and 103 instances of relationships in the DD model (Figure 29).

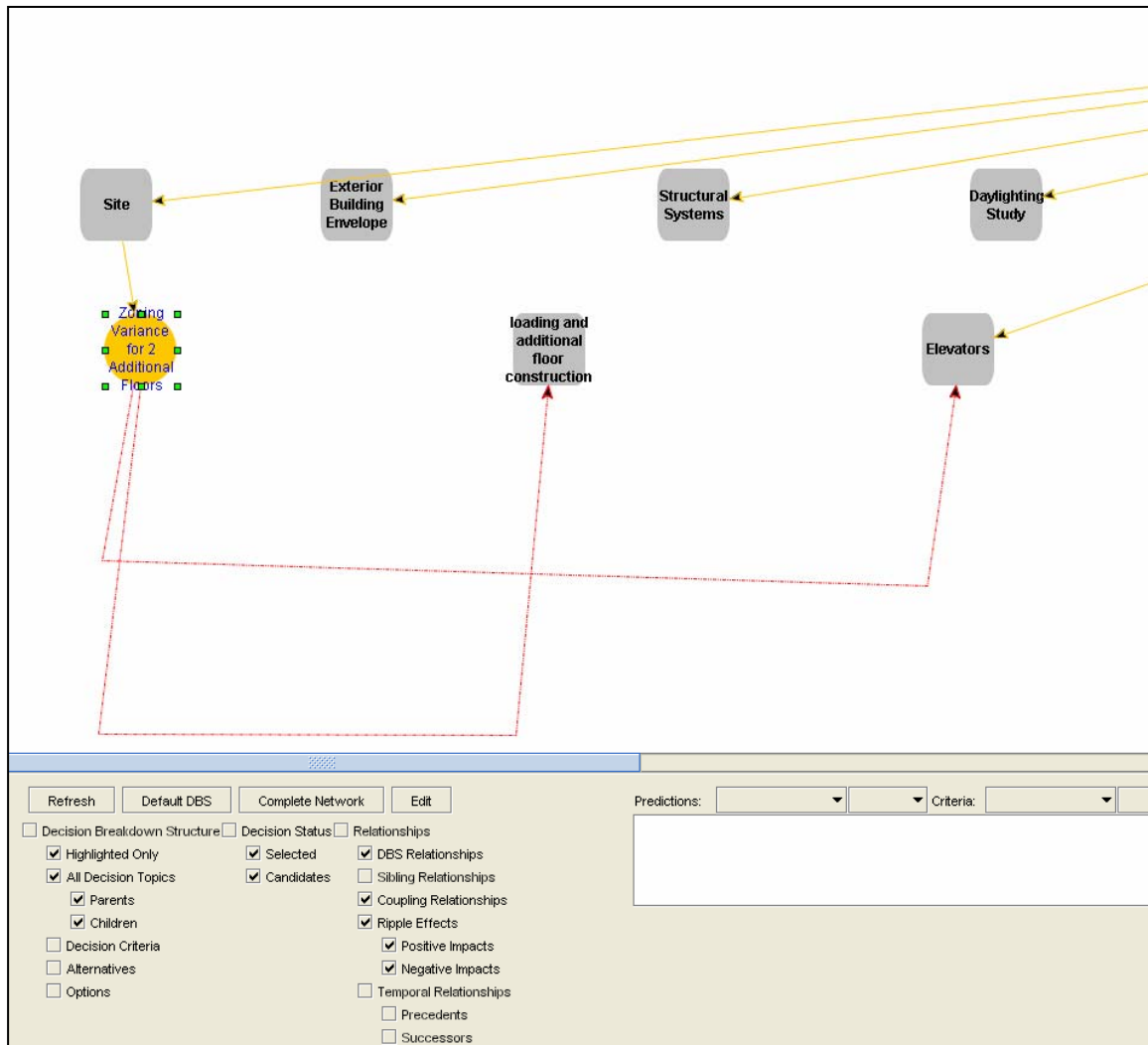


Figure 29. With the DMM, a DD user can quickly highlight an option (i.e., "Zoning Variance for 2 Additional Floors") and quickly identify all the ripple consequences on/from other decision topics (i.e., "loading and additional floor construction" and "elevators").

ANALYSIS

Being able to isolate the pertinent decision information sooner means that decision stakeholders allocate more time in evaluative and analytical tasks rather than tasks that focus on uncovering pertinent information for comprehension purposes. The more time the decision stakeholders can spend on analyzing a decision scenario, the more likely the decision stakeholders can remain informed about a larger number of solution choices. On the other hand, the more time that is being spent on uncovering the basic facts, the more likely the decision stakeholders may have to settle between the most basic choices of acceptance versus rejection of a limited number of alternatives, and thereby missing out on the value of other potential options or alternatives. Since the DMM greatly reduces the time it takes to uncover pertinent decision information, the DD presents a valuable opportunity for decision stakeholders to improve the information basis of their decision making.

DECISION-ENABLING TASK #8: EXPLAIN AND COMPREHEND ACCELERATION PROPOSALS

In this decision-enabling task from TC #4, the decision stakeholders needed to comprehend the decision information (e.g., the assumptions and proposal details) of various competing acceleration proposals. This task provides the performance results for the metrics of informativeness and quickness from current and DD-based practices. The task demonstrates the value of the following base and composite methods in the Decision Method Model:

B1: Manage Decision Information, Relationships, and Attributes

C1: Formulate a Decision Breakdown Structure

C3: Interact in the iRoom Environment

C4: Filter Graphical Representation of a Decision Breakdown Structure

DMM APPLICATION AND PERFORMANCE

The background as well as the performance results documented from current practice of decision-enabling task #8 were detailed in section 2.4. The development of a DBS in the DD to represent and organize different scenarios and their corresponding decision information leads to an informative and quick explanation process. With DMM Composite Method C1, decision facilitators can explicitly break down the choice

associated with each acceleration proposal, e.g., whether a specific acceleration proposal uses a double crew or a single crew. The DD as a decision-support tool enables the decision facilitators to highlight any of the acceleration proposal scenarios and use the graphical filter to show graphically what that scenario entails (DMM Composite Method C4, see Figure 30). Thus, this DMM method contributes to an informative decision explanation process.

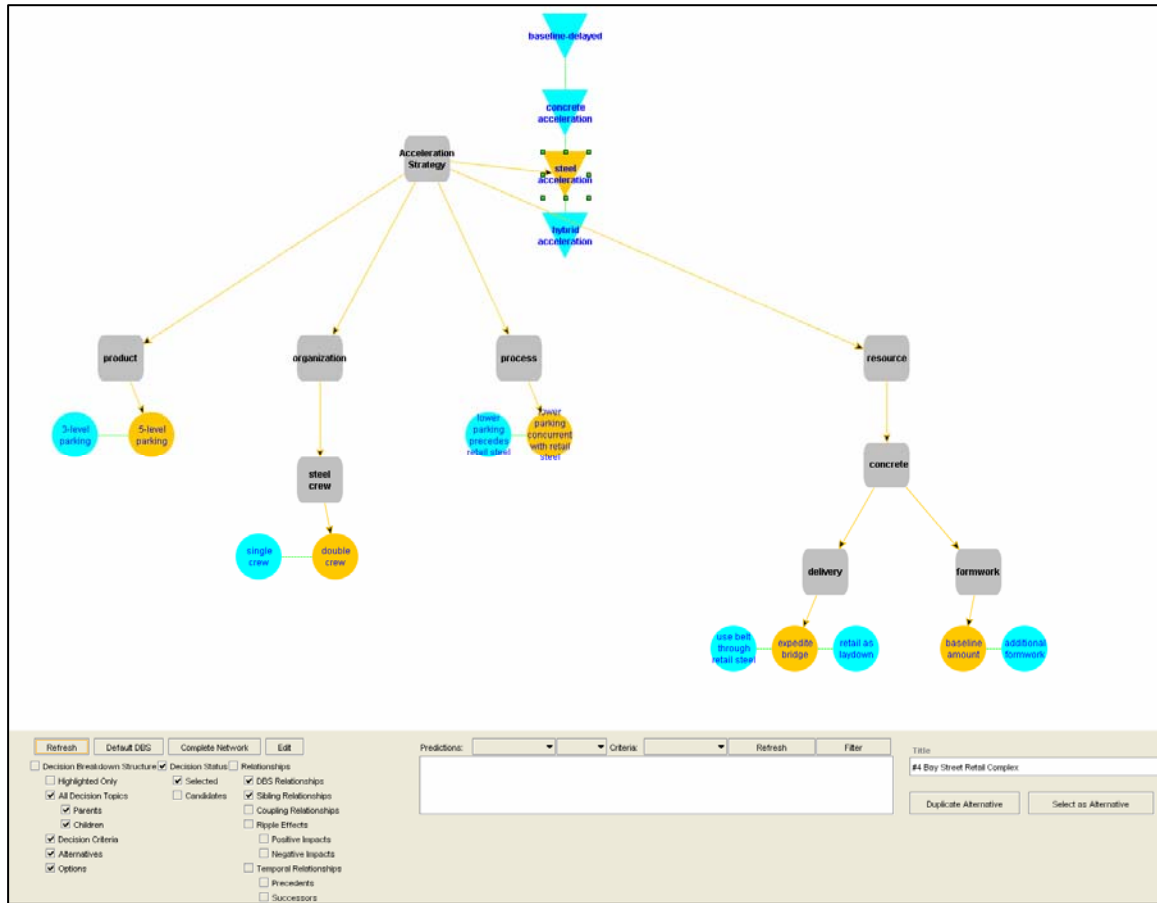


Figure 30. The DMM in TC#4 allows DD users to dynamically focus on any of the four acceleration alternatives (e.g., steel acceleration in the illustration) and learn about the specific composition (e.g., which options are selected and not) of those alternatives.

To obtain specific decision assumptions, predictive values, or details, any decision stakeholder can query for embedded level-1 decision information (DMM Base Method B1) or launch the relevant referenced project file in the CIFE iRoom with a single click on a specific ontology element instance (DMM Composite Method C3, see Figure 6 in section 1.3.7). The DD allows its users to launch any referenced project file with the

appropriate software application on any of the iRoom computers. Hence, these DMM base and composite methods reduce the time it takes the decision facilitator to bring up the pertinent decision information to the decision stakeholders (from minutes in current iRoom practice to seconds with automated DD references). Thus, they contribute to a quicker decision evaluation process (see also section 6.2) when compared to current practice.

ANALYSIS

Decision facilitators have different choices of decision-support tools. They can use MS PowerPoint, the Decision Dashboard, or other decision-support tools to manage the decision information present in a decision scenario. This decision-enabling task in TC#4 shows that with the DMM, the formulation of a DBS as part of the process to manage decision information offers advantages in the evaluation phase of information management in AEC decision making. One advantage is that the decision facilitators can save time and effort in explaining the scope, assumption, and the big picture of the decision scenario. Another advantage is that the decision facilitators can also save time and effort in making connections between an array of supporting reference files and their corresponding decision information. In current practice, the decision facilitators need to create custom introductory slides, need to customize folder and naming conventions, and very often, these facilitators also need to rely on their mental recollection or verbal explanation to ensure an informative explanation process. In contrast, DD-based management of decision information empowers the DMM to eliminate such extra time and the effort required to maintain an informative explanation process. Moreover, the Dynamic DBS can become a decision-support tool to orchestrate decision-enabling tasks in decision environments such as the CIFE iRoom.

5.4 CHAPTER CONCLUSION

Having established a Decision Breakdown Structure (by means of a formal AEC Decision Ontology) to represent heterogeneous decision information in Chapter 4, this Chapter examined how AEC decision stakeholders interact with this formally represented information to complete decision-enabling tasks. As VDC and AEC theories do not support the formal representation of choices and their interrelationships, decision facilitators in my

case studies used generic decision-support tools and methods to perform decision-enabling tasks. As detailed in the eight different types of decision-enabling tasks, these tools and methods are not flexible or resumable and thus, result in a decision basis that is not informative and that leads to slow decision making. The application of DA methods (e.g., alternative generation using strategy-generation tables, rationalizing decision making using a stochastic decision tree, appraisal with sensitivity analysis, constructing an influence diagram, etc.) have been few and limited in the building industry. My assessment is that traditional DA theories and methodologies do not fit well with the heterogeneous and evolutionary nature of AEC decision making. In light of this reason, my contribution of a dynamic DMM extends my theoretical points of departure by bridging the generation and evaluation of decision choices across multiple levels of details. My DMM is not exhaustive. It does, however, support eight different types of decision-enabling tasks and more importantly, offers a foundation for further formalization of a decision-support methodology for AEC decision making.

CHAPTER 6—DYNAMIC DBS FRAMEWORK

Not only do the representation of heterogeneous decision information and the task-based methodology for managing evolutionary decision information affect the information basis of decisions, they also influence the continuity, and hence the resumability, of the decision-making process. My research contributions of a Decision Breakdown Structure (Chapter 4) and its supplementary dynamic methodology (Chapter 5) formalize how decision facilitators represent decision information and complete decision-enabling tasks. These two contributions focus on discrete sets of decision information as well as isolated decision tasks; my third contribution puts them into the decision-making process. This Chapter presents my third and final contribution of a Dynamic DBS Framework, which formalizes the applications of the DBS and the dynamic methodology throughout the decision-making process.

Given the changing requirements and circumstances throughout the decision process, decision stakeholders often use decision-support methods and tools for a specific decision-enabling task during a particular phase of the decision process. The ripple effect of this narrow perspective often limits the access, evaluation, and adjustment (or in general, management) of decision information later in the decision process as requirements and circumstances change. For instance, in the office modernization project, stakeholders in the decision scenario in TC#3 used a paper-based report to convey their findings in an asynchronous manner. As the modernization project proceeded from the programming phase (i.e., TC#3) to the schematic design phase (i.e., the decision scenario depicted in TC#1), the stakeholders had to resort to another tool, in this case MS PowerPoint, to support a series of face-to-face review meetings. However, this caused decision information and its interrelationships to become more inaccessible (dispersed) and hence, not informative. Furthermore, the inflexibility and inability of the decision-support tools to help decision facilitators to resume the decision process, to respond to impromptu evaluations, and to test what-if suggestions also resulted in rework and delay (section 5.3). There is a lack of distinction between the different information management activities and their corresponding requirements within a decision process. Consequently, ad hoc current practice and use of decision-support tools may serve the short-term tasks, but do not support subsequent information management needs at later points in the decision process under different circumstances. To maintain a good decision basis in spite of the lack of informativeness, flexibility, resumability,

and quickness in current practice, decision stakeholders have to invest in extra rework to complete decision-enabling tasks.

One of the important requirements of AEC decision making is to succinctly inform the decision makers (during the evaluation phase) about the recommendations (put together during the formulation phase) made by the decision facilitators, who based their recommendations on balancing what the decision makers want (captured during the definition phase) versus what the professionals offer (proposed during the formulation phase). Consequently, decision makers and facilitators evaluate the recommendations (during the evaluation phase), and further refine the criteria, options, and/or alternatives (during the iteration phase) until decisions are made (during the decision phase). In spite of these requirements that I have captured from the industry test cases, current practice and theories lack an information management strategy across different phases of the AEC decision-making process. Theories in decision analysis provide a framework based on formulative, probabilistic, and evaluation phases, however, this does not fully address the heterogeneous and evolutionary nature and challenges associated with AEC decision making (section 6.1). Virtual design and construction theories discuss a framework to evaluate the quality of meetings and the value of visualization, but there is a void to specify the information management aspects that shape the quality and visualization in meetings. Therefore, my third contribution is a formal framework for managing decision information with a formalization of five information management phases within the decision-making process. The formal framework integrates the decision ontology and methodology to specify information management strategies that pertain to the five phases in the framework—definition, formulation, evaluation, iteration, and decision phases. This contribution provides the principles and their corresponding means and methods that are required for the DBS to add value to different decision-enabling tasks in AEC decision making. The formal framework specifies how stakeholders can rely on the Dynamic DBS to complete an array of different decision-enabling tasks across different phases of the decision process based on an integrated information basis. It guides decision stakeholders to build ontology-based decision models and apply DMM-based methods, both of which lead to a decision-support framework that promotes informativeness, flexibility, resumability, and quickness in managing decision information.

The third validation study analyzes the application of the Dynamic DBS Framework across five information management phases based on the metrics of informativeness, flexibility, resumability, and quickness using evidence examples from all six industry test cases. The fourth validation

complements the other three metric-based validations with a broader analysis (i.e., beyond the metrics and beyond my personal fact-based analyses) of my research contributions. It captures the qualitative feedback from a group of twenty-one industry and research experts, who attended one of my four demonstration sessions. The sessions focused the experts' attention on the motivating case example in Chapter 1. I went through the same decision-making scenarios with current practice decision-support tools and the decision dashboard. The expert participants comprehended, evaluated, rated, and commented on the Dynamic DBS Framework.

6.1 POINTS OF DEPARTURE

As my third and final research question centers on the management of decision information in the computer during the AEC decision-making process^{xvii}, I first investigate the formal decision process established in Decision Analysis (DA). Building on this formal decision process, I then review its relationship with the many AEC processes^{xviii} established in current literature. Based on this review, I suggest that the AEC decision process is applicable in analyzing various AEC processes. The characteristics of these AEC processes pose information management requirements, which are missing in current literature, on different information management phases throughout the AEC decision process.

6.1.1 DECISION PROCESS BASED ON DECISION ANALYSIS

Belton and Stewart (2002) view the DA process as an aid to decision making, with the first goal of integrating objective measurements with a value judgment (e.g., evaluation of decision criteria) and the second goal of making [criteria] explicit and managing [decisions] subjectively. Howard (1988) suggests that the intention of the decision analysis process is to

^{xvii} As explained in Chapter 1, the term “decision process” in this dissertation means that it is an “AEC decision-making process.” However in this chapter, I investigate both Decision Analysis-based and AEC-based decision processes. Therefore, I use the terms “AEC decision process” and “DA decision process” to clarify the use of this term in this chapter.

^{xviii} In this chapter, I also distinguish between AEC processes (such as planning, design, construction, value engineering processes) and the AEC decision process.

apply a sequence of transparent steps to transform opaque decision problems into transparent ones, while providing decision makers with “clarity of insight” into the problem.

The DA process begins with a real decision problem and results in a real action (Howard 1988). The “sequence of transparent steps” in between the problem and action consists of formulation, followed by evaluation, appraisal, and iterative refinements until the appraisal leads to a course of real actions. My research has adapted this DA process framework to fit the management of decision information without using stochastic evaluations.

While DA treats the decision problem and real action as the beginning and end states that are not part of the DA process, my framework includes the definition and decision as two integral phases in the AEC decision process. This is because these two phases present decision stakeholders with specific information management characteristics and requirements that need to be differentiated from other AEC decision phases. Examples of such specific characteristics include the needs to lay out the decision criteria or the big ideas and to document the decision rationale (see sections 6.2.1, 6.2.5, 6.3.1, and 6.3.5 for more explanations and examples). Meanwhile, the appraisal phase in DA provides a sensitivity analysis to follow the probabilistic evaluation phase. Because my AEC decision methods do not build on DA’s probabilistic assignment (section 5.1), the appraisal phase in the DA process is therefore not an extensible point of departure within the current scope of my research. An evaluation of the decision information by the decision stakeholders determines whether the decision process should proceed to the iteration phase or the decision phase.

My research builds on the deterministic phases of the DA process, while offering AEC decision stakeholders a process to evaluate the decision basis informatively and flexibly without stochastic evaluations and appraisals. As I detail in section 6.2, I categorize the AEC decision process into five phases (i.e., definition, formulation, evaluation, iteration, and decision) and formalize the specific information management characteristics and requirements for each of these phases.

6.1.2 AEC PROCESSES AND THEIR RELATIONSHIPS WITH THE AEC DECISION PROCESS

Adapting the decision process from DA theories as the basis of the AEC decision process, I examine a design process theory that is core to the AEC process and explain how the design theory relates to my define-formulate-evaluate-iterate-decide framework.

Gero (1990, 1998) evaluates Asimov's designing^{xix} process of analysis (formulation^{xx})-synthesis-evaluation and explains how his function-behavior-structure model has further abstracted the designing process. He distinguishes behavior between expected and structure (i.e., actual). He explains that designing is made up of eight design processes: (1) formulation, (2) synthesis, (3) analysis, (4) evaluation, (5) documentation, (6) re-formulation-1 that reformulates structure, (7) re-formulation-2 that reformulates expected behavior, and (8) re-formulation-3 that reformulates function and expected behavior) that cover different interrelationships among function, behavior (expected and actual), structure, and documentation (Gero 1998).

To explain the relationship between Gero's F-B-S model and my AEC decision-making framework, it is important to first highlight the difference between their foci. The F-B-S model takes the designer as the center of its focus; it examines and generalizes the many types of design activities taken by the designers. On the other hand, my dynamic Decision Breakdown Structure framework centers on the needs of all decision stakeholders (i.e., professionals including designers, decision facilitators, and decision makers) to manage decision information to make a project decision (e.g., design decision, schedule acceleration decision, system selection decision, and an integrated decision that covers one or more of these decisions). First, I include the decision definition phase in my framework (section 6.2.1), because this sets an important step for all subsequent phases concerning the generation and management of decision information. My framework then combines Gero's (1) formulation and (2) synthesis to form the formulation phase (section 6.2.2), which

^{xix} Gero (1998) differentiates between the terms designing (i.e., process) and design (i.e., the product).

^{xx} Gero (1998) suggests that the term "analysis" has been replaced by the term "formulation" in current language.

specifies the information management needs for professionals to formulate and for facilitators to synthesize decision solutions over a longer (relative to other phases) collaboration process. My framework also combines (3) analysis and (4) evaluation to form the evaluation phase (section 6.2.3), which focuses on the information needs between the decision makers and their facilitators over a shorter (relative to the formulation phase) exchange process. As I discuss in section 6.2.4, my iteration phase covers the three types of re-formulation scenarios that Gero suggests as (6) re-formulation-1, (7) re-formulation 2, and (8) re-formulation-3. Finally, my decision phase (section 6.2.5) addresses the documentation needs that Gero motivates in his (5) documentation process. By formalizing the AEC decision-making process into five distinctive phases, I maintain the essence of the F-B-S model in design while grouping its sub-processes to reflect their impacts on the stakeholders and relationships with respect to the DA process, from which my framework is adapted.

6.1.3 AEC PROCESSES AND THEIR CORRESPONDING INFORMATION MANAGEMENT REQUIREMENTS ON AEC DECISION PROCESS

While theories in the previous section break down various AEC processes, the following paragraphs establish the metrics that are applicable for gauging the effectiveness of decision making in their associated processes.

Ballard (2000) contrasts set-based design and point-based design. He addresses the implications of set-based design: “decision-making will turn out to be an objective, well organized process, in which all the possible alternatives and factors of all the teams are taken into account, instead of a sequential, isolated process, in which decisions are made separately by each of the teams, only taking into consideration their own convenience, and not the impact of the decision on the other teams.” The thesis of his statement aligns with the motivation of this research, which illustrates that the best domain-specific solution at an earlier phase may not necessarily represent the best multidisciplinary interest at a later phase when additional information is available. Although there are no details about the means or methods for information-handling existing in the set-based design literature, it reinforces the requirements of flexibility and resumability in supporting a set-based design.

Rosenau (1992) defines performance, time, and cost as “The Triple Constraint.” He explains how ambiguous specifications, absence of planned resources, and optimistic cost estimates

are obstacles to satisfying the Triple Constraint. To determine the relative importance of each dimension of the Triple Constraint in projects, Rosenau calls for adequate discussions at the project's inception and clear conveyance of the customer's emphasis and rationale. In other words, the Triple Constraint advocates an informative and explicit sharing of conflicting constraints and recommendations.

In promoting the relationship between clients and project teams in the AEC industry, Barrett and Stanley (1999) discuss how clients are "caged in" by their original statements or decisions and explain the importance to decide as little as possible at each stage, leaving flexibility until further information becomes available. Thus, resumability and flexibility are keys to avoid a decision cage.

While McNeill et. al. (1998) study design sessions and observe the way designers spend time between design analysis (or formulation), synthesis, and evaluation (ASE); CIFE researchers Liston (2000) and Garcia et. al. (2003) assess the effectiveness of meetings. Liston et. al. (2002) provide a basis to qualify the time spent in meetings with a "Describe-Explain-Evaluate-Predict" (DEEP) framework, which Garcia et. al. (2003) have extended to include "Alternative Formulation-Negotiate-Decide/Select" (i.e., DEEP-AND). Liston et. al. (2002) further suggest that for meetings to be effective, activities should shift from relatively less value-adding tasks (e.g., descriptive and explanative tasks) to relatively more value-adding tasks (e.g., evaluative and predictive tasks).

These "ASE," "DEEP," and "DEEPAND" frameworks focus on design sessions or specific meetings. These are specific phases (e.g., formulation and evaluation) in my framework, which also assesses the ways the decision information is defined prior to formulation (i.e., the decision phase) as well as how the decision information is adjusted or reformulated after the meetings (i.e., the iteration and decision phases). In spite of the differences in foci, the processes of "ASE," "DEEP," and "DEEPAND" match well to my define-formulate-evaluate-iterate-decide framework that is adapted from Decision Analysis. Specifically, "formulate" in my framework corresponds to Asimov's "analysis" and "synthesis." "Evaluate" in my framework corresponds to Liston's "Describe," "Explain," "Evaluate," and Asimov's "evaluate." "Iterate" in my framework corresponds to Liston's "Predict," Garcia's "Alternate," and "Negotiate." Logically, my "Decide" maps to Garcia's "Decide." Hence, the Decision Analysis terminology is also applicable to other established AEC processes.

In terms of metrics, these “ASE,” “DEEP,” and “DEEPAND” frameworks focus on the allocation of time and the distinction of activity types that take place in design sessions or meetings. On the other hand, my framework focuses on the effectiveness (e.g., informativeness, quickness, flexibility, etc.) of the supporting tools and methods, which the stakeholders depend on to carry out these different types of activities. Hence, my framework is different in focus from, but is related to, the allocation of time across different activities in design sessions or meetings. These frameworks take time (e.g., the time it takes to describe a solution) as their metric. To shorten the time it takes to complete decision-enabling tasks, my research framework studies other metrics, such as informativeness, flexibility, and resumability, all of which also influence quickness. My framework promotes the effective completion of decision-enabling tasks and thus, improves the quality and shortens the time it takes to analyze, synthesize, evaluate, describe, explain, etc. Thus, my research provides a basis for decision stakeholders to measure their design and meeting activities with three other metrics in addition to time, while potentially providing them the discretion to shift time allocation among different tasks based on their assessment of their DEEP or DEEP-AND objectives.

6.2 CONTRIBUTION #3—AEC DECISION-MAKING FRAMEWORK AND THE APPLICATION OF THE DYNAMIC DYNAMIC DECISION BREAKDOWN STRUCTURE

Building on the Decision Analysis process and the concept of iteration from design theories, my third contribution is a framework that formalizes information management strategies for specific phases throughout the AEC decision-making process. The strategies center around the concept of a dynamic Decision Breakdown Structure, which serves as a decision-support tool for decision stakeholders to manage decision information. The framework dissects the decision-making process into five information management phases; explores information management characteristics and requirements during those phases; and assigns specific ontology and DMM-based methods to satisfy the requirements across the phases (Figure 31). In the subsequent sections, I validate my formal framework with industry test cases and experts’ feedback. The validation provides evidence that the framework improves the quality—in terms of informativeness, flexibility, resumability, and quickness—of information management in AEC decision making.

Similar to the AEC Decision Ontology, the concepts presented below are semantically appropriate in that they cover a broad set of information management phases, characteristics, requirements, and applications of the AEC Decision Ontology and the Decision Method Model. While my validation evidence in section 6.3 covers all five information management phases, the validation examples from the six industry cases can only represent a subset of information characteristics, requirements, and applications of the ontology and method model.

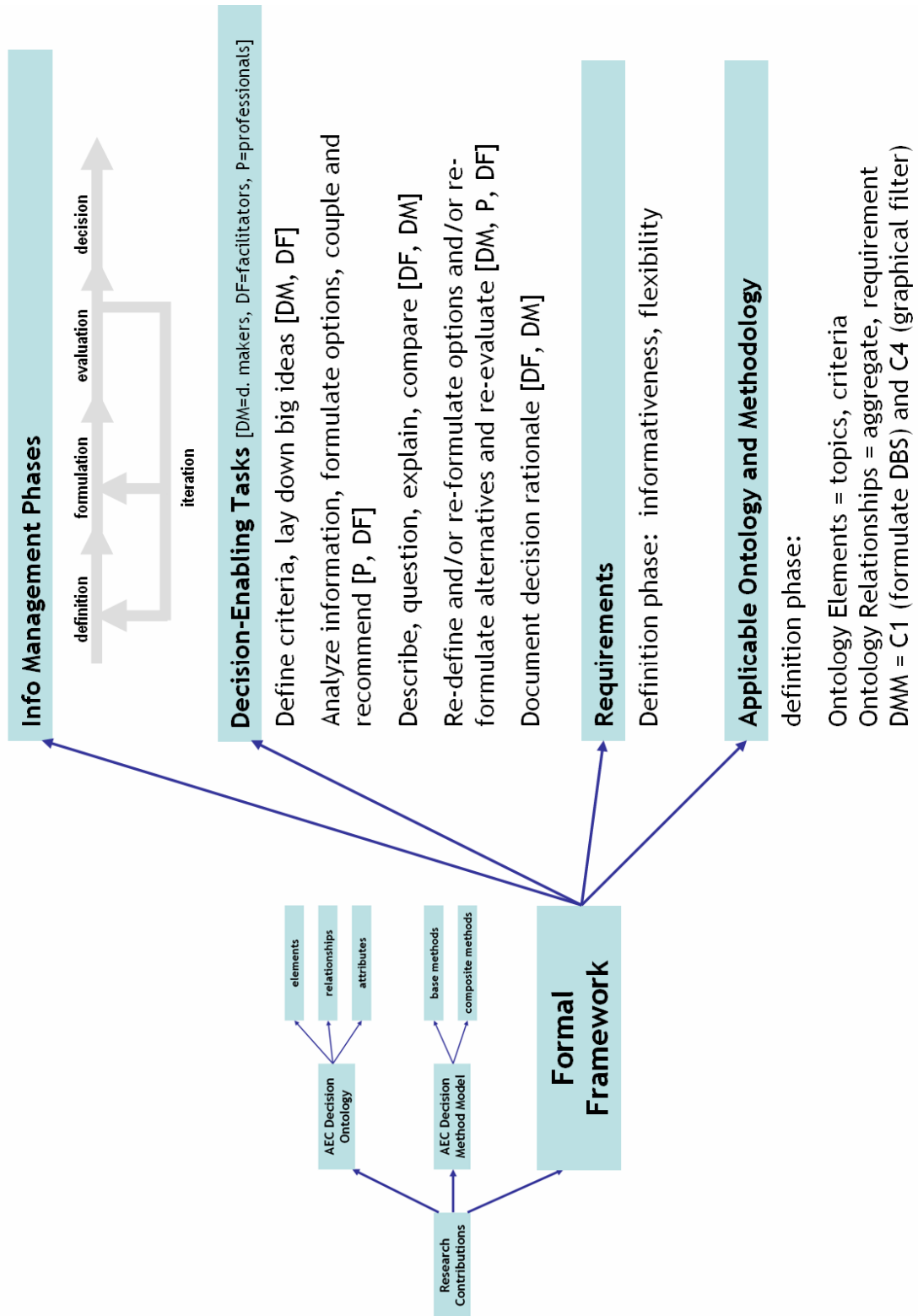


Figure 31. The Dynamic Decision Breakdown Structure Framework dissects the AEC decision-making process into five information management phases, each of which is associated with a set of phase-specific decision-enabling tasks, requirements, and applicable ontology components and methods.

The Dynamic DBS Framework associates specific decision-enabling tasks with one of the five phases. Table 8 provides an overview of the framework that is further explained in the upcoming subsections. Putting the many decision-enabling tasks presented so far in the context of the framework, I abbreviate each one of these tasks with a “DET#” (i.e., decision-enabling task number^{xxi}). These DET#’s are listed in the corresponding framework phases in Table 8. All together, there are 15 decision-enabling tasks from the motivating case example (Table 1) as well as the industry test cases (Chapters 2 and 5). Here are these tasks and their corresponding DET#’s:

Eight Decision-Enabling Tasks that have been followed in Chapters 2 and 5:

- Re-Formulate a Hybrid Solution (DET#1)
- Respond to an Impromptu Query about Decision Information in a decoupled form (DET#2)
- Respond to an impromptu evaluation between alternatives and criteria (DET#3)
- Explain prediction assumptions and make necessary corrections (DET#4)
- Evaluate macro and micro impacts among three case scenarios (DET#5)
- Evaluate decision information in the executive summary (DET#6)
- Comprehend the ripple consequences of a specific decision option (DET#7)
- Explain and comprehend different decision alternatives (DET#8)

^{xxi} DET#’s 1 through 8 listed in this section follow the same numbering convention as the decision-enabling tasks presented in Chapters 2 and 5.

Seven Decision-Enabling Tasks from the Motivating Case Example in Chapter 1 (section 1.2.1):

- Define Decision Criteria (DET#9)
- Formulate Decision Options (DET#10)
- Formulate Decision Alternatives (DET#11)
- Recommend Decision Alternatives (DET#12)
- Explain/Access Decision Information (DET#13)
- Predict/Evaluate Decision Information (DET#14)
- Iterate What-If Adjustments (DET#15)

Framework Phases	Characteristics of Information Management (types of decision-enabling tasks)	Metrics	Applicable Ontology and DMM
Decision Definition	<p>decision makers define criteria</p> <p>decision makers and facilitators lay down the big ideas</p> <p>Examples: DET#9 and TC#5 (section 6.3.1)</p>	<p>informativeness</p> <p>flexibility</p>	<p>Outline the Decision Breakdown Structure (DBS) with the following ontology parts: Elements: decision topics, criteria Relationships: aggregate, requirement</p> <p>C1: Formulate a Decision Breakdown Structure C4: Filter Graphical Representation of a Decision Breakdown Structure</p>
Formulation	<p>professionals analyze information from definition phase</p> <p>professionals come up with different options</p> <p>based on analytical skills and experience, facilitators integrate (or couple) options into alternatives for recommendations</p> <p>Examples: DET#6, 10, 11 and TC#6 (section 6.3.2)</p>	<p>informativeness</p> <p>flexibility</p> <p>quickness</p>	<p>All ontology elements and relationships that are needed to develop a complete DBS</p> <p>B6: Evaluate in Different Contexts and Across Different Levels of Detail C1: Formulate a Decision Breakdown Structure C2: Swap Decision Information Between Selected and Candidate States C4: Filter Graphical Representation of a Decision Breakdown Structure</p>

Evaluation	<p>facilitators describe recommended proposals</p> <p>decision makers question and facilitators explain</p> <p>decision makers compare proposals against criteria</p> <p>Examples: DET#2, 3, 5, 6, 7, 8, 12, 13, and 14</p>	<p>informativeness</p> <p>flexibility</p> <p>quickness</p>	<p>All ontology elements and relationships from the DBS</p> <p>B1: Manage Decision Information, Relationships, and Attributes</p> <p>B6: Evaluate in Different Contexts and Across Different Levels of Detail</p> <p>C3: Interact in the iRoom Environment</p> <p>C4: Filter Graphical Representation of a Decision Breakdown Structure</p>
Iteration	<p>when evaluation determines that the recommendations do not meet the criteria or when there is time and there is room for improvement:</p> <p>decision makers re-define (relax or constrict) decision criteria; and/or</p> <p>professionals re-formulate new options; and/or</p> <p>facilitators re-formulate new alternatives (i.e., coupling of options); and</p> <p>decision makers re-evaluate (new) criteria against new proposals</p> <p>Examples: DET#1,4, and 15</p>	<p>resumability</p>	<p>All ontology elements and relationships that are needed to modify the existing DBS</p> <p>B1: Manage Decision Information, Relationships, and Attributes</p> <p>B6: Evaluate in Different Contexts and Across Different Levels of Detail</p> <p>C1: Formulate a Decision Breakdown Structure</p> <p>C2: Swap Decision Information Between Selected and Candidate States</p> <p>C3: Interact in the iRoom Environment</p> <p>C4: Filter Graphical Representation of a Decision Breakdown Structure</p>
Decision	<p>document decision rationale</p> <p>Example: Transition from TC#3 to TC#1 (section 6.3.5)</p>	<p>informativeness</p>	<p>Document and archive the DBS with the ontology attributes present in the elements and relationships</p> <p>B1: Manage Decision Information, Relationships, and Attributes</p> <p>B4: Reference Existing Decision Information</p>

Table 8. An overview of the contribution of an information management framework for the application of the dynamic Decision Breakdown Structure.

6.2.1 DEFINITION PHASE

The decision definition phase is the beginning of a decision-making process. This is the phase when the decision stakeholders lay down a decision scenario, when they define the scope and objectives of the decision-making process, when they lay out their big ideas about the criteria, opportunities, concepts, and available decision information associated with the decision scenario (e.g., prescribed budget, irrevocable milestones, or incurred delay that needs to be mitigated, etc.). The decision makers often take a more active role during the definition phase than in later phases as they define the big ideas for their decision facilitators and professionals to work out during the decision formulation phase.

6.2.1.1 DECISION INFORMATION CHARACTERISTICS

During the decision definition phase, the decision stakeholders often deal with the following decision information: decision scope, criteria, the big ideas, opportunities, concepts, milestones, schedule information, and available referenced documents (such as design guides and budget).

6.2.1.2 INFORMATION MANAGEMENT REQUIREMENTS

For decision stakeholders to be able to effectively lay out the decision information described above, they should manage the information in a way that is both informative and flexible. In the subsequent section, I show how these requirements serve as the metrics for my validation analysis of the decision definition phase.

Informativeness

The ability of a decision-support tool and its method to handle a diverse amount of decision information that arises from the definition phase determines whether the decision stakeholders can undergo an informed decision process. Informativeness may be compromised if the decision-support tool requires mitigating interventions from its users to incorporate, integrate, and distinguish a dispersed set of multidisciplinary information.

Flexibility

In addition to the requirement of informativeness, the decision-support tool and its method also have to allow decision stakeholders to manage the set of decision

information with flexibility. Flexible information management during the definition phase allows stakeholders to effectively incorporate new information and adjust its organization as new ideas and conditions arise.

6.2.1.3 APPLICABILITY OF AEC DECISION ONTOLOGY TO THE DEFINITION PHASE

The decision information of the definition phase can be represented in the DD using the AEC Decision Ontology (Chapter 4). Instances of a decision topic can be populated by decision stakeholders to represent the decision scope, the big ideas, and the solution concepts. Instances of a decision criterion assist decision stakeholders to document the criteria and the metrics that shape the decision-making process. Aggregate and requirement relationships enable decision stakeholders to organize the decision topic instances in this early phase development of a DBS. Meanwhile, level-1 decision information such as specific milestone dates, schedule information, and budget numbers can be embedded as attributes within the ontology element or relationship instances. Decision stakeholders can also use the attribute in the DD to reference level-2 decision information in the form of available electronic documents, such as design guides and budget spreadsheets. These concepts are illustrated in the context of validation with industry test cases in section 6.3.1.

6.2.1.4 APPLICABILITY OF THE DMM TO THE DEFINITION PHASE

The following DMM composite methods are particularly applicable during the definition phase:

C1: Formulate a Decision Breakdown Structure

C4: Filter Graphical Representation of a Decision Breakdown Structure

DMM Composite Method C1 enables decision stakeholders to represent the information with the AEC Decision Ontology as discussed in the above section. During this phase, decision stakeholders primarily work with a high-level DBS, which outlines the decision scenario with the big ideas and concepts. DD users may choose to create a DBS using a top-down (i.e., follow the hierarchy of the decision scenario from macro to micro issues), bottom-up (i.e., let the details drive the hierarchy), or hybrid approach. In any of the three approaches, composite method C1 allows DD users to incorporate, integrate, and distinguish a diverse set of decision information. Furthermore, users can

sort out and filter the decision information anytime during the definition process (Composite Method C4). Based on the case-specific applications of these methods, section 6.3.1 validates that the AEC Decision Ontology and the DMM improve the informativeness and flexibility of information management during the decision definition phase.

6.2.2 FORMULATION PHASE

During the decision formulation phase, the facilitators and the professionals (leaders, their team members, and their sub-consultants) work iteratively to analyze the decision information gathered during the definition phase and come up with different solution proposals for recommendation during the evaluation phase. In AEC projects, professionals such as structural engineers, HVAC consultants, and cost estimators usually work asynchronously and in parallel to provide discipline-specific inputs in formulation of domain-specific proposals. Decision facilitators, such as owner's representatives or lead architects, integrate inputs gathered from the professionals and come up with holistic and multidisciplinary decision proposals that, according to their professional analytical skills or experience, best respond to the opportunities and challenges laid out during the definition phase. The decision facilitators take a leading role in formulating a strategy or recommendation for presentation to the decision makers during the decision evaluation phase.

6.2.2.1 DECISION INFORMATION CHARACTERISTICS

During the decision formulation phase, the AEC professionals generate and manage the bulk of decision information involved in the decision-making process. The decision information generated may include intra-disciplinary assumptions, ideas, and predictions; recommended options and their competing choices; product, organization, and process models; cross-disciplinary relationships and ripple consequences; recommended and competing sets of alternatives; and evaluation tables, etc. In addition, the professionals continue to generate and manage all the decision information outlined in the definition phase, such as criteria, the big ideas, and milestones, etc.

6.2.2.2 INFORMATION MANAGEMENT REQUIREMENTS

The generation of different solution proposals during the formulation phase requires that information management be informative, flexible, and quick. These requirements ensure that the decision information management process is conducted effectively.

Informativeness

Informativeness during the formulation phase refers to the ability of a decision-support tool and method to inform the stakeholders about the states, details, and interrelationships between decision information. This determines whether the stakeholders can provide and retrieve information about the individual options, their predicted behaviors, and their ripple consequences, and whether they are included or not under different alternatives. Having an informative management is significant because it ensures that the stakeholders are knowledgeable about the most current limitations and opportunities in the decision scenario to allow them to better apply their professional judgment when formulating alternatives for recommendation.

Flexibility

Similar to the definition phase, flexibility and informativeness are required when formulating decision solutions. Flexibility is desirable when decision facilitators generate different evaluation tables that need to cover decision issues spanning different levels of detail. Flexibility allows decision facilitators to couple and decouple decision information, and thus dynamically adjust and re-organize the recommendations in response to new inputs gathered from professionals across different disciplines. Therefore, flexibility provides decision stakeholders the opportunity to respond to new information and delay their final commitment to a specific course of recommendation.

Quickness

The amount of decision information that needs to be managed during the formulation phase means that quickness in completing those information management tasks is important for efficiency and quality. The quicker the incorporation of new options, the coupling of options into alternatives, and the preparation of the recommendation set, the more efficient the formulation process. Quickness complements informativeness and flexibility. If decision-support tools and methods compromise quickness in achieving informativeness and flexibility, the value of the formulation phase in exploring multiple options and uncovering interrelationships between information is jeopardized.

6.2.2.3 APPLICABILITY OF AEC DECISION ONTOLOGY TO THE FORMULATION PHASE

As the formulation phase involves the handling of the most diverse set of decision information, it also requires the complete set of my ontology elements, relationships, and attributes to handle the diverse information in the DBS. Instances of the ontology elements topic, criterion, option, and alternative allow DD users to represent information such as ideas, requirements, options and their competing choices, and recommended or competing sets of alternatives. Instances of the ontology relationships aggregate, choice, requirement, impact, and process are respectively capable of representing the structure of the recommended alternative, competing choices, constraints and requirements, cross-disciplinary relationships and ripple consequences, and temporal dependencies. Finally, attributes embedded within ontology elements and relationships enable DD users to integrate or reference a variety of detailed decision information to the DBS. Examples of attributes include assumptions, rationales, predictions, schedule, evaluation tables, electronic files, POP models, and hyperlinks.

6.2.2.4 APPLICABILITY OF THE DMM TO THE FORMULATION PHASE

The DMM offers the following base and composite methods that are applicable during the formulation phase:

B6: Evaluate in Different Contexts and Across Different Levels of Detail

C1: Formulate a Decision Breakdown Structure

C2: Swap Decision Information Between Selected and Candidate States

C4: Filter Graphical Representation of a Decision Breakdown Structure

To follow up with the DBS outline initiated during the definition phase, decision facilitators and professionals continue to use DMM Composite Methods C1 and C4 in building and assessing a Dynamic DBS. With the use of the ontology to represent decision information (as discussed in the above section), they can enrich the DBS with Composite Methods C1 and C2 to further distinguish the states of an ontology instance, incorporate information details, flexibly adjust the decision state of information, and formulate competing sets of alternatives, etc. These enrichments are integral to the DBS and, therefore, provide a quick and informative tool for decision facilitators to manage the diverse and evolutionary set of decision information. Furthermore, in preparation for the evaluation phase, decision facilitators and professionals can generate

evaluation tables quickly and flexibly between criteria and proposed solutions at macro, micro, or hybrid levels of detail (Base Method B6).

6.2.3 EVALUATION PHASE

During the decision evaluation phase, decision facilitators present their recommendations to the decision makers. This evaluation may take place synchronously (in a face-to-face briefing scenario, e.g., TC#1 and #4) or asynchronously (as a report submission, e.g., TC#2 and #3). In either case, the decision makers need to comprehend the proposed recommendations set forth by the facilitators. Should the decision makers have any questions or confusions, the facilitators would respond and explain them. Comprehension and explanation are followed by analysis of the decision information. Decision makers, with professional advice from the facilitators, analyze the recommendations and determine whether the alternatives meet the criteria and solve the problems laid out during the definition phase. If the decision makers are satisfied with the alternatives, the decision-making process can proceed to the decision phase. Otherwise, the process needs to go through additional iterations of re-definition and/or re-formulation to refine the criteria and/or the solution. The iteration phase (see section 6.2.4) also involves re-evaluation and possibly additional cycles of re-definition and/or re-formulation and re-evaluation until the decision makers accept the alternative(s) and move on to the decision phase.

6.2.3.1 DECISION INFORMATION CHARACTERISTICS

As the decision-making process proceeds to the evaluation phase, the raw decision information from the definition and formulation phases has been synthesized by facilitators into an organized form for the purposes of presentation, explanation, comprehension, and analysis. This transformation into an organized form often gives rise to new pieces of decision information of their own, such as new presentation media, comprehensive documentation for explanation, visual aids for comprehension, and evaluation tables for analysis.

6.2.3.2 INFORMATION MANAGEMENT REQUIREMENTS

In synchronous evaluation, decision facilitators often rely on the decision-support tools, methods, and media to assist in their explanation of the recommended solutions. In

asynchronous evaluation when decision facilitators are absent, decision makers rely on the decision-support tools, methods, and media to assist in their comprehension of the recommended solutions. Be it synchronous or asynchronous, the more informative, flexible, and quicker the decision-support tools, the better the evaluation phase, and the lesser the burden on the decision facilitators to respond to confusion experienced by the decision makers.

Informativeness

An important requirement for the evaluation phase is to succinctly inform the decision makers (e.g., owners, end-users, owner's representatives, etc.) about the recommendations made by the decision facilitators, who based their recommendations on balancing what the decision makers want (gathered during the definition phase) versus what the professionals offer (gathered during the formulation phase). Therefore, the decision-support tool and method should assist the facilitators in informing the decision makers about the available sets of solution proposals, their interrelationships or ripple consequences among one another, rationale, predictions, criteria, judgments, strengths, and weaknesses. Informativeness requires access to evaluation tables and an array of decision information (e.g., criteria, documentation, assumptions, POP models, etc.).

Flexibility

Flexibility facilitates effective access to and evaluation of pertinent decision information during the evaluation phase. Flexible decision-support tools and methods allow stakeholders to access and evaluate decision information across varying media and across different levels of detail. This is particularly important for facilitators to provide explanations to impromptu questions posed by the decision makers. Without a flexible tool or method, decision facilitators are restricted by the predetermined form and focus of decision information that are often the sources of restriction that give rise to questions or confusion among the decision makers.

Quickness

Quickness matters during the evaluation phase because evaluation usually takes place in meetings or during a short review cycle. It is crucial for every single decision maker involved to comprehend the recommended alternatives as quickly as possible. The quicker the explanation and comprehension, the sooner the stakeholders can move on to

elevate their collective attention to tasks that are more value-adding, such as decision analysis and negotiation.

6.2.3.3 APPLICABILITY OF AEC DECISION ONTOLOGY TO THE EVALUATION PHASE

Following the Decision Dashboard approach, DD users can rely on the Decision Breakdown Structure (which is built during the definition and formulation phases) to facilitate the presentation, explanation, comprehension, and analysis of the organized decision information. The DBS is a master set of the complete network of ontology elements, relationships, and attributes generated in the previous decision phases. With its graphical window, the DD uses symbolic shapes, arrows, and a color system to abstractly represent decision information relevant to the decision evaluation. Synchronous and asynchronous presentations can be conducted with the DBS itself, eliminating the need to custom-generate a parallel medium for presentation and comprehension purposes. The DD graphical window and its accompanied DMM-based method to filter the DBS (Composite Method C4) serve as a visual aid for comprehension. Documentation and evaluation tables are available in the form of attributes within the elements and relationships in the DBS.

6.2.3.4 APPLICABILITY OF THE DMM TO THE EVALUATION PHASE

The DMM offers the following base and composite methods that contribute to an informative, flexible, and quick evaluation:

B1: Manage Decision Information, Relationships, and Attributes

B6: Evaluate in Different Contexts and Across Different Levels of Detail

C3: Interact in the iRoom Environment

C4: Filter Graphical Representation of a Decision Breakdown Structure

Using a DBS developed during the definition and formulation phase, the decision facilitators can take advantage of its dynamic behavior to perform various decision-enabling tasks during the evaluation phase. For instance, DD users (decision makers or facilitators) may inform themselves or their audience about the assumptions, scope, details, and predictions pertaining to different options and alternatives (Base Method B1). They may flexibly and quickly bring up referenced information within the same computer or across different computers and displays across the CIFE iRoom

(Composite Method C3). Furthermore, the DD gives its users an informative, flexible, and quick focus on the big ideas and/or detailed information across different levels of detail (Composite Method C4), while taking criteria and competing choices into consideration in a dynamic and interactive manner (Base Method B6).

6.2.4 ITERATION PHASE

After the decision evaluation phase, the decision stakeholders may find that the proposed recommendations are not meeting the decision criteria or that there is still opportunity to refine the decision options or alternatives. In either case, they may choose to go through additional iteration(s) of decision re-definition and/or re-formulation and re-evaluation. During the iteration phase, there are three scenarios for the decision stakeholders to continue the decision-making process. First, as the decision makers learn more about the predicted performance of the available proposals, they may choose to relax or constrict the decision criteria (e.g., functional requirements). This leads the decision making into a re-definition phase, which requires the facilitators and the professionals to refine their formulation to accommodate the different conditions of the decision scenario. Second, the decision stakeholders may come up with better proposals to solve the same set of decision criteria. This may involve generation of new options and/or new coupling of existing options to re-formulate new alternatives. Third, the decision stakeholders may decide to refine the criteria and come up with new formulation plans. In any of these three scenarios, the stakeholders need to re-evaluate the latest version of recommendations against that of the criteria. During re-evaluation, the decision stakeholders can collectively decide whether the decision-making process should continue with the iteration phase or proceed to the decision phase.

6.2.4.1 DECISION INFORMATION CHARACTERISTICS

Given the nature of the iteration phase, the decision stakeholders may update and adjust the available set of decision information. They may also introduce new instances, but not new types, of decision information.

6.2.4.2 INFORMATION MANAGEMENT REQUIREMENTS

Informativeness, quickness, and flexibility are requirements that are inherited from the definition, formulation, and evaluation phases. Meanwhile, resumability is the unique

requirement that complements these three requirements, while distinguishing the iteration phase from the previous three phases.

Resumability

Resumability is an important requirement that is unique for the iteration phase, which involves adjustments to the decision information introduced during the definition and/or the formulation phase(s). The nature of resumable information management embodies the ability to fully inherit a previous state of decision information and continue with further adjustments. The higher the degree of resumability in a decision-support tool or method, the lesser the delay (due to latency) and fewer the errors (due to rework) in the iteration phase. Delays and errors are closely related to the requirements of quickness and informativeness, respectively.

6.2.4.3 APPLICABILITY OF AEC DECISION ONTOLOGY AND THE DMM TO THE ITERATION PHASE

The iteration phase inherits the concept and applicability of the AEC Decision Ontology and DMM-based methods from the definition, formulation, and evaluation phases. Following is the collective set of DMM base and composite methods from the three previous phases:

B1: Manage Decision Information, Relationships, and Attributes

B6: Evaluate in Different Contexts and Across Different Levels of Detail

C1: Formulate a Decision Breakdown Structure

C2: Swap Decision Information Between Selected and Candidate States

C3: Interact in the iRoom Environment

C4: Filter Graphical Representation of a Decision Breakdown Structure

In terms of information management, the iteration phase involves the introduction of new decision information and/or the adjustment of existing decision information. While the previous sections discussed the applicability of the AEC Decision Ontology and the DMM in defining, formulating, and evaluating new decision information, the following discussion centers on the methods of adjusting existing decision information with the DD.

DD users may re-define the criteria, the big ideas, and the solution concepts by using the “edit” method feature in the DD using DMM Base Method B1. In re-formulation, they may resume the AEC decision-making process with the previous set of information by de-coupling and re-coupling decision options, by swapping the states of decision information, and by changing the structure of a recommended proposal (Base Method B1 and Composite Methods C1 and C2). In re-formulation and re-evaluation, DD users can re-associate decision information with updated sets of electronic references; they can then retrieve these references with the proper software applications with a personal computer and/or computers in the iRoom environment (Composite Method C3). Furthermore, they can quickly and flexibly adjust the focus, choices, criteria, and/or attributes that are displayed in an existing evaluation table (Base Method B6).

6.2.5 DECISION PHASE

The final phase of information management in AEC decision making is the decision phase. Ideally, decision stakeholders arrive at this phase because they find one or multiple alternatives satisfactory in relation to the decision criteria for a final selection. However, the reality of AEC projects and the mismatch between what decision makers want versus what the alternatives offer may force decision stakeholders to make a suboptimal and premature decision due to project schedule reasons. In other words, there may be no satisfactory proposals available that can meet the owner’s schedule, budget, and performance requirements by the time that the stakeholders must make a final project plan decision. Either in the ideal or in the suboptimal case, the decision stakeholders need to decide upon a specific set of action plans and commit to resource allocation in the decision phase. They shall document the rationale of their decision as well as the details of what the decision entails.

The decision phase concludes the decision-making process with respect to one specific decision scenario. This may lead to the execution of the action plans as determined by this decision-making process (e.g., in TC#4, the decision is followed by the execution of the selected acceleration proposal). Otherwise, if the current decision pertains to a sub-decision within a set of decisions, the conclusion may lead to additional decision scenarios pertaining to other related decision issues (e.g., in TC#1, the decision pertained to the schematic design phase and was preceded by the pre-design study, i.e., TC#3; and was followed by another

decision-making process to address other design and construction issues during the design development phase).

6.2.5.1 DECISION INFORMATION CHARACTERISTICS

During the decision phase, decision stakeholders may generate new decision information to enrich the current information set. This enrichment may involve documentation of decision rationale or detailing of the final chosen solution.

6.2.5.2 INFORMATION MANAGEMENT REQUIREMENTS

Whether or not the decision support tool and method promote an informative documentation determines the quality of the information management in the decision phase.

Informativeness

The decision rationale, the approved course of action, the specific plans of resource allocation, the action items, and the agreed-upon roles and responsibilities shall be captured and archived before the decision stakeholders conclude the decision process. This decision information will become a crucial information basis for the successful execution of the decision that has been carefully put together during the decision-making process. Hence, the more informative the final state of information, the better the execution of the decision. In execution of the decision, unforeseen conditions and new states of information may affect the development of the tactical plans. To accommodate the new conditions, one may need to comprehend the rationale of the decision to adjust tactical operations without violating the intent of the original decision. Therefore, informativeness also affects the support for future queries about the decision rationale and for alterations of the existing decision for any unforeseen strategic or tactical reasons.

6.2.5.3 APPLICABILITY OF AEC DECISION ONTOLOGY TO THE DECISION PHASE

Documentation of decision rationale and detailing of the final chosen solution can be incorporated into the DBS with the ontology attributes. DD users can associate relevant

comments and the decision rationale, in the form of a text field attribute, with the appropriate ontology elements in the DBS.

6.2.5.4 APPLICABILITY OF THE DMM TO THE DECISION PHASE

The decision phase calls for the following DMM Base Methods in support of the documentation needs:

B1: Manage Decision Information, Relationships, and Attributes

B4: Reference Existing Decision Information

With Base Method B1, DD users can generate new attribute fields or edit existing attributes when they need to incorporate new decision rationale or enrich existing documentation about the decision. Furthermore, they can continue to reuse the DBS in future decision-making processes while keeping an archived version of the current decision in the same model (archive method feature in Base Method B1). Should there be additional electronic references that can enrich the current decision rationale or documentation, DD users can associate them with the appropriate element or relationship instances in the DBS.

6.2.6 CONCLUSION FROM CONTRIBUTION #3

All decision information and associated knowledge captured throughout the five information management phases in AEC decision making are present in a DBS. The dynamic behaviors of the DMM allows decision stakeholders to informatively query, flexibly adjust, easily resume, and quickly manage such decision information during and after the decision phase.

In the above sections, I explained the five information management phases in AEC decision making. For each phase, I described the characteristics of the decision information as well as the requirements pertaining to the decision-support tool and method. With respect to these particular characteristics and requirements, I presented the applicability of my AEC Decision Ontology as well as the Decision Method Model. In the following sections, I validate this framework with industry test cases and expert feedback.

6.3 VALIDATION STUDY #3—INFORMATIVE, FLEXIBLE, RESUMABLE, AND QUICK DECISION PROCESS

In Validation Study #3, I analyze the Dynamic DBS framework across its five information management phases in AEC decision making (i.e., definition, formulation, evaluation, iteration, and decision phases). For each of these phases, I analyze the AEC decision-making processes and categorize the impacts of the Dynamic DBS Framework and the application of the Dynamic DBS on the six industry cases by my validation metrics—*informativeness, flexibility, resumability, and quickness*—that I introduced in Chapter 3.

6.3.1 ANALYSIS OF DYNAMIC DBS FRAMEWORK DURING THE DECISION DEFINITION PHASE

Requirements

Informativeness and Flexibility

Applicable AEC Decision Ontology

1. Elements: Topic and Criterion
2. Relationships: Aggregate and Requirement
3. Attributes

Applicable DMM Methods

C1: Formulate a Decision Breakdown Structure

C4: Filter Graphical Representation of a Decision Breakdown Structure

Evidence Examples

- 1: An afternoon definition meeting with two industry professionals (TC#5)
- 2: Definition of TC#1
- 3: Definition of TC#2
- 4: Definition of TC#3
- 5: Definition of TC#4

ANALYSIS

This section compares and analyzes conventional versus DBS-based methods and tools in support of informative and flexible information management during the definition phase. In current practice, the definition of the decision information (e.g., decision scenario, the big ideas, the scope of the decision making, and concepts of alternatives and options) involves brainstorming sessions among the stakeholders, jotting down blue-sky ideas on the white boards, producing session minutes using word-processing tools, and coming up with the definition statement in a report form.

Using the Dynamic DBS, decision stakeholders can start managing the decision information with the same decision-support tool that continues to accrue decision information and support information management throughout the decision-making process. This continuity eliminates the need to rely on multiple tools that may involve information re-entry. Meanwhile, current practice may use word-processing methods such as sub-headings and bullets to organize or distinguish information. This approach is less informative and flexible when compared to the building of a DBS, which allows DD users to informatively distinguish decision information with different types and states of ontology elements and flexibly organize the information with a set of explicit relationships.

In an afternoon meeting with two industry professionals (a project executive and a director), I introduced them to the concepts embodied in the Decision Dashboard. Together, we built a decision definition model using the DD, its ontology representation and DMM (TC#5). The project executive showed me a piece of paper with his personal notes, featured with circles, numbers, and lots of descriptions about the project. This was the current method he used to document his perspective of the decision information. He concurred that when exchanging his notes and ideas with his project team, they relied on white boards and paper-based minutes as their documentation tools.

We began the DD-based session by first defining the decision need and the major factors affecting the decision (using the decision topic element and Composite Method C1). Once we had instances of annotated decision topics randomly inserted in the DD graphical window, we organized the decision topics into a two-tiered, and subsequently a three-tiered, Decision Breakdown Structure (using the aggregate relationship and

Composite Method C1). We identified that cost was a major parameter that affects the decision scenario and that the challenge was to generate, track, and manage different cost accounts in the project. We documented this important parameter in the DD with the ontology attribute, we documented the value of the major cost items by filling the attribute value in the DD. We then introduced a parallel tier of decision topics, with aggregate relationships instantiated to the appropriate topics, to track the major cost accounts. Throughout the session, DMM Composite Method C4 assisted our definition process by dynamically isolating and focusing the elements or relationships that pertained to our discussion.

At the end of the 2-hour definition session using the DD, we came up with an outline of a project DBS. The Dynamic DBS was more informative than current methods since it allowed all stakeholders to get a public and explicit understanding about all the decision information, its type, state, and relationship in one central version. The Dynamic DBS was also more flexible, since it enabled stakeholders to test attribute propagation, isolate a decision focus, and change the state, relationship, or type of decision information during the decision definition phase. The two professionals also believed that the informative and flexible nature of the DBS could contribute to the integration of their internal work breakdown structure and cost accounting practice. Last, their recommendation to continue with the Dynamic DBS in the project with the extended project team (provided that the project passes through the approval stage) was another positive testament of the power and value of the Dynamic DBS.

6.3.2 ANALYSIS OF DYNAMIC DBS FRAMEWORK DURING THE FORMULATION PHASE

Requirements

Informativeness, Flexibility, and Quickness

Applicable AEC Decision Ontology

1. Elements: Topic, Criterion, Option, and Alternative
2. Relationships: Aggregate, Requirement, Choice, Impact, and Process
3. Attributes

Applicable DMM Methods

B6: Evaluate in Different Contexts and Across Different Levels of Detail

C1: Formulate a Decision Breakdown Structure

C2: Swap Decision Information Between Selected and Candidate States

C4: Filter Graphical Representation of a Decision Breakdown Structure

Evidence Examples

1: Uncovering of assumption error in a seismic upgrade project (TC#6)

2: Uncovering of calculation error in TC#2

3: Formulation of TC#1

4: Formulation of TC#2

5: Formulation of TC#3

6: Formulation of TC#4

ANALYSIS

Following the DBS Framework, I applied the ontology and the DMM to formulate five dynamic Decision Breakdown Structures for five decision scenarios (i.e., TC#1-4, and TC#6). When compared to conventional decision-support methods and tool sets, the DBS formulation enables the uncovering of information errors and the management of diverse sets of decision information in a way that is quicker and more flexible than current practice.

It is also important to note that definition and formulation phases play an important role in seeding the information basis for subsequent information management needs during the evaluation, iteration, and decision phases. In other words, evidence of positive DBS applications in the subsequent decision phases also demonstrates the power and generality of DBS definition and formulation (in addition to the following analysis).

Informativeness

In the test cases, current practice relies on a variety of decision-support tools and methods to manage information for decision formulation. The previous chapters described and explained that decision stakeholders in the test cases relied upon generic

(non AEC-specific) tools, such as MS PowerPoint and word-processing tools, as well as generic methods, such as pre-determined evaluation tables, slide presentations, and document sub headings to manage heterogeneous decision information. These tools and methods are not tailored for handling the characteristics of AEC decision information. They do not integrate or reference decision information. When formulating a set of proposed alternatives for recommendation, current practice requires decision facilitators and professionals to re-generate slide presentations (TC#1 and TC#4) or paper-based reports (TC#2 and TC#3) that have no integration or reference relationships with the working set of decision information. Furthermore, there are no methods to informatively categorize or distinguish dispersed information. As a result, facilitators and professionals need to manage dispersed sets of decision information and need to make mental connections to fill in the knowledge associated with the interrelationships among the information. After summarizing the DBS approach in the DD, the following sections present additional evidence examples on how current practice undermines the stakeholders' ability to uncover findings informatively.

Following the DBS Framework to build the industry test cases, I was able to use a single and central decision-support tool that interacts with the decision information. This single information management support allowed me to reconstruct the representation and organization of the decision information using the applicable ontology and DMM (section 4.3). Consequently, the resulting sets of recommended alternatives explicitly distinguish the types (e.g., topic or criteria), states (candidate or selected), relationships, ripple consequences, and references that are associated with the decision information. Such explicit documentation and organization provides a more informative basis for DD users to generate and analyze different alternatives.

In particular, my formulation of TC#2 and TC#6 in the DD gave me opportunities to integrate different sets of attributes while propagating them across different topics and alternatives (see following two paragraphs). The integrative nature of the DBS enabled me to uncover assumption conflicts and calculation errors that were more difficult to identify, and had not been uncovered by professionals using conventional tools and methods.

In TC#2, the paper-based cost-benefit analysis report represented the simple payback result of the Green Roof feature three times. Since data was not integrated in the report, the payback result had to be re-entered individually. In my reconstruction of the same payback result with DMM-based methods, I only used one formula to compute the payback result, and propagate this result to other dependent ontology elements (rather than re-entering the information three times). Comparing the DD results with the paper-based report, I was able to identify a discrepancy between the provided data (which proved the payback period as 15.3 years) and the re-entered payback period (which was printed as 11 years in two appearances).

Similarly in TC#6, I rebuilt a professional cost consultant's document-based report in the DD. My DD reconstruction allowed me to incorporate all the assumption values (e.g., additive overtime cost, deductive overhead savings, and deductive inspection cost, etc.) as a unified set of attributes that could be propagated (rather than re-entered as in current practice) across a DBS using DMM-based methods. Working with a single set of parameters allowed me to uncover a fundamental error (associated with the computation of deductive cost in schedule acceleration) with the formula listed in the document-based report. This assumption error translated into a significantly different cost-benefit ranking of the available alternatives. I immediately brought this DD-based finding to the attention of the project executive and the project manager, who were able to incorporate this major cost impact in their formulation of a recommended project alternative. At the same time, the project manager also informed the cost consultant about the DD-based finding. The cost consultant also concurred with the DD-based finding.

These two cases demonstrate that the integration approach of the DBS fosters informativeness by cross-checking the data and coordinating the data with single representation, central references, explicit organization, and consistent propagation.

Flexibility

Flexibility during the formulation phase allows decision facilitators to couple and decouple decision information, it also allows facilitators to flexibly adjust the content and focus of evaluation. The evidence examples show that the DD supports a higher degree of flexibility than conventional decision-support tools and methods used in

current practice. Decision facilitators in the formulation of all five evidence examples were only able to either couple or discard decision information with MS PowerPoint or a word-processing tool. The process of generating presentation slides or printed reports does not offer any flexibility for access to decision information that was discarded by the facilitators during the formulation process. In contrast, the ontology and DMM-based DD offer this flexibility. DD users can flexibly turn an ontology element into a candidate or selected state (Composite Method C2) while formulating the recommended proposal (Composite Method C1). This flexibility preserves all seemingly invalid decision information throughout the decision-making process in the DBS, allowing DD users to flexibly and quickly couple, de-couple, and re-couple information without the needs for deletion or re-entry.

Evaluation tables formed an important basis for decision making in TC#1 and TC#2. Current methods lack the flexibility to affect the focus and content of evaluation tables during the formulation phase, and thus adversely impact the informativeness of the decision makers during the evaluation phase (Decision-Enabling Task #3 and Decision-Enabling Task #6 in Validation Study #2, Chapter 5). On the other hand, the Base Method B6 provides a flexible solution for DD users to change the evaluation focus by highlighting the particular decision topic of interest, to evaluate content across macro, micro, and hybrid levels of detail by assigning aggregate and requirement relationships in association with an evaluation table, and to dynamically and interactively change the attributes displayed in an evaluation table. Such flexibility was evidenced in Decision-Enabling Task #6 (section 5.3).

The DD overcomes the limitations of pre-determined coupling and evaluation of decision information in current practice. As discussed in the contribution section (i.e., section 6.2.2), this added flexibility benefits decision stakeholders with the opportunity to respond to new information, reconsider scenarios, while having additional time to make their final commitment to a specific course of recommendation.

Quickness

As I suggested in Chapter 3, the metric of quickness qualifies the metrics of informativeness, flexibility, and resumability. Comparing conventional practice and the

Dynamic DBS during the formulation phase, quickness reinforces the contribution of the DBS-based ontology and DMM to the metrics of informativeness and flexibility. Specifically, the DD offers quicker propagation, decoupling, swapping, and evaluation adjustment of decision information when compared to current methods or tools. For instance, Decision-Enabling Task #2 described that the DD allowed instantaneous propagation of attribute values, whereas Decision-Enabling Task #6 described the instantaneous adjustment of evaluation tables with DMM Base Methods. Therefore, the DD offers quicker information management during the formulation phase, enabling decision facilitators to explore additional decision choices and interrelated factors rather than spending non value-adding time in information management with current tools.

6.3.3 ANALYSIS OF DYNAMIC DBS FRAMEWORK DURING THE EVALUATION PHASE

Requirements

Informativeness, Flexibility, and Quickness

Applicable AEC Decision Ontology

1. The Decision Breakdown Structure built during the definition and formulation phase
2. Attributes

Applicable DMM Methods

- B1: Manage Decision Information, Relationships, and Attributes
- B6: Evaluate in Different Contexts and Across Different Levels of Detail
- C3: Interact in the iRoom Environment
- C4: Filter Graphical Representation of a Decision Breakdown Structure

Evidence Examples

- 1: Impromptu Query of Common Space Area (Decision-Enabling Task #2)
- 2: Impromptu Evaluation of Space Information (Decision-Enabling Task #3)
- 3: Evaluation and Explanation of 3 Productivity Scenarios (Decision-Enabling Task #5)
- 4: Evaluation of Sustainable Design Features (Decision-Enabling Task #6)

5: Evaluation and Explanation of Ripple Consequences (Decision-Enabling Task #7)

6: Evaluation and Explanation of Acceleration Proposal (Decision-Enabling Task #8)

ANALYSIS

The evaluation phase provides an opportunity for the decision facilitators to present their recommendations to the decision makers. It requires a concerted effort by the facilitators to balance their facilitation skills and the capabilities of their decision-support tools. Section 6.2.3 explained that the more informative, the more flexible, and the quicker the decision support tools and methods, the better the facilitators can drive the evaluation to more valuable decision tasks. In the following subsections, I compare current and DD-based decision support tools and methods in their support of the evaluation phase of information management in AEC decision making.

Informativeness

Informativeness in the evaluation phase refers to the information basis of the stakeholders and the ease of accessing relevant decision information to support the explanation, comprehension, and analysis of recommended proposals. In the 6 evidence examples listed above, decision-support tools and methods used by the industry professionals across all test cases did not match the informativeness offered by the Decision Dashboard.

First, in terms of the information basis, current methods and tools do not have explicit documentation or differentiation of decision information. For instance, as the design team used MS PowerPoint to explain their recommended proposals in TC#1, the owner's review team present in the meeting had a difficult time understanding which options could be decoupled and which options could not. There was no formal method to document the states or interrelationships of decision information in current practice. The design team had to verbally explain whether an option could be mixed and matched with another option. Conversely, DD users can be better informed by the AEC Decision Ontology, which distinguishes the states, types, and interrelationships of decision information. A similar limitation of information basis happened in evidence examples 5 and 6, where current practice did not offer decision makers an

understanding about the ripple consequences or decision assumptions. Specifically, evidence example 5 relied on text-based narratives in a 283-page report. As explained in Decision-Enabling Task #7 (section 5.3), there were no formal methods to succinctly highlight the interrelationships impacted or caused by a particular decision option. In these evidence examples, DD users can benefit from the information categorization offered by the AEC Decision Ontology to formally represent the decision options, integrate level-1 values, and reference level-2 digital data. They can also leverage the ontology to explicitly represent specific impact relationships or detailed assumptions by applying Base Method B1 and Composite Method C4.

Second, in terms of information access, current methods and tools only support the briefing of a subset of decision information, based on the judgment, organization, and filtering proposed by the decision facilitators. Should the decision makers inquire about any assumptions, details, or predictions beyond the scope of the facilitator's pre-organized set of information, current tools often fall short in helping facilitators to respond to impromptu questions. Under current practice in evidence examples 1, 2, and 6, acquiring the area information (Decision-Enabling Task #2), coming up with a specific evaluation table (Decision-Enabling Task #3), or bringing up relevant acceleration proposals (Decision-Enabling Task #8) could not be performed with the decision-support tools on hand. Facilitators had to overcome the limitation of the tools with vague answers, verbal promises, postponement of formal responses, and mental connections and predictions, all of which adversely affect the informativeness during the evaluation phase. On the other hand, evaluation with the aid of a DBS in the DD offers a more complete and explicit set of decision information while allowing DD users to highlight and go through a specific subset of recommended (or selected) alternatives. By allowing DD users to distinguish the states and types of decision information, embed attributes, and reference external electronic information, the DMM offers a more comprehensive approach to ensure that the DD can serve as a central decision-support tool for information access. The DD is capable of integrating decision information of different formats from different stakeholders during the formulation phase; such that during evaluation, decision makers can obtain an informative comprehension of the decision scenario, across varying levels of details that are integrated and structured according to a dynamic set of decision topics being evaluated. As evidenced in the aforementioned test cases, DD users can respond to impromptu

questions arising from evidence example 1 (Decision-Enabling Task #2 in section 5.3), can present relevant data or assumptions in support of evidence example 2 (Decision-Enabling Task #3 in section 5.3), and directly bring up relevant acceleration proposals in the CIFE iRoom in evidence example 6 (Decision-Enabling Task #8 in section 5.3). In all cases, the Decision Breakdown Structure proves to be a more informative resource than current methods or tools.

Flexibility

Flexibility plays an important role in improving the access to the decision information. Pre-determined sequence, representation, organization, and comparison of decision information under current practice do not provide as much flexibility as the Dynamic DBS during the evaluation phase. The inflexibility to decouple lumped area information, to mix and match different scenarios, to compare criteria with options, and to evaluate alternate sets of decision information in current practice were described in decision-enabling tasks #2, 3, 5, and 6 (section 5.3). In these cases, the evaluation processes were limited by the fixed decision information in the presentation slides, the printed reports, and the pre-determined evaluation tables. As decision makers queried for new supplementary representations or different organizations of the decision information, the facilitators did not have any decision-support tools to rely upon.

With the DBS formulated in the DD, decision stakeholders have the flexibility to dynamically adjust the display, organization, focus, and comparison of a more comprehensive set of decision information than with current practice. For instance, Base Method B6 supports impromptu evaluation among competing decision topics and criteria at varying levels of detail. The Dashboard Panel in the DD offers an evaluation table that performs such evaluation based on any attribute metric at the discretion of the stakeholders. Base Method B1 and Composite Method C4 allow flexible isolation of decision information and query of element attributes in coupled lump-sum form and decoupled component form. These flexible contributions of DMM-based methods were documented in the corresponding decision-enabling tasks in evidence examples 1, 2, 3, and 4 (section 5.3). The DD promotes a more flexible shift of inquiry, focus, and management of decision information from task to task than current decision-support tools.

Quickness

How quickly a decision-support tool assists decision facilitators to perform a decision-enabling task directly affects the flow of the decision-making process. In all evidence examples listed above, the DD completes the tasks instantaneously due to the formal DMM; whereas facilitators using current tools had to defer responses as follow-up tasks (evidence examples 1 and 2) or manually go through 283 pages of the Program Development Study to search for ripple consequences (evidence example 5). Furthermore in evidence example 1, in spite of the lack of an informative or flexible decision-support tool, the decision facilitators attempted to answer the impromptu query with verbal promises and rough approximations. Not only did such attempts turn out to be unsatisfactory, they also further delayed the decision-making processes. In comparison with current methods or tools, the more informative and flexible Decision Dashboard contributes to a quicker decision evaluation.

6.3.4 ANALYSIS OF DYNAMIC DBS FRAMEWORK DURING THE ITERATION PHASE

Requirements

Primary: Resumability

Secondary: Informativeness, Flexibility, and Quickness

Applicable AEC Decision Ontology

1. The Decision Breakdown Structure built during the definition and formulation phase
2. Elements: Topic, Criterion, Option, and Alternative
3. Relationships: Aggregate, Requirement, Choice, Impact, and Process
4. Attributes

Applicable DMM Methods

B1: Manage Decision Information, Relationships, and Attributes

B6: Evaluate in Different Contexts and Across Different Levels of Detail

C1: Formulate a Decision Breakdown Structure

C2: Swap Decision Information Between Selected and Candidate States

C3: Interact in the iRoom Environment

C4: Filter Graphical Representation of a Decision Breakdown Structure

Evidence Examples

- 1: Re-Formulation of a Hybrid Solution (Decision-Enabling Task #1)
- 2: Adjustment of Decision Assumptions (Decision-Enabling Task #4)

ANALYSIS

As explained in the contribution section (section 6.2.4), the iteration phase brings the decision-making process back to the definition or formulation phase. The process iterates through re-definition and/or re-formulation, and is followed by a re-evaluation phase. Therefore, the iteration phase also inherits the metrics of informativeness, flexibility, and quickness. In the above listed evidence examples, the AEC Decision Ontology and the DMM prevail over current decision-support methods or tools in completing the decision-enabling tasks. The DD improves the information basis required to decide whether or not to go with a hybrid solution (evidence example 1), while informing the stakeholders about specific parameters and assumptions (evidence example 2). The DD also offers a more flexible solution by de-coupling and re-coupling entrance options in the re-formulation of a hybrid solution, while ensuring fast re-formulation or adjustment with DMM-based methods.

While the value of the DD in supporting informativeness, flexibility, and quickness shares the same requirements between the iteration phase and the prior phases, the metric of resumability is unique to the iteration phase.

Resumability

In both evidence examples, facilitators and professionals had to spend more effort in rework to re-formulate or re-define decision information with current methods or tools than with the DD. In evidence example 1, an impromptu hybrid solution can be quickly re-formulated by swapping between the selected and candidate options within the DBS (Composite Methods C1 and C2) rather than taking 4 additional weeks to re-create a new solution as documented in the current approach (Decision-Enabling Task #1, section 5.3). This is made possible by collecting, distinguishing, and not discarding

selected and candidate decision information during the formulation phase (AEC Decision Ontology and Base Method B1, C1, and C4). Hence, as the director in TC#1 came up with a “what-if” re-formulation idea, the DD would have allowed an instantaneous re-coupling of existing options and re-propagation of their attribute values (Figure 32).

Similarly, when an error was noticed and as the stakeholders decided to iterate the process with an improved assumption or a corrected value, the paper-based report in TC#2 required rework to re-calculate and re-document the change; whereas the Dynamic DBS would have allowed its users to directly apply the correction to its source, that is, the attribute value in a decision topic (Base Method B1). In a DBS, previous sets of decision information are readily accessible and correctable with minimal rework. In summary, the DBS and DMM promote a higher degree of resumability than current practice as less rework is required by the stakeholders to complete information management tasks during the iteration phase.

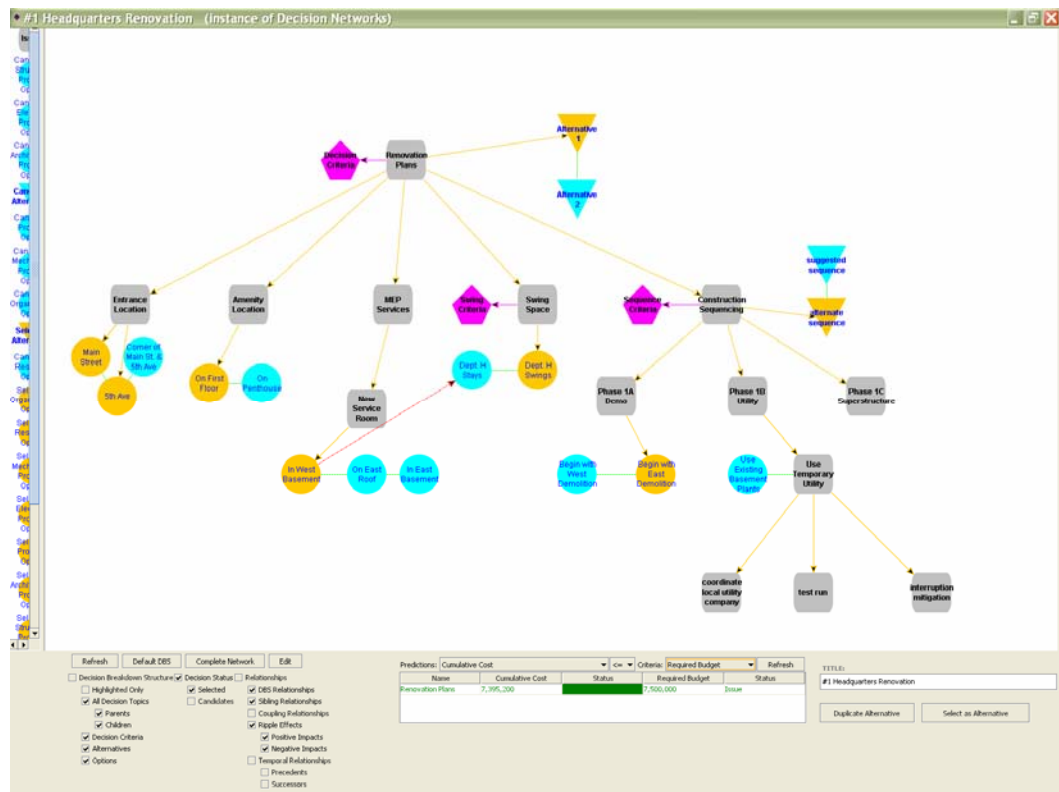
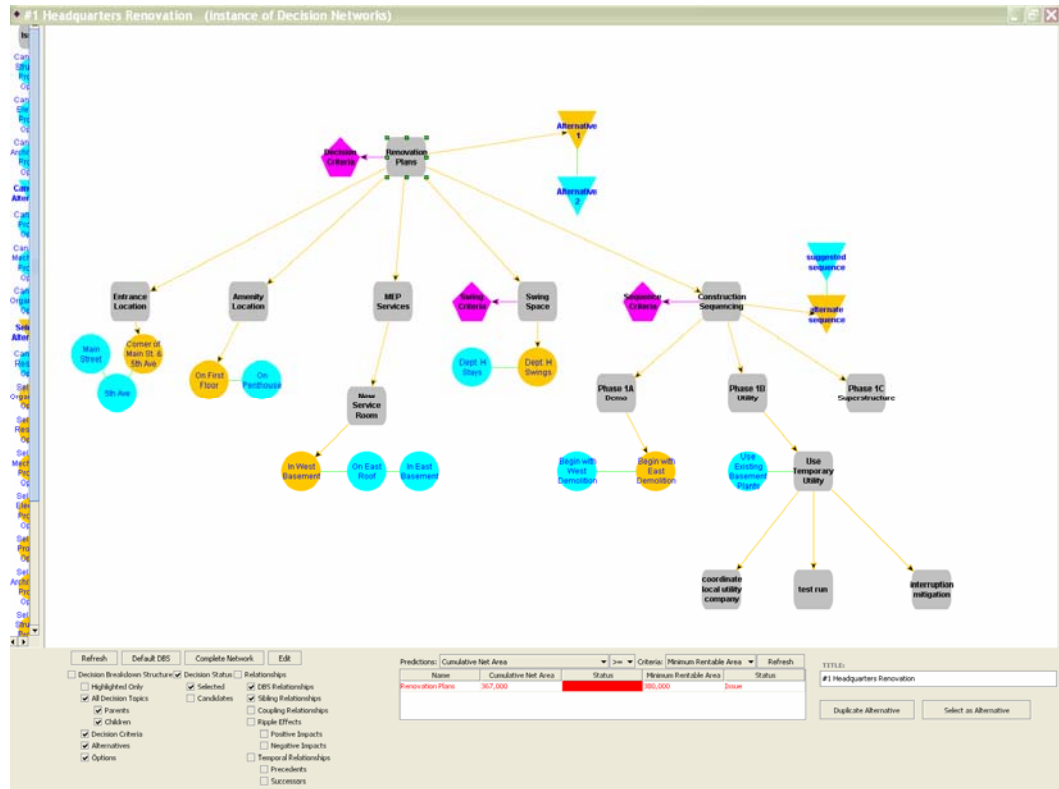


Figure 32. The Dynamic DBS enables decision facilitators to test what-if combinations of decision options (entry locations) and obtain instantaneous feedback (budget) in the evaluation table.

6.3.5 ANALYSIS OF DYNAMIC DBS FRAMEWORK DURING THE DECISION PHASE

Requirements

Informativeness

Applicable AEC Decision Ontology

1. The Decision Breakdown Structure built during the definition, formulation, and iteration phase
2. Attributes

Applicable DMM Methods

- B1: Manage Decision Information, Relationships, and Attributes
- B6: Evaluate in Different Contexts and Across Different Levels of Detail
- C1: Formulate a Decision Breakdown Structure
- C2: Swap Decision Information Between Selected and Candidate States
- C3: Interact in the iRoom Environment
- C4: Filter Graphical Representation of a Decision Breakdown Structure

Evidence Example

- 1: Information Gap As Decision Proceeds From TC#3 to TC#1

ANALYSIS

The five phase decision-making process formalized in this chapter is about the making of a decision. Whether a well-negotiated and well-considered decision will translate into better outcomes in reality depends—among other things—on the tactical execution of the decision. This is outside the scope of this research. Nevertheless, a decision and its rationale should be documented as informatively as possible during this final decision phase (section 6.2.5). However, industry professionals using current methods often fail to enrich and finalize their information set when making a decision.

For instance, as the design process concluded the pre-design study (TC#3) and proceeded to the schematic design phase (TC#1), the design professionals and the decision facilitators switched their decision-support tool from one medium (i.e., paper-based report) to another medium (i.e., MS PowerPoint). The switching of tools was necessary because the mode of decision making had changed from an asynchronous mode to a synchronous mode and because the tools they had used did not support both modes. However, informativeness was compromised. The synchronous meetings in TC#1 were not able to access, re-use, and learn from the information set compiled by TC#3. As a result, interrelationships and ripple consequences found from a prior due diligence effort (e.g., zoning requirements and additional floor construction from TC#3) were not explicitly represented or incorporated in the presentation on a related topic (e.g., penthouse common space limitation and opportunity in TC#1) during the schematic design.

DD-based decision-support improves the informativeness and resumability of current tools or methods. Since the DD is designed for, and has been retrospectively applied in, synchronous and asynchronous settings, it can serve as a central information management tool that supports successive decision-making processes. Towards the end of a decision process, DD users can decide on the final selection by reviewing the evaluation table, by bringing out relevant decision information, and by studying a partial or the complete DBS (Base Method B6 and Composite Methods C1, C3, and C4). They can maintain the most current set of decision information and make the final decision by turning the appropriate decision information into an active selection state, while enriching the decision documentation with rationale and explanation (Base Method B1 and Composite Method C2). This information set can be archived (Base Method B1) and can become the new basis for subsequent decision-making processes, where decision stakeholders can directly and dynamically interact (e.g., query, evaluate, elaborate, and analyze) with the archived set of decision information as well as its digital references.

6.3.6 CONCLUSION FROM VALIDATION STUDY #3

In the above sections on validation study #3, I analyzed the six test cases (four of which I detailed in sections 4.3 and 5.3) by the five information management phases. Following the metrics required in each information management phase, I highlighted what current decision-support tools and methods encompassed while discussing the value of the DD-based AEC Decision Ontology and the Decision Method Model. Table 9 summarizes the AEC Decision Ontology (elements, relationships, and attributes), the Decision Method Model (base and composite methods), and their applications across different phases in the Dynamic DBS Framework.

Framework Phases	Definition	Formulation	Evaluation	Iteration	Decision
Ontology Elements					
Topic	X	X	X	X	
Criterion	X	X	X	X	
Option		X	X	X	
Alternative		X	X	X	
Ontology Relationships					
Aggregate	X	X	X	X	
Requirement	X	X	X	X	
Choice		X	X	X	
Impact		X	X	X	
Process		X	X	X	
Ontology Attributes					
Level-1	X	X	X	X	X
Level-2	X	X	X	X	X
DMM Base Methods					
B1	X	X	X	X	X
B2	X	X		x	
B3	X	X	X	X	
B4	x	X	X	X	X
B5	x	x	X	X	
B6		X	X	X	
DMM Composite Methods					
C1	X	X		X	
C2		X		X	
C3			X	X	
C4	X	X	X	x	
Examples in Validation Study #3					
Numbers	5	6	6	2	1

Table 9. A table summarizing the application of the AEC Decision Ontology and the Decision Method Model in the evidence examples across different phases in the Dynamic DBS Framework.

The recurring theme of my analysis is that following a DBS-based definition and formulation of decision information, decision stakeholders can establish a central and

resourceful means to represent and organize diverse sets of decision information. Investment in the DBS (i.e., to define and formulate decision information using the DBS) seeded during the early phases can pay off during the evaluation, iteration, and decision phases, when an array of DBS-based methods empowers stakeholders with dynamic interaction capabilities. These dynamic behaviors in turn enable stakeholders to manage the decision information more informatively, flexibly, resumably, and quickly than in current practice.

6.4 VALIDATION STUDY #4—EXPERT FEEDBACK

In the prior three validation studies, I analyzed the decision information, decision-enabling tasks, and the information management phases based on the test cases with five specific metrics. My fourth and final validation study complements the other three metric-based validation studies with a broader analysis (i.e., beyond the five metrics and beyond my personal fact-based analyses) of my research contributions. This validation study captures the qualitative feedback from a group of industry and research experts. The group includes over thirty industry and research experts, who attended one of four demonstration sessions. The sessions focused the experts' attention on the motivating case example in Chapter 1, which is a simplified version of TC#1. I went through the same decision-making scenarios with current practice decision-support tools and the Decision Dashboard. The expert participants comprehended, evaluated, rated, and commented on the Dynamic DBS Framework. The following paragraphs present the rating and feedback captured from a survey conducted immediately after the demonstration sessions^{xxii}. In addition, I explain how these responses affected my refinement of the DBS (that contributed to the final specification of the Dynamic DBS as presented in Chapters 4 and 5) and led to a subsequent follow-up meeting with 2 industry professionals, which became TC#5.

^{xxii} Only 21 out of the 30+ participants attended the full session and were able to complete the survey.

6.4.1 OBJECTIVES

In June 2004, I invited industry professionals and researchers to participate in my demonstration sessions. The objectives of the demonstration sessions were:

- (1) for the participants to learn about one specific example of the CIFE research process while getting a first-hand opportunity to compare current practice and the DD interaction in the CIFE iRoom,
- (2) to validate that my observation of the limitations of current practice are real and general based on the experience of the attendants, and
- (3) to collect validation evidence of the respective value of decision-support tools between current practice and the DD based on the feedback by the participants, some of whom had been directly involved in the industry test cases.

6.4.2 PARTICIPANTS

Over thirty professionals and researchers from the United States and abroad attended my four demonstration sessions (Figure 33), which lasted between one to two hours each. Twenty-one of the attendants completed a survey that aimed at collecting their expert opinions on objectives (2) and (3).

6.4.3 THE SESSIONS

The demonstration followed my test case on the headquarters renovation decision scenario (introduced in sections 1.3 and 2.1.1). In preparation for the sessions, I used the same set of decision information to reconstruct two identical briefings using two different decision-support tools—MS PowerPoint and the Decision Dashboard (section 4.3.1). Each session was similar to the owner briefing meeting described in sections 4.3.1 and 5.3. I played the architect's role as the decision facilitator while the participants played the owner's review team's role as the decision makers.



Figure 33. A photo from the fourth demonstration session that took place on June 24, 2004.

The sessions started with my introduction of the objectives, followed by my briefings on the decision scenario with PowerPoint and with the DD. In an effort to keep the participants neutral about their pre-conception and the perceived values of the two decision-support tools, I divided the briefings into a series of short briefings (about 5-minute each) and alternated the short briefings between the two decision-support tools. I also used a series of different but parallel questions (e.g., a question of the entry location and a question of the common program location are a set of parallel questions) after each short briefing to engage the attendants in the project scenario and to elucidate the information management differences of the two decision-support tools. While my pre-session preparation would classify as the formulation phase in my framework for management of decision information, the sessions focused on the evaluation and iteration phases in the context of my framework (section 6.2).

6.4.4 THE SURVEY

All attendants were invited to fill out a survey (Figure 34) after the session ended. They had the options to remain anonymous by only disclosing their background, e.g., researcher, owner, designer, contractor, etc.). In the one-page survey, there were both quantitative and

qualitative sections. In the quantitative section, the attendants were asked to score, on a scale of 1 to 10, their assessment of the information management value of the Decision Dashboard. The lowest allowable score was 1, which meant that the DD was not valuable at all; the neutral score was 5; whereas the highest allowable score was 10, signaling that the DD was extremely valuable. Six questions^{xxiii} were asked on the value of the DD in:

- (1) describing decision criteria, options, and alternatives,
- (2) referencing external digital information across the iRoom,
- (3) explaining the interrelationships of decision information (e.g., ripple impacts),
- (4) propagating and manipulating attributes (e.g., cost values, area information, etc.),
- (5) evaluating decision information with tables, and
- (6) de-coupling and re-coupling options to formulate new alternatives with new attribute propagation.

On the other hand, the qualitative section allowed the attendants to comment on:

- (1) wishlist items for the DD,
- (2) whether my characterization of the limitation of current practice was appropriate, and
- (3) any issues that the attendants wanted to comment on.

^{xxiii} The demonstration took place before my research has formalized the concepts of a “Decision-Enabling Task” and a “Decision Method Model.” Therefore, the survey included questions on both concepts with less a distinctive organization than the rest of the dissertation.

Feedback Survey on the Decision Dashboard Prototype

From the perspective of an AEC decision maker (e.g., project executives, managers, owners, tenants, etc.), please rate the value of the Decision Dashboard in the:

description of decision criteria, options, and alternatives

Scale of 1 to 10 (1 = unworthy || 5 = no difference || 10 = valuable): _____

iRoom linkage of relevant images, spreadsheets, and data

Scale of 1 to 10 (1 = unworthy || 5 = no difference || 10 = valuable): _____

explanation of inter-relationships (e.g., impacts of one decision on another) and decision history

Scale of 1 to 10 (1 = unworthy || 5 = no difference || 10 = valuable): _____

inclusion, population, and manipulation of attributes (e.g., cost values, aesthetic rating, area)

Scale of 1 to 10 (1 = unworthy || 5 = no difference || 10 = valuable): _____

evaluation of decision criteria, options, and alternatives through tables and color status

Scale of 1 to 10 (1 = unworthy || 5 = no difference || 10 = valuable): _____

re-mixing options and alternatives for updated value responses against decision criteria

Scale of 1 to 10 (1 = unworthy || 5 = no difference || 10 = valuable): _____

What do you see as the most critical wish-list item(s) for the Decision Dashboard prototype?

How relevant are the research observations of conventional practice (e.g., lack of explicit documentation of options, alternatives, and criteria; lack of formal means and methods to de-couple or re-couple options; lack of access to quantitative parameters in decision making; etc.):?

Other Comments:

Your Profession (owner, architect, engineer, contractor, researcher, or ...?): _____ **Name (Optional):** _____

Figure 34. A copy of the survey form given out after the demonstration sessions.

6.4.5 QUANTITATIVE AND QUALITATIVE FEEDBACK

Twenty-one attendants filled out the survey at the conclusion of the demonstration. They included fifteen professionals and six CIFE researchers (Table 10). The average score of all six quantitative questions gathered from all twenty-one attendants was 8.4. Specifically, the fifteen professionals gave an average score of 8.7 whereas the six CIFE researchers gave an average score of 7.5. While each respondent might share a different subjective scale with respect to scoring, 121 out of 125 individual scores were rated between 6 and 10. In particular, there were 31 scores that were rated at the top score of 10, they represented 24.8% of all individual scores collected. Based on evidence of the data, the twenty-one attendants had determined that the DD was a more valuable decision-support tool than the PowerPoint slides in support of the decision-enabling tasks in TC#1.

June 15, 2:30pm to 4:30pm	
pract+researcher	8.2
pract+researcher	8.8
owner	9.2
owner	7.8
owner	8.2
owner	9.0
Architect	7.0
Standards Developer/NIST	9.6
June 18 (Friday) 3:00pm to 5:00pm	
researcher	7.2
researcher	5.8
researcher	6.8
researcher	8.8
researcher	8.5
June 21 (Monday) 3:00pm to 5:00pm	
researcher	7.8
June 24 (Thursday) 6:30pm to 8:00pm (CIFE Summer Program)	
owner	8.7
architect	9.0
engineer/researcher	10.0
Engineer Management	9.0
engineer	8.3
researcher	10.0
engineer	7.8
professor/researcher	
	Average
	8.4
15 Practitioners	8.7
6 CIFE Researchers	7.5

Table 10. Summary data for the rating of the Dynamic DBS versus conventional practice, averaged for the six questions of Figure 34.

The attendants ranked the relative value of specific DD methods in the following order:

- to reference digital information in the CIFE iRoom (scored 8.8),
- to describe criteria and choices (scored 8.7),
- to explain interrelationships of decision information (scored 8.6),
- to evaluate decision criteria, options, and alternatives with tables and status (scored 8.3),
- to re-formulate options and alternatives while updating the evaluation tables (scored 8.2), and
- to embed, manipulate, and propagate attributes (scored 7.7).

This ranking shows that the attendants preferred the DD to make reference to digital information existing among the iRoom computers rather than to embed, manipulate, and propagate attributes. However, even though the handling of attributes scored low in relation to other DD method features, it was still determined to be more valuable than current decision-support tools since it earned a score that was above the neutral score of 5.0.

Meanwhile, the qualitative section of the survey gave the attendants the opportunity to comment on my assumptions pertaining to current practice, on their wish-list items for the DD, and on any other comments that the attendants wanted to offer. In terms of my observation and reconstruction of current practice with the PowerPoint tool, the attendants noted that my observation was “very relevant,” “extremely relevant,” “highly relevant,” “very valid”, and that “the problem is complex and real.” There was also a suggestion by a researcher who asked me to conduct a more comprehensive research. The time limit of the demonstration session did not allow me to explain all my case observations in detail, but this dissertation has documented five other test cases (i.e., TC#2, 3, 4, 5, and 6) that address the concerns raised by the researcher.

I have sorted the open comments and wish-list items into three categories—positive approval, areas for improvements (with my responses), and suggestions that are beyond the scope of my research. First, the following quotations are the approval comments and positive suggestions:

“You are already addressing my wish-list item: impacts and decision history, ability to roll back and reconsider.”

“A+, I wonder if you could get better support and go faster if you pitched this tool to a different industry sector?!”

“Even as issue-based information system ONLY, this is a very useful tool for architects.”

“Very relevant. Linkage of performance criteria and predictions to external data is/would be a significant advantage.”

“The strength of this approach is that it documents the decisions [specific choices and explicit linkages] of the relationships between the elements that lead to the decision.”

“Extremely relevant. An excellent piece of work!”

“Very valid. I think being explicit at alternatives, options, criteria is a good abstraction.”

On the other hand, the following are criticisms and suggested areas for improvements.

“Very relevant, but may be difficult to get project participants organized enough to fully use the tool.”

“The dashboard is a very programmed and prepared way of decision making. Can you really have all the attributes and relations already mapped prior to a meeting?”

“improve graphical clarity of the diagram for more complicated decisions (maybe constraining the position of the graphical elements)”

“question scalability to scope of interdependent design decisions involved in a significant size project (for which design team resorts to intuition in conventional process).”

Pertaining to the perception that the DD would require all relationships and information to be organized or pre-programmed, my response is that the effort it takes to formulate a DBS

in the DD is not substantially different from the preparation of a slide presentation or a comprehensive study report. Across my six test cases, the duration of the formulation phase varies from several weeks to several months, whereas the evaluation phase takes place in just a few hours time because all the decision makers are also invited to participate. Hence, the time difference in terms of formulating a recommendation is not as critical as the time difference pertaining to evaluating the recommendation. Furthermore, the DBS approach is dynamic and hence, the stakeholders can continue to develop and adjust the decision information during the formulation phase. However, the time constraint of my demonstration did not allow me to work on a live evolutionary set of data with the participants. Pertaining to the scalability issue, I responded with the development of a new DBS (see section 6.4.6) that was incorporated in the final specification of the Dynamic DBS (as presented in Chapter 4 and 5).

Last, the following are suggestions on the most critical wishlist items and other open comments that are beyond the scope of my current research:

“Heads-up summary of results showing matrix performance/selected option.”

“Linkage to modeling package (e.g., ArchiCAD as add-on) to evaluate performance of modeled options in real time.”

“Additionally, if design team members can update performance criteria and predictions via web or remote link in ADVANCE or facilitated meeting, then usefulness improves.”

“Adapted [Adapt the DD] to visualize work breakdown structure via 4D models.”

“Consider it as a leasing tool.”

“Excellent visual tool. Link to 3D visualization. Consider linking to MSP schedule.”

“Perhaps connection to partial models (model servers), but not necessary during thesis work.”

“decision history”

“would like to control the dashboard from my mobile phone”

“A little better/more fluid UI would really help. Right click to manipulate graph”

6.4.6 POST-DEMONSTRATION REFINEMENT—THE DECISION BREAKDOWN STRUCTURE

After my four demonstration sessions, I reviewed all the comments I had gathered and evaluated them against the objectives of my research and the refinements that were needed to strengthen my research contributions. The two areas that I have developed more substantially after the demonstrations were the concepts of a Decision Breakdown Structure (section 4.2.4) and a graphical methodology for the dynamic filtering of the DBS (i.e., Composite Method C4, section 5.2). These developments were incorporated in the final specification of the Dynamic DBS as detailed in this dissertation and in the DD research prototype that was used to conduct Validation Studies #1, 2, and 3 after the demonstrations (i.e., Validation Study #4).

6.5 CHAPTER CONCLUSION

In this Chapter, I have presented my third and final contribution—a formal framework for the application of the Dynamic DBS throughout the AEC decision-making process. Based on my literature research, existing theories do not formalize the AEC decision-making process. There are theories on design processes but they are different from the AEC decision processes, in part because they do not cover the specific decision-enabling tasks needed to deal with decision choices and their interrelationships. Taking the DA process as the extensible point of departure, my research contribution assesses the characteristics (e.g., duration, stakeholders involved, decision-enabling tasks needed, etc.) and requirements of information management throughout the AEC decision-making process based on an observation of industry cases. Instead of treating definition and decision as two end states in DA theories, I have incorporated them as two core phases in the AEC decision-making process. On the other hand, rather than having two phases that concentrate on the probabilistic evaluation and appraisal of decisions as applied in DA theories, I propose a single evaluation phase for AEC decision making. Thus, this contribution provides the framework for the formal application of the Dynamic DBS by integrating the information, people, and process of AEC decision making.

CHAPTER 7—SUMMARY, SIGNIFICANCE, AND CLOSING REMARKS

Section 7.1 summarizes my doctoral research that I detailed in the previous six chapters. Reflecting on my observations of current practice, assessment of current theories and methods, and my research contributions, I discuss the theoretical significance of my work as well as its impact on practice. I also comment on the limitations of the dynamic Decision Breakdown Structure and the Decision Dashboard prototype in their current forms and suggest potential areas for future research.

7.1 RESEARCH SUMMARY

7.1.1 LIMITATIONS OF CURRENT PRACTICE

Current practice lacks decision-support methods and tools to represent heterogeneous and evolutionary decision information, complete decision-enabling tasks, and resume the decision-making processes. As section 3.2 explains, decision facilitators and professionals often use generic decision-support tools and their associated methods to support AEC decision making. However, generic tools and methods compromise the multidisciplinary and iterative nature of AEC decision making and hence, they compromise heterogeneous and evolutionary decision information. These tools and methods offer limited or no support in: (1) referencing or integration of dispersed information, e.g., inability to access feature-specific area information in the motivating case example, (2) the representation of heterogeneous decision information and the explicit handling of its interrelationships, e.g., no representation or distinction of decision information such as area requirements and ripple consequences of MEP location on common program locations, (3) offering dynamic and flexible methods for completing decision-enabling tasks, e.g., pre-packaged alternatives and pre-determined evaluation tables with one-way information feed, and (4) the integrated and resumable use of decision information across all decision-making phases. As sections 3.2, 5.3, and 6.3 analyze, these limitations undermine the informativeness, flexibility, resumability, and quickness in AEC decision making. By burdening the decision stakeholders to reconcile these limitations with their mental recollections, verbal explanations, rework and time, the limitations of current practice adversely affect the basis and therefore, the quality, of AEC decision making. Furthermore, there are no formal

strategies for building upon existing sets of decision information or previously completed decision-enabling tasks across different phases of the AEC decision-making process (section 6.3). Current practice relies on a variety of generic tools and methods to complete decision-enabling tasks across different stages of AEC decision making. Such an ad hoc and disjointed approach makes it difficult for facilitators to resume and leverage their prior efforts and thus results in information gaps, rework, and delays. In light of these limitations, my research addressed three main areas—*representation*, *methodology*, and *process*, which I further explain in the following section.

7.1.2 RESEARCH QUESTIONS AND POINTS OF DEPARTURE

The limitations and negative impacts of current management of decision information have motivated my doctoral research. In sections 3.3 and 3.4, I discuss my research methodology and a series of questions about the limitations of current practice that guide my literature research and the formulation of my three research questions. These research questions center on the representation of AEC decision information, the methodology for completing AEC decision-enabling tasks, and the process for managing the AEC decision-making process:

1. How to formalize AEC decision information and its interrelationships with a computer representation?
2. What computer-based reasoning methods can utilize formally represented decision information to support AEC decision-enabling tasks?
3. How to formalize the management of decision information during the AEC decision-making process?

Decision Analysis (DA), Virtual Design and Construction (VDC), Design Theory, and other Architecture-Engineering-Construction (AEC) theories form the basis of my theoretical point of departure, which I introduce in section 3.3 and in detail in sections 4.1, 5.1, and 6.1.

VDC and AEC theories promote the importance of generating multiple and creative alternatives, balancing heterogeneous types of predictions against criteria, leveraging the

value of decision making during early project phases to capitalize on life-cycle benefits, and delaying the coupling of project options (section 1.1). These theories concur with the importance of a good decision basis and quality as established by DA theory. Together, these theories allowed me to establish the requirements and metrics for my research validations, e.g., there should be choices in the decision making process and decision makers should be able to make informed and quick decisions, etc. (section 3.5). Although DA, VDC, and AEC theories concur in decision-making objectives, they do not provide a representation, methodology, and process for AEC decision information management to achieve good decision basis and consequently good decision quality.

Specifically, VDC theory details the explicit representation of an AEC decision through its associated Function, Form, and Behavior (FFB) of a facility's Product, Organization, and Process (POP) across different levels of detail; but VDC theory does not account for an explicit and formal strategy to represent and manage choices (section 4.1). Similarly, AEC and Project Management theories formalize the representation and methodology to process POP information (e.g., Work Breakdown Structure, Critical Path Method, etc. see sections 4.1 and 5.1); however, they do not specify the management of decision choices and their ripple consequences on one another.

DA theory covers choices and decision making, but it does not address the characteristics of multidisciplinary stakeholders, evolutionary process, and heterogeneous information that are unique in AEC decision information management. For instance, DA's representation of choices is limited to one level of detail (e.g., a strategy) and the different courses of action are arranged in a stochastic binary representation. There is no formal representation of the multidisciplinary and evolutionary interrelationships in DA's process of alternative generation (section 4.1). Interrelationships among decision choices are factored by the decision analysts and the decision makers mentally. Such implicit management of interrelationships and levels of detail do not fit well to the many AEC decision stakeholders and the evolutionary AEC decision-making process. DA theory separates the method to generate alternatives from the method to evaluate alternatives (section 5.1). Hence, DA's representation and methodology do not fit well in supporting the AEC decision process, which can be characterized by multidisciplinary stakeholders, an iterative process, and thus, heterogeneous and evolutionary decision information (sections 4.1 and 5.1).

The void among DA, VDC, and AEC theories to provide a representation, methodology, and process of AEC decision information management results in the dispersed, homogenized, implicit, static, and disjointed management of decision information. My research contributions extend existing theories in the representation of AEC decision information (e.g., FFB-POP, WBS, ontology development, etc., see section 4.1), the methodology to process formally represented information (e.g., iRoom Methods, Strategy Generation Table, Project Management Methods, etc., see section 5.1), and the decision-making process (e.g., DA process, Design Process, etc., see section 6.1). These extensions bring together DA, VDC, and AEC theories to support AEC decision facilitators in managing decision information throughout the AEC decision-making process.

7.1.3 RESEARCH CONTRIBUTIONS

In response to the three research questions and their points of departure, my research provides industry-based studies and three contributions that make up a Framework for the Dynamic Decision Breakdown Structure (Figure 35).

First, I formalize an AEC Decision Ontology for the representation of heterogeneous decision information and its interrelationships. Building on the representation of AEC decision information, the ontology is composed of elements (topic, criterion, option, and alternative), relationships (aggregate, choice, requirement, impact, and process), and attributes and is further explained in Chapter 4. This ontology allows decision facilitators to formulate a Decision Breakdown Structure (DBS).

Second, I formalize a Decision Method Model (DMM), which builds upon the AEC Decision Ontology to manage evolutionary decision information. Extending VDC, DA, and AEC methodology to process formally represented information, the DMM includes a set of base methods and method features, which are combinable to form different composite methods to support the completion of individual decision-enabling tasks. Chapter 5 explains how the DMM enables facilitators to manage the DBS dynamically.

Third, I formalize a framework for the application of the Dynamic Decision Breakdown Structure. Taking DA and Design Processes as points of departure, the framework dissects the AEC decision-making process into five information management phases (definition,

formulation, evaluation, iteration, and decision phases), and analyzes the characteristics and requirements of the decision information and information management involved in each of the specific phases. The framework associates the applicable AEC Decision Ontology and DMM with each of the five decision phases. Chapter 6 specifies this framework for decision facilitators to apply the Dynamic Decision Breakdown Structure across different decision-enabling tasks throughout the AEC decision-making process.

In reference to the motivating case example, my contributions allow decision stakeholders to integrate or reference heterogeneous decision information under a DBS. The dynamic DMM allows stakeholders to better distinguish decision information according to the types (e.g., whether the information about the entrance is a criterion or an option), to access decision information based on impromptu situations (e.g., use DMM methods to uncover the interrelationship between MEP and common program locations), and to evaluate or adjust decision information. Furthermore, my framework specifies the information management characteristics, their requirements and supporting DBS methods for the decision stakeholders to reuse decision information and resume decision-enabling tasks during different phases of the decision making process (e.g., information management characteristics for professionals and facilitators before, during, and after the meeting).

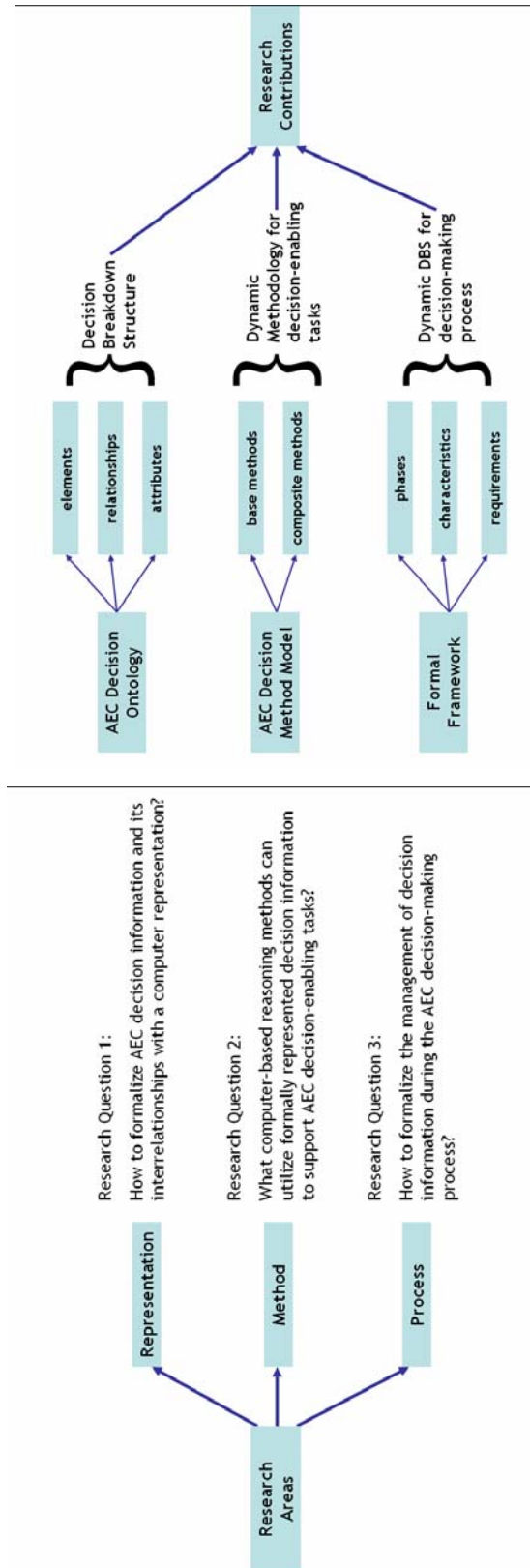


Figure 35. Building upon Figure 10 in Chapter 3, this figure summarizes the three primary focus areas of this doctoral research, their corresponding research questions, and contributions.

7.1.4 RESEARCH VALIDATION

I conducted four validation studies to collect evidence of power and generality (section 7.1.5) for my research contributions. The performance of current practice, as observed in industry test cases, serves as the benchmark in my validation studies. Taking the same decision scenario with decision information, decision-enabling tasks, and decision-making process as the test cases, I and four industry professionals (two professionals in TC#5 and two other professionals in TC#6) built six Decision Breakdown Structures and completed eight decision-enabling tasks across five different decision phases. Such construction of DBS, completion of decision-enabling tasks, and application of the Dynamic DBS in the decision-making process have allowed me (in Validation Studies #1, 2, and 3) and twenty-one expert professionals and researchers (in Validation Study #4) to evaluate and assess the performance of the Dynamic DBS Framework (as implemented in the Decision Dashboard prototype), relative to the benchmark performance evidence collected from current practice.

Validation Study #1 tests whether my AEC Decision Ontology is general and powerful. I took four different sets of decision information from industry test cases and tested if the ontology elements, relationships, and attributes were sufficient to formally represent and distinguish these different sets of decision information (Figure 36 Box Label 1). This validation study shows that the number of decision choices and their interrelationships, which are implicit in current practice, can now be explicitly and formally represented by the DBS (sections 3.5 and 4.3).

Validation Study #2 examines how decision facilitators perform eight different types of decision-enabling tasks based on the representations of decision information in Validation Study #1. Comparing between decision-support methods in current practice and the dynamic methodology with the DMM, I assess how respective methods contribute to the informative, flexible, resumable, and fast completion of impromptu decision-enabling tasks (Figure 36 Box Labels 2, 1, and 4). This study validates that when compared to a variety of decision-support tools and methods used in current practice, the Dynamic DBS enables facilitators to better complete decision-enabling tasks and hence improve the basis for decision makers to make quick and informed decisions (sections 3.5 and 5.3).

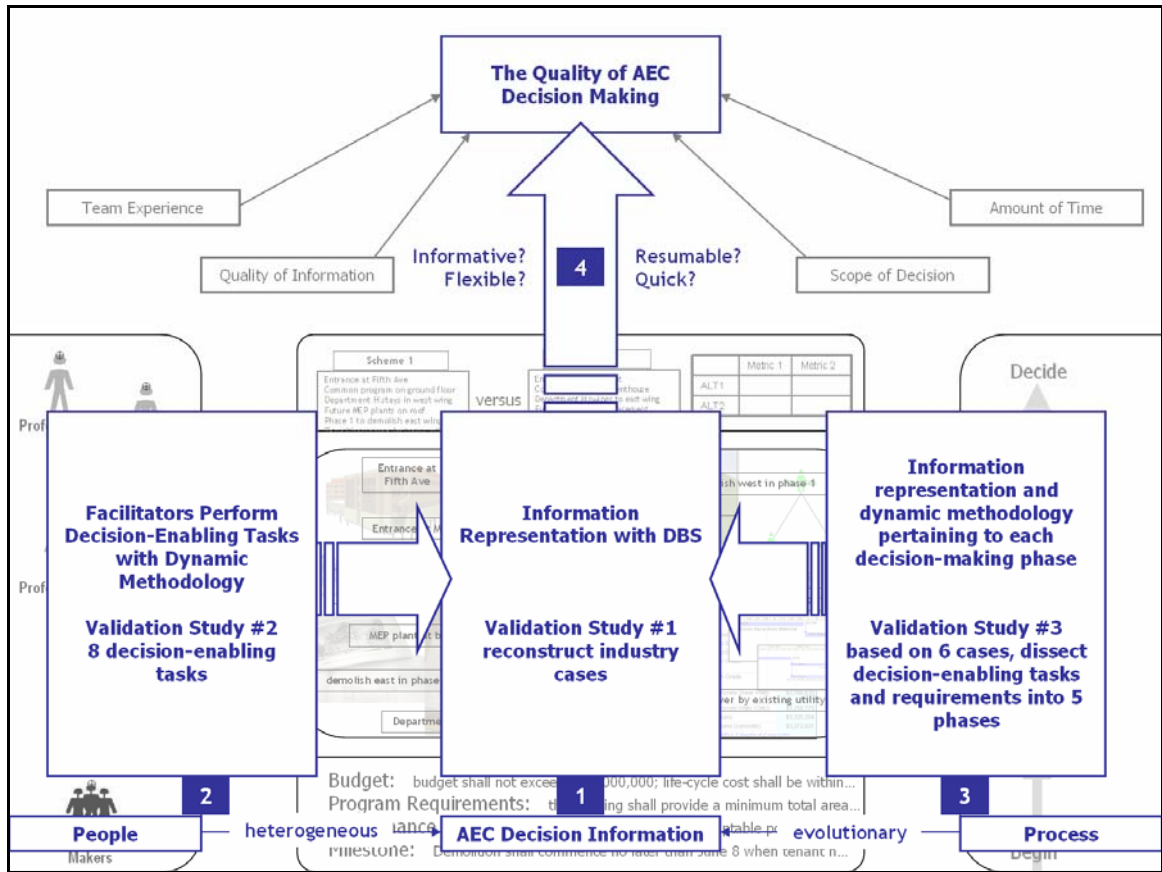


Figure 36. Interrelationships among the stakeholders, process, decision information, validation studies, decision basis, and the quality of AEC decision making (building upon the concepts presented in Figure 1).

Validation Study #3 categorizes the representation of decision information and the completion of decision-enabling tasks from all six industry test cases according to the five decision phases established in the Dynamic DBS Framework (Figure 36 Box Labels 3, 1, and 4). This study validates that the six test cases and their associated decision information and decision-enabling tasks fit into the unique characteristics and different requirements established in each of the five decision phases. Furthermore, this validation study also compares and analyzes the performance evidence of current practice and the Dynamic DBS in the definition, formulation, evaluation, iteration, and decision phases of AEC decision making. I also assess the impacts of ad-hoc decision-support strategies on the ability of facilitators to resume decision-enabling tasks across different decision phases and decision processes (sections 3.5 and 6.3).

In Validation Study #4, I demonstrated the Dynamic DBS Framework to twenty-one expert professionals and researchers in four demonstration sessions. During these sessions, I went through a simplified version of TC#1 in both current and Dynamic DBS-based tools and methods. This validation study allowed industry experts to ratify the generality and applicability of my research observations, while assessing the power of my research contributions (sections 3.5 and 6.4).

In reference to the case example, one of my validation examples shows that the DD provides a quick (almost instantaneous) re-coupling of existing options to re-formulate a new design alternative in support of a decision-enabling task (i.e., the task to re-package entrance locations into a new hybrid design), which required 4 weeks of professional re-formulation time, rework, and delay in current practice. Meanwhile, the DD provides a dynamic interface for the decision makers to continually monitor the total rentable area of the changing design based on integrated quantitative data, another decision-enabling task that cannot be performed with current decision-support tool given an impromptu evaluation need. This performance evidence is further described in sections 4.3, 5.3, 6.3, and 6.4.

7.1.5 POWER AND GENERALITY

My validation studies have provided evidence for power of the AEC Decision Ontology, the Decision Method Model, and the associated decision information management framework. The Dynamic DBS Framework has enabled facilitators to complete decision-enabling tasks in ways that are more informative, flexible, resumable, and faster than in current practice. This evidence for power is further evidenced by the relative strength and performance of the Dynamic DBS versus that of a variety of methods and tools used by renowned AEC facilitators along with their decision makers and professionals, who are involved in the six large-scale (i.e., above \$50,000,000 in project cost on average) industry test cases.

Furthermore, the value of the Dynamic DBS is ratified by twenty-one expert professionals and researchers (section 6.4). They include directors from public and private owners, the chief technology officer from a leading architectural firm, and a research group leader from the National Institute of Standards and Technology. After attending a demonstration session of my research prototype, a director from a Fortune 500 corporation initiated a follow-up visit to CIFE with a project executive. Together, we spent a day exploring the value of the

Decision Dashboard with a decision scenario, which has become my TC#5. Having participated in the one-day visitation, CIFE Executive Director Dr. John Kunz noted,

“What happened [that day] was remarkable. A CIFE member friend brought a line project manager up here to see the work of an individual graduate student, on his own initiative (not ours!). I cannot recall that ever happening before at CIFE.”

In addition, the application of the Dynamic DBS has provided a positive and significant intervention in an ongoing capital project (TC#6). The use of the Dynamic DBS has contributed to the uncovering of a major cost estimating error in a cost report, which was prepared by a professional consulting firm. The finding was ratified by the project manager, executive, and the consulting firm, which then incorporated the corrections in its cost estimate.

Summarizing the evidence gathered from my validation studies, the Dynamic DBS has improved performance over decision-support methods and tools in current practice in the following ways:

- (1) The Dynamic DBS is more informative than current methods since it allows all stakeholders to get a public and explicit understanding about all the decision information, its type, state, and relationship in one central representation. The Dynamic DBS is also more flexible, since it enables stakeholders to test attribute propagation (when evaluating ripple consequences of a decision), isolate decision focus, and change the state, relationship, or type of decision information.
- (2) The Dynamic DBS provides an explicit view of the decision scenario, graphically connecting the interrelated options and alternatives, such that decision stakeholders are aware of the decision context and the available choices.
- (3) Investment in the Dynamic DBS (i.e., to define and formulate decision information using the DBS) seeded during the early phases can pay off during the evaluation, iteration, and decision phases, when an array of DMM-based methods empowers stakeholders with dynamic interaction capabilities. These dynamic behaviors in turn enable stakeholders to manage the decision information more informatively, flexibly, resumably, and quickly than with current methods.
- (4) The formulation of decision alternatives with the Dynamic DBS enables the uncovering of information errors and the management of diverse sets of decision information in a way that is quicker and more flexible than current practice.

- (5) The Dynamic DBS promotes a more flexible shift of inquiry, focus, and management of decision information than current decision-support tools. The Dynamic DBS is more informative and flexible, contributing to a quicker decision evaluation.
- (6) In current practice, the process of generating presentation slides or printed reports does not offer any flexibility for access to decision information that is discarded by the facilitators during the formulation process. The Dynamic DBS offers the flexibility to preserve seemingly invalid decision information throughout the decision-making process, allowing decision facilitators to flexibly and quickly couple, de-couple, and re-couple options without discarding or re-entering existing information.
- (7) The Dynamic DBS promotes a higher degree of resumability than current practice as it requires less rework by the stakeholders to complete information management tasks when the decision context changes.
- (8) In current practice, the switching of decision-support tools is necessary because today's tools do not fully support decision-making in asynchronous and synchronous modes. Using the Dynamic DBS, decision stakeholders can start managing the decision information with the same decision-support tool in both modes. The Dynamic DBS serves as a central information management tool, which continues to accrue decision information and support information management, throughout successive decision-making phases and processes. This continuity eliminates the need to rely on multiple tools that may involve information re-entry.

At the same time, my validation studies have also demonstrated the generality of my research contributions through the application of the Dynamic DBS on a diverse set of industry test cases. These test cases cover a broad range of AEC project phases—from concept definition (TC#5) to programming (TC#3), schematic design (TC#1 and TC#2), design development (TC#6), and construction (TC#4). They involve a diverse set of decision information, which includes the Function, Form, and Behavior information and choices of the facilities' Products, Organizations, and Processes (Table 11). The cases also involve a variety of decision-support tools, methods, and representation media (refer to Table 3 in Chapter 2) used by different project teams of owners, designers, and contractors practicing in different parts of the United States. Hence, the basis of my validation studies is drawn from a broad, yet powerful, set of industry test cases. This breadth of coverage constitutes the evidence for the generality of the Dynamic DBS Framework.

Test Case	TC#1	TC#2	TC#3	TC#4	TC#5	TC#6
Project Types	Office Renovation	Office	Office Renovation	Retail	Recreational	Seismic Upgrade
Project Phases	Schematic Design	Schematic Design	Programming	Construction	Design Development	Concept Definition
Decision Info.	Product, Organization, Process, Form, Function, and Behavior	Product, Form, Function, and Behavior	Product, Organization, Process, Form, Function, and Behavior	Product, Organization, Process, Form, Function, and Behavior	Product, Process, and Form	Product, Organization, Process, Form, Function, and Behavior
Decision Stakeholders	Decision Makers, Facilitators, and Professionals	Decision Makers, Facilitators, and Professionals	Decision Makers, Facilitators, and Professionals	Decision Makers, Facilitators, and Professionals	Decision Makers and Facilitators	Facilitators and Professionals
Decision Mode	Synchronous	Asynchronous	Asynchronous	Synchronous	Synchronous	Synchronous

Table 11. Summary of the broad class of project types, project phases, decision information, decision stakeholders, and mode of decision making of the six industry cases used to validate the Dynamic DBS Framework.

7.2 THEORETICAL SIGNIFICANCE

My research complements the existing literature with a number of concepts for representing and managing decision information in the AEC context. My research extends and bridges theories in DA, VDC, and AEC by:

- (1) documenting industry cases in the form of case studies to understand and analyze the AEC decision-making process,
- (2) defining the heterogeneous and evolutionary nature of AEC decision information,
- (3) highlighting the importance of re-constructability, informativeness, flexibility, resumability, and quickness in information management,
- (4) offering a formal theoretical basis to represent and manage decision choices, rationale, and ripple consequences,
- (5) distinguishing the difference between options and alternatives in terms of coupling and de-coupling, and
- (6) formalizing the unique information management requirements across different phases in the decision process.

My research has formalized the necessary concepts to improve AEC decision information management that were missing, implicit, or vague in existing literature. I have provided an industry-based study of AEC decision-enabling tasks, decision-support tools and methods, and decision-making processes. Through my formalization of a Decision Breakdown Structure, a dynamic methodology, and an application framework, I have extended the concept of decision basis and decision quality in DA with an integration of alternative generation and evaluation; while supplementing VDC (e.g., POP, DEEP, and DEEPAND, see section 4.1, 5.1, and 6.1) and AEC theories with the management of choices and their interrelationships across different phases (including synchronous and asynchronous modes) of decision making. I have offered a non-stochastic method to incorporate the concept of Decision Analysis for the building industry. While decision analysis relies on the skills of decision analysts and tools such as the Strategy-Generation Table to formulate alternatives, my research provides a formal basis for decision stakeholders to formulate and manage not only alternatives, but also their interrelationships, couplings and decouplings, as well as the rationale that goes into the formulation, evaluation, re-formulation, and decision of alternatives. While DA methods separate the process of alternative generation and alternative evaluation, my research integrates the two. My research suggests that in the AEC context, this integration would dramatically improve the quality of the decision basis without the overhead of applying stochastic methods. This integration provides a more intuitive, informative, flexible, and resumable basis for stakeholders to generate, explore, change, decouple, and re-couple alternate courses of actions during the evaluation process. Thus, decision stakeholders no longer need to rely on a sequential and disjointed approach, which first determines the alternatives prior to the application of a separate evaluation method. The need for such a flexible approach is exemplified in a recent Scientific American article that criticizes the limitations of fixing strategies and “crashing” for a decision as well as the shortcomings of “addressing only a handful of the many plausible futures” (Popper et. al 2005; see also section 5.1.1).

My work also extends AEC-based theories. My research formalizes the representation, methodology, tasks, requirements, and processes for handling heterogeneous and evolutionary AEC decision information, including choices and preferences, associated with decision making in the building industry. As discussed in my points of departure (sections 4.1, 5.1, and 6.1), theories in design (such as analysis-synthesis-evaluation and function-form-behavior), virtual design and construction theories (such as product, organization, and

process modeling), project management (such as set-based design, work breakdown structure, and the critical path method), and industry standards (e.g., the Industry Foundation Classes, Omniclass, etc.) do not have any formal foundation to manage choices. My work provides this foundation—not only a foundation to consider the choices or manage information within the abovementioned theories and methods, but also a foundation for integrating these varying theories and methods under one decision-making context.

7.3 IMPACT ON PRACTICE

With respect to the impact on practice, the validation studies illustrate that my research contributions empower multidisciplinary stakeholders to improve the decision quality when dealing with discrete decision choices in the building industry. Because AEC stakeholders have a Dynamic DBS-based decision method and framework to support the decision-making process, they no longer have to focus their attention, time, and effort on mitigating the effects of the dispersed and homogenized representation as well as the implicit and static management of decision information. They can benefit from the Dynamic DBS to improve the re-constructability, informativeness, flexibility, resumability, and quickness across different decision-making tasks and phases and thereby, shift their attention, time, and effort to improving the quality of decision information and the making of good decisions. Furthermore, my research could have an impact on decision making beyond the building industry, as suggested by a group leader of a national research organization after participating in one of my demonstration sessions (section 6.4.5).

In this dissertation, a recurring theme is that existing decision-support methods and tools are limited by the evolutionary and heterogeneous nature of AEC decision information. The Dynamic DBS, on the other hand, focuses on the nature of AEC decision information and the process of AEC decision making as it builds a new approach for decision support. In its current state, the Decision Dashboard (and all the concepts that it embodies) is merely a decision-support tool and its impact is largely dependent on its users. However, as my industry test cases demonstrate, given the same set of decision information, under the same decision scenario, and among the same group of AEC stakeholders, the Dynamic DBS has the potential to improve the decision basis of the AEC stakeholders in the industry. By providing a theoretical basis and a proof-of-concept prototype, my research contributes to a dynamic decision-support method and tool that has the potential to serve practitioners across

different information management phases throughout the decision making process. My research contributions have the potential to empower individual AEC stakeholders to complement their facilitation skills. They can spend less time decoupling decision alternatives, looking for dispersed or discarded decision information, and packaging decision information for recommendation or evaluation. Thus, they can focus more time and attention on formulating, evaluating, iterating, and making decisions, rather than managing decision information. This quality and efficiency gain is particularly critical during synchronous modes of decision making when individuals from every decision stakeholder are spending time together, and hence, the impacts of the Dynamic DBS framework on improving the quality and efficiency of the decision-making process is particularly valuable.

While the prospective applications of the Dynamic DBS have made significant impacts on Test Cases #5 and #6 (sections 2.5, 2.6, and 6.3), my research could have improved the decision bases of Test Cases #1, #2, #3, and #4 if applied during the actual decision-making processes. As illustrated in validation studies #2 and #3 (sections 5.3 and 6.3), decision facilitators in these test cases could have utilized the Dynamic DBS to expedite the reformulation of a hybrid decision alternative in TC#1, generate evaluation tables with flexibility across macro, micro, and hybrid levels of detail in TC#2, uncover ripple consequences informingly and quickly in TC#3, and retrieve alternative or option-specific assumptions with quickness in TC#4. Furthermore, as the headquarters renovation project transitioned from the programming project phase (i.e., TC#3) into schematic design development (i.e., TC#1), the lead architect (i.e., the decision facilitator) could have used the Decision Dashboard as a single and continuous decision-support tool across different modes and phases of decision making. Thus, practitioners could have avoided data re-entry and ensured a more seamless knowledge transfer during the evolutionary and fragmented AEC decision-making process. Furthermore, there are opportunities for further research and development to spread the abovementioned impacts into reality on a greater number of capital projects. I address a few potential areas of future research in the following section.

7.4 LIMITATIONS AND FUTURE WORK

I have prioritized my research scope and contributions based on my assessment of the core limitations in today's theories and practice. The dynamic Decision Breakdown Structure, in its current state, does not support non-discrete decision scenarios, automated data handling,

and alternate visualizations of the decision information. These are areas for future extension of my research.

(1) The scope of research is limited to discrete decision information:

My research does not cover all types of decision choices in AEC decision making. I focus on discrete choices (e.g., major design variations, system selections, materials, and three major productivity scenarios in TC#2) rather than uncertainty (e.g., probability of a choice or an event) or a range of distributed choices (e.g., finding the optimal angle from a range of angle orientations, the optimum concrete strength, etc.). The Dynamic DBS approach advocates the modeling of relevant discrete choices rather than an exhaustive representation of all possible options and alternatives. Among all six test cases, Test Case #3 represents the most rigorous use of the DD. It supports 97 instances of discrete ontology elements and 103 instances of ontology relationships across 6 levels of detail. There are existing theories (e.g., on stochastic modeling, on optimization, etc.) that specify the means and methods to come up with uncertainty and distributed choice sets, hence, it is a matter of further development to integrate these methods with the Dynamic DBS. Logically, such probabilistic and distributed decision information should be categorized as attributes of a DBS within the AEC Decision Ontology. Once integrated, decision stakeholders can explore a more diverse set of decision choices. They can extend the coverage of major discrete decision choices to include finer sets of choices.

(2) The AEC Decision Ontology has not been extensively integrated with existing AEC methods and theories:

My research provides a small set of ontology elements, relationships, and attributes that focus on supporting a general, yet powerful, vocabulary to support FFB choices of POP. It focuses on major discrete choices and relies on external references to associate detailed decision information. Hence, there is an opportunity for future research to extend my AEC Decision Ontology with existing AEC methods and theories. For instance, my decision topic can be further elaborated by Rittel's discussion on issues (1979), my decision criterion can be further elaborated by Kiviniemi's requirements model (2005), my decision attributes can be further elaborated by Garcia's Active Design Document (1993), while my impact relationships can be further classified by Koo's "impeding" and "enabling" concepts (2003). Meanwhile, Professor Martin Fischer, Dr. John Haymaker, and I have recently been awarded CIFE seed funding to

integrate the POP (Kunz and Fischer 2005), Narrative (Haymaker 2004), and Decision Dashboard modeling concepts. My postdoctoral research on this CIFE seed project will allow me to further leverage and consolidate the Dynamic DBS concept with POP and the Narrative concepts.

(3) The DMM (i.e., dynamic methodology) does not support automated data handing:

In its current implementation, the DMM supports automatic propagation and consistent reporting of Level-1 decision information across different ontology elements and evaluation tables. The DMM also allows the referencing and automatic launching of digital information with external computer applications (section 5.2). However, the initial input of the data requires the users to enter them manually. Thus, there is an opportunity for future research to provide automatic data synchronization with other information generation tools before, during, and after the manipulation of decision information in the DD (e.g., synchronize data with cost estimating, scheduling, and 3D building information modeling applications). The propagation of Level-1 decision information in the DBS is limited to linear relationships, e.g., the summation of costs for all ontology elements (that are connected by “aggregate relationships”) to automatically compute the cumulative total cost of a particular decision. To propagate non-linear effects that may arise due to the coupling effects or ripple consequences, the current Decision Dashboard would require additional programming beyond its current support for basic mathematical operations. Furthermore, future research may build on the model server technology (e.g., EPM Technology^{xxiv} and Enterprixe^{xxv}) to compile partial data models and formulate an updated FFB-POP model based on the adjustments made in the DD.

(4) The DD does not automatically check or optimize decision information:

My current research does not distinguish whether options are mutually exclusive or not. Current DD design allows a decision topic to have multiple active “selected” options at once. To properly represent mutually exclusive options, the current Decision Dashboard

^{xxiv} <http://www.epmtech.jotne.com>

^{xxv} <http://www.enterprixe.com>

relies on “negative impact” relationships (shown as red arrows in the DD) and their embedded descriptions among mutually exclusive options to provide a visual warning about the interrelationship to decision makers. Future work may generate automatic rejections or error messages to prevent any decisions to include or combine mutually exclusive options. Hence, future research may extend my ontology relationships and attributes by leveraging optimization and data checking concepts to help check, optimize, and qualify the decision information in the DD.

- (5) The Dynamic Decision Breakdown Structure concept and the Decision Dashboard prototype require a special skill set to master them:

To fully master the concepts and methods associated with the dynamic Decision Breakdown Structure, AEC decision facilitators probably need to read through this dissertation and take a Decision Dashboard training. However, this is not unlike what their counterparts (i.e., decision analysts) need to go through in preparation for a consulting position in Decision Analysis. Those decision analysts often need to obtain a graduate degree in management science and engineering and master the courses in Mathematics and Decision Analysis to fully understand the philosophy and mechanics of Decision Analysis. Meanwhile, visual tools such as Microsoft Visio^{xxvi}, Mindjet^{xxvii}, Kartoo^{xxviii}, and Visual Thesaurus^{xxix} share similar user interfaces as the Decision Dashboard. These tools are becoming popular for AEC stakeholders to take personal notes and organize personal data, hence, have the potential to prepare AEC stakeholders for the transition to manage their decision scenarios with a DBS.

- (6) The DD prototype has limited supports for alternate means and methods to visualize the DBS:

Current implementation of the DD involves a graphical representation of the DBS in a

^{xxvi} <http://office.microsoft.com/visio>

^{xxvii} <http://www.mindjet.com/us>

^{xxviii} <http://www.kartoo.com>

^{xxix} <http://www.visualthesaurus.com>

network form. Within the current graphical representation, the DD user has the freedom to lay out the decision information. All test cases in this dissertation follow an implicit layout convention, e.g., top-down layout of DBS where decision topics are structured hierarchically, decision topics are placed by implicit layout convention such that decision criteria are placed vertically to their left, alternatives are placed vertically to their right, whereas options are placed horizontally to their bottom. Future work can offer more formalism in terms of graphical representation of the DBS. Furthermore, current evaluation tables in the DD show only 3 columns, while allowing users to change the attributes to be shown by selecting specific attributes in a drop-down menu. Additional attributes could be shown simultaneously by adding more columns. The graphical representation as implemented in the DD only represents one view of the decision information. The concept of the Dynamic DBS can also be implemented with other information visualization methods (e.g., in a directory form, in a table form, in a tree hierarchy, etc.) and it is a human-computer interaction and software development issue to support the many visualizations of the same DBS and its associated set of decision information. My intuition is that a non-graphical representation will be more scalable to incorporate more decision information, but may be less effective in informing the decision stakeholders about the ripple consequences and interrelationships. Hence, the support for graphical and non-graphical representations of the same DBS would complement the AEC decision information management well.

(7) The DD prototype does not support knowledge repositories:

Currently, AEC stakeholders need to build a new DD model for every decision scenario. As a corporate director who participated in my demonstration session and the live session in TC#5 suggested, a potential value of the DD is to formalize the knowledge about AEC decision making in a DBS-based repository. As discussed in section 4.1.1, the Influence Diagram from Decision Analysis provides a good theoretical basis to formalize knowledge representation (Howard 1988). Hence, future research can evaluate the applicability of the DBS in supporting AEC knowledge templates for decision scenarios, e.g., choices to consider when developing a platinum-rated LEED

(Leadership in Energy and Environmental Design^{xxx}) project for sustainability. This would require all decision stakeholders to carefully analyze the decision context and establish a DBS and design its levels of detail, which would be powerful to support project-specific knowledge capture, while being general and easily applicable to other projects that may benefit from such knowledge repositories.

7.5 CLOSING REMARKS

Building owners, investing in major capital projects, rely on the decision processes to inject their influence onto their investments and on the environment of the occupants for the life-cycle of the facility. Therefore, it is critical for these AEC decision makers to make informed decisions.

AEC professionals, balancing their creativity with technical skills, rely on the decision processes to develop and iterate their many ideas and proposals for the design and construction of a building. The fragmented and prototypical nature of the building industry challenges these professionals' ability to coordinate heterogeneous and evolutionary decision information.

Leading design or construction project executives, responding to what the owners demand and managing what the professionals supply, rely on the decision processes to steer the design/construction directions for recommendations to the building owners. Without an effective decision-support tool, these decision facilitators are hindered by the limitations of information management in current practice. By bridging between Decision Analysis and AEC theories, the Dynamic Decision Breakdown Structure offers a new concept and methodology to support decision facilitators in completing AEC decision-enabling tasks.

Serving as a CIFE/Stanford University Visiting Fellow at the United States General Services Administration (GSA) Public Buildings Service (PBS) Office of the Chief Architect (OCA) in Washington D.C, I have been advocating the adoption of Virtual Design and Construction,

^{xxx} <http://www.usgbc.org>

Building Information Modeling (BIM), and open standards. In the past two years, I have witnessed and helped influence an encouraging rate of VDC and BIM adoptions in the U.S. building industry and beyond. As VDC and BIM are becoming an indispensable part of AEC practice, the needs for a Decision Breakdown Structure, a dynamic methodology, and a decision-making framework that can effectively manage VDC-based information (e.g., simulation results, representation models, etc.) as well as its many criteria, topics, choices, interrelationships, and details for better decision making are becoming more imminent.

Being passionate about the contributions that I have claimed in this doctoral research, I am looking forward to the exciting opportunities in my post-doctoral career to further research, develop, apply, and disseminate the Dynamic Decision Breakdown Structure, its application framework, and the Decision Dashboard in the building industry and beyond.

REFERENCES

1. ACRONYMS AND GLOSSARY

AEC

AEC is the short form for Architecture, Engineering, and Construction. In this research, the term “AEC” refers to the whole building industry, which also includes real estate and facility management in addition to the literal meaning (i.e., only the design and construction aspects) of AEC.

Unless there are specific notes of exception, the AEC context applies to all of the following terms, such as decision-making process, phases, professionals, decision information, decision ontology, decision dashboard, methodology, decision-enabling tasks, and formal framework, etc. In other words, all “decision-making processes” in this dissertation are “AEC decision-making processes,” “professionals” are “AEC professionals,” and so on.

ASYNCHRONOUS

As an antonym of “synchronous”, an asynchronous mode of decision making describes the completion of decision-enabling tasks when decision stakeholders need not be present at the same time or at the same place.

CHOICE

In this dissertation, “choice” is a generic term that is applicable to decision information and to the AEC Decision Ontology. For instance, a set of multiple topics, criteria, options, and alternatives under consideration is a set of choices.

CIFE

CIFE stands for the Center for Integrated Facility Engineering, where my office and the CIFE iRoom (interactive environment) is located.

DECISION-MAKING PROCESS

The decision-making process is the course of information finding, solution exploration, negotiation, and iterations with the aim of arriving at a decision. In the building industry, the decision-making process runs in parallel throughout building design and construction. Conceptual design, design development, construction documentation, and construction are all examples of decision-making processes in which the project stakeholders strive to decide upon the design concept, the design details, the construction methods, etc. through a course of explorations, studies, and refinements.

DECISION-SUPPORT TOOLS

Decision-support tools are the tangible means (in physical forms or computer systems) of conducting decision-enabling tasks. The tools enable the completion of decision-enabling tasks, which in turn assist decision makers to specify decision needs, formulate action plans, evaluate proposals, and re-formulate action plans. Examples of such tools include the Decision Dashboard, MS Word, MS PowerPoint, MS Excel, Mindmap [reference], and the CIFE iRoom (interactive workspace). The experience and brainpower of individual decision-making stakeholders to mentally relate and predict decision information are intangible and, hence, not considered as decision-support tools.

DECISION-ENABLING TASKS (DET)

Decision making in the AEC context requires that specific actions be made to support the decision-making process. Such actions may include the explanation of a decision scenario, the evaluation of multiple decision choices, and the response to a “what-if” situation. This dissertation refers to these actions as AEC decision-enabling tasks, and my research formalizes the enabling methodologies to accomplish them. For each AEC decision-enabling task specified in this research, there is a specific methodology to prescribe the procedural techniques (which utilize the AEC Decision Ontology and the decision dashboard) to perform the task.

DECISION BREAKDOWN STRUCTURE

Decision Breakdown Structure (DBS) is a hierarchical organization of decision information, its associated knowledge, and its interrelationships. DBS is constructed with the AEC Decision Ontology (i.e., ontology elements, relationships, and attributes). Decision stakeholders have the discretion to include information and knowledge of relevance (i.e.,

level-1 decision information) in a scenario-based DBS. The information and associated knowledge can be a sole or hybrid mixture of product issues, organization issues, process issues, and/or resource issues. Potentially, there are various information visualization channels for DBS's, such as a digital directory, relational database, graphical network, etc. The Decision Dashboard adopts a graphical network as an information visualization solution for the DBS. See section 4.2.4 for further details.

DECISION DASHBOARD

Decision Dashboard (DD) is the name of my research prototype. I have developed it as a decision-support tool, implemented as a software application for personal computers.

Decision—this research focuses on decisions that are related to the planning, design, construction, and operation of building construction, although the impacts of this research could have a broader impact on other industries.

Dashboard—a panel extending across the interior of a vehicle (as an automobile) below the windshield and usually containing dials and controls (reference to Merriam-Webster Dictionary). The research prototype integrates dispersed information into a central reporting and controlling interface to help stakeholders to make informed decisions. The concept here is analogous to dashboards, which gather essential information and enable drivers or pilots alike to make informed decisions.

DECISION FACILITATORS

Decision facilitators are individuals who moderate the decision-making process. They may represent the owners as representatives; they may be professionals and members of the design and construction team (e.g., lead design architects, construction managers, etc.).

DECISION INFORMATION

Decision information covers all the contents that serve as the background, basis, and prediction of a decision. Examples of decision information are criteria (e.g., budget), facts (e.g., site conditions), rationale (e.g., recommendation basis), intuitions (e.g., instinctive beliefs in specific systems), preferences (e.g., personal or institutional desires), assumptions (e.g., unit cost), and predictions (e.g., cost estimate) pertaining to decisions and their choices. Because the information spans across multidisciplinary stakeholders and matures throughout

the decision-making processes, it is heterogeneous, multidisciplinary, and evolutionary in nature.

DECISION METHOD MODEL

The Decision Method Model (DMM)—one of my three contributions—is the focus of Chapter 5. The DMM builds on the AEC Decision Ontology and specifies sets of methodologies, or procedural techniques, which are embedded in the decision dashboard. Composed of 6 base methods and 4 composite methods, the DMM solves specific decision-enabling tasks across different phases of the decision-making processes. The DMM is often associated with the adjective “dynamic” in this dissertation, see “Dynamic.”

BASE METHOD

The formalization of ontology behaviors and the specification of procedures for applying these behaviors become the base methods.

COMPOSITE METHOD

The combination of different base methods provides a synergy effect that is captured in the composite methods.

The definitions of the specific base and composite method terms such as “Swapping,” “Candidate,” “Selected,” and “Coupling,” etc. are available in Chapter 5.

DECISION ONTOLOGY

One of the key contributions of this research, an architecture-engineering-construction (AEC) Decision Ontology, is a vocabulary adhered to by my research and prototype. This vocabulary serves as a common language for humans and computer systems to recognize decision information and structure its interrelationships. It allows decision stakeholders to integrate or reference heterogeneous decision information and hence, offers a solution to reduce information dispersal given the number of AEC stakeholders involved in AEC decision making.

The definitions of the terms “Decision Topic,” “Criterion,” “Option,” “Alternative,” “Aggregate Relationships,” “Choice Relationships,” “Requirement Relationships,” “Impact Relationships,” “Process Relationships,” and “Attributes” are available in Chapter 4.

ELEMENTS

Decision Topic

see section 4.2.1.1

Decision Criterion

see section 4.2.1.2

Decision Option

see section 4.2.1.3

Decision Alternative

see section 4.2.1.4

RELATIONSHIPS

Aggregate Relationships

see section 4.2.2.1

Choice Relationships

see section 4.2.2.2

Requirement Relationships

see section 4.2.2.3

Impact Relationships

see section 4.2.2.4

Process Relationships

see section 4.2.2.5

ATTRIBUTES

see section 4.2.3

DISPERSED INFORMATION

As Chapter 2 explains, my criticism of the existing state of decision information is that it is dispersed throughout the many stakeholders involved in the decision-making process.

Different stakeholders possess different fragments of decision information. For instance, owners update their decision criteria; architects are responsible for the building program; energy consultants possess energy simulation results; and general contractors manage the cost estimates. Decision facilitators need to process such decision information to develop solutions and make tradeoff recommendations. My analysis of current decision-support tools is that they are not able to reduce information dispersal. Current practice often relies on individuals' brainpower to mentally relate the interrelated, but dispersed, decision information.

DYNAMIC

“Dynamic” conveys the non-static character of the DBS. The DMM has enhanced the static DBS with a dynamic quality (e.g., allows stakeholders to couple, decouple, or re-couple discrete but related information in the DBS) in managing decision information and its associated knowledge.

EVOLUTIONARY

see section 2.7.2

FORMAL FRAMEWORK

The formal framework is one of my three contributions. It offers stakeholders with conceptual principles for stakeholders to manage decision information across different information management phases in the decision making process. The framework also specifies a formal application of the AEC Decision Ontology and the DMM, which complement the conceptual principles, to improve the ad-hoc and inefficient completion of decision-enabling tasks in current practice.

GENERIC

Generic decision-support tools refer to general tools that are not AEC context or nature-specific.

HETEROGENEOUS

see section 2.7.1

HOMOGENIZED

Homogenized representation of AEC decision information refers to the inability of the decision-support tools and/or decision stakeholders to maintain the distinctive characteristics (e.g., types, states, forms, etc.) of AEC decision information, e.g., whether an information item is an option under recommendation or under consideration. The term is used to describe the limitation of current practice when heterogeneous information is “flattened” (i.e., represented without its heterogeneous characteristics) by the decision facilitators and their decision-support tools.

INFORMATION MANAGEMENT (MANAGEMENT OF DECISION INFORMATION)

Information management refers to the handling of information in general. Such handling includes the generation, population, organization, propagation, query, editing, reorganization, duplication, archiving, and/or deletion of information. The term “information management” is equivalent to “management of decision information” in this dissertation.

KNOWLEDGE ASSOCIATED WITH DECISION INFORMATION

One of the objectives of my research is to formalize the explicit representation of knowledge associated with decision information. Such knowledge includes ripple consequences, sequences, and the composition of alternatives, etc. The knowledge may reside explicitly in a textual narrative, implicitly in a professional’s mind, or may not have been identified by the stakeholders.

LEVEL-1 AND LEVEL-2 DECISION INFORMATION

In the Decision Dashboard, level-1 decision information refers to information that is embedded and integrated in the DD model, whereas level-2 decision information is referenced by the DD as electronic information. Since level-1 decision information is embedded as attribute text or values in the DD, decision stakeholders can modify it as well as propagate it for calculation or prediction purposes. On the other hand, level-2 decision information is referenced to an external authoring computer applications, which control its access, representation, and modification.

PHASES

This research categorizes the Decision-Making Process into five phases: (1) Decision Definition Phase, (2) Formulation Phase, (3) Evaluation Phase, (4) Iteration Phase, and (5)

Decision Phase. Chapter 6 details the differences between and interrelationships among the phases.

PROFESSIONALS

Architects, structural engineers, mechanical/electrical/plumbing (MEP) consultants, energy consultants, construction managers, cost estimators, general contractors, subcontractors, and facility managers, etc. are referred to as professionals in this dissertation.

STAKEHOLDERS

Stakeholders are all the groups of individuals involved in the decision-making process. The groups are comprised of individuals representing their respective organizations, e.g., the owner, occupant, decision facilitator, and professional organizations.

SYNCHRONOUS

Opposite to asynchronous, a synchronous mode of decision making describes the completion of decision-enabling tasks when decision stakeholders are present at the same time at the same place.

TC#

To simplify the referencing of the six industry test cases in this dissertation, my first, second, third, etc. test cases are abbreviated as “TC#1,” “TC#2,” “TC#3,” etc., respectively, in this dissertation.

2. BIBLIOGRAPHY

Assaf, Sadi; Jannadi, Osama; and Al-Tamimi, Ahmed (2000). "Computerized System for Application of Value Engineering Methodology." *Journal of Computing in Civil Engineering*. American Society of Civil Engineers, Volume 14, Issue 3, 206-214.

Ballard, Glenn (2000). "Positive vs Negative Iteration in Design." *Proceedings of the Eighth Annual Conference of the International Group for Lean Construction, IGLC-6*, Brighton, UK, July 17-19.

Barrett, P. and Stanley, C. (1999). "Better Construction Briefing." Blackwell Science, Oxford, UK.

Belton, Valerie and Stewart, Theodor (2002). "Multiple Criteria Decision Analysis: An Integrated Approach." Kluwer Academic Publishers, MA.

Blum, Erik; Giarrusso, Frederick; Zorovic, Sasha; and Tatum, Bob (1994). "Decision Analysis Techniques for Integration Technology Decisions." Center for Integrated Facility Engineering, Technical Report, Number 95. Stanford University, CA.

Burns, Scott; Liu, Liang; and Feng, Chung-Wei (1996). "The LP/IP Hybrid Method for Construction Time-Cost Trade-off Analysis." *Construction Management and Economics*, 14, USA, 265-276.

Clayton, Mark J.; Teicholz, Paul; Fischer, Martin; and Kunz, John (1999). "Virtual components consisting of form, function, and behavior." *Automation in Construction*, 8, 351-367.

Clough, Richard; Sears, Glenn; and Sears, Keoki (2000). "Construction Project Management." Fourth Edition. John Wiley and Sons, Inc., NY.

Dell'Isola, Alphonse (1982). "Value Engineering in the Construction Industry." Third Edition. Van Nostrand Reinhold Company, Inc., NY.

Dell'Isola, Alphonse (1997). "Value Engineering: Practical Applications ... for Design, Construction, Maintenance & Operations." RS Means Company, Inc., MA.

Fischer, Martin (2005). "Information Technology in Construction—What's Ahead." Presentation at the Executive Forum, Technology for Construction Conference, Las Vegas, NV, January 18, 2005.

Fischer, Martin and Kam, Calvin (2002). "Product Model and the Fourth Dimension—Final Report." Center for Integrated Facility Engineering, Technical Report, Number 143. Stanford University, CA.

Fischer, Martin and Kunz, John (2001). "The CIFE Research Model." Internal Presentation. Center for Integrated Facility Engineering, Stanford University, CA.

Fischer, Martin and Kunz, John (2004). "The Scope and Role of Information Technology in Construction." *Journal of Construction Management and Engineering*, JSCE, No. 763/VI-63, pp. 1-18.

Fischer, Martin; Stone, Maureen; Liston, Kathleen; Kunz, John; and Singhal, Vibha (2002). "Multi-stakeholder collaboration: The CIFE iRoom." Conference Proceedings of the International Council for Research and Innovation in Building and Construction, CIB w78. Aarhus, Denmark, 1-8.

Froese, Thomas (1992). "Integrated Computer-Aided Product Management Through Standard Object-Oriented Models." Center for Integrated Facility Engineering, Technical Report, Number 68A. Stanford University, CA.

Garcia, Cristina; Kunz, John; and Fischer, Martin (2003). "Meeting Details: Methods to Instrument Meetings and Use Agenda Voting to Make Them More Effective." Center for Integrated Facility Engineering, Technical Report, Number 147. Stanford University, CA.

Garcia, Cristina; Kunz, John; Ekström, Martin; and Kiviniemi, Arto (2003). "Building a Project Ontology with Extreme Collaboration and Virtual Design and Construction." Center

for Integrated Facility Engineering, Technical Report, Number 152. Stanford University, CA.

Garcia, Cristina (1993). "Active Design Documents: A New Approach for Supporting Documentation in Preliminary Routine Design." Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University, CA.

Genzuk, Michael (2003). "A Synthesis of Ethnographic Research." Occasional Papers Series. Center for Multilingual, Multicultural Research, Rossier School of Education, University of Southern California. Los Angeles, CA.

Gero, J. S. (1998). Towards a model of designing which includes its situatedness, in H. Grabowski, S. Rude and G. Green (eds), *Universal Design Theory*, Shaker Verlag, Aachen, pp. 47-56.

Gero, J. S. (1990). Design prototypes: a knowledge representation schema for design, *AI Magazine*, 11(4), pp. 26-36.

Griffin, Jane (2002). "Information Strategy: A Philosophical Blueprint for Building the Executive Dashboard." *DM Review*, August Issue. Thomson Media Group, NY.

Gruber, Thomas (1993). "Toward principles for the design of ontologies used for knowledge sharing." Originally in N. Guarino and R. Poli, (Eds.), *International Workshop on Formal Ontology*, Padova, Italy. *International Journal of Human-Computer Studies*, Special Issue on the Role of Formal Ontology in Information Technology, Volume 43 , Issue 5-6 Nov./Dec. 1995, pp. 907-928.

Haymaker, John; Kunz, John, Suter, Ben; and Fischer; Martin (2004). "Perspectors: Composable, Reusable Reasoning Modules To Construct An Engineering View From Other Engineering Views." *Journal of Advanced Engineering Informatics*, Elsevier B.V. Volume 18, Issue 1, Pages 49-67.

Howard, Ronald (1966). "Decision Analysis: Applied Decision Theory." Proceedings of the Fourth International Conference on Operational Research. Wiley-Interscience, New York, 55-71.

Howard, Ronald (1983). "The Evolution of Decision Analysis." The Principles and Applications of Decision Analysis. Volume 1. Strategic Decisions Group, CA.

Howard, Ronald (1988). "Decision Analysis: Practice and Promise." Management Science. The Institute of Management Sciences, USA, 679-695.

Howard, Ronald (1990). "From Influence to Relevance to Knowledge." Influence Diagrams, Belief Nets, and Decision Analysis, edited by R.M. Oliver and J.Q. Smith, John Wiley & Sons Ltd., Chichester, West Sussex, England.

Johanson, Brad; Fox, Armando; and Winograd, Terry (2002). "The Interactive Workspace Project: Experiences with Ubiquitous Computing Rooms." Pervasive Computing Magazine Special Issue on Systems, April-June Issue, Pages 67-74.

Kam, Calvin and Fischer; Martin (2004). "Capitalizing on early project decision-making opportunities to improve facility design, construction, and life-cycle performance—POP, PM4D, and decision dashboard approaches." Journal of Automation in Construction, Elsevier B.V. Volume 13, Issue 1, Pages 53-65.

Kam, Calvin; Fischer, Martin; and Kunz, John (2003). "CIFE iRoom—An Interactive Workspace for Multidisciplinary Decision Briefing." Proceedings of the Second International Conference on Construction in the 21st Century—Sustainability and Innovation in Management and Technology, Syed M. Ahmed, Irtishad Ahmad, S.L. Tang, and Salman Azhar (Editors), Hong Kong. December 10-12, 2003, pp. 505-510.

Kam, Calvin; Fischer, Martin; Hänninen, Reijo; Karjalainen, Auli; and Laitinen, Jarmo (2003). "The Product Model and Fourth Dimension Project." Electronic Journal of Information Technology in Construction, ITcon Vol. 8, pp. 137-166.

Kam, Calvin; Fischer, Martin; Hänninen, Reijo; Lehto, Seppo; and Laitinen, Jarmo (2002). "Capitalizing on Early Project Opportunities to Improve Facility Life-Cycle Performance." Proceedings of the 19th International Symposium on Automation and Robotics in Construction, William Stone (Editor), National Institute of Standards and Technology, Gaithersburg, MD. September 23-25, 2002, pp. 73-78.

Kam, Calvin; Fischer, Martin; Hänninen, Reijo; Lehto, Seppo; and Laitinen, Jarmo (2002). "Implementation Challenges and Research Needs of the Industry Foundation Classes (IFC) Interoperability Standard." Computing in Civil Engineering, Proceedings of the International Workshop on Information Technology in Civil Engineering, Anthony Songer and John Miles (Editors), Washington, DC. November 2-3, 2002, pp. 211-220.

Kamara, John; Anumba, Chimay; and Evbuomwan, Nosa (2002). "Capturing Client Requirements in Construction Projects." Thomas Telford Limited, London, UK.

Kiviniemi, Arto (2005). "Requirements Management Interface to Building Product Models." Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University, CA.

Koo, Bonsang (2003). "Formalizing Construction Sequence Constraints for the Rapid Generation of Scheduling Alternatives." Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University, CA.

Kunz, John and Fischer, Martin (2005). "Virtual Design and Construction: Themes, Case Studies and Implementation Suggestions." Center for Integrated Facility Engineering, Working Paper, Number 97. Stanford University, CA.

Kunz, John; Luiten, Gijsbertus; Fischer, Martin; Jin, Yan; and Levitt, Raymond (1996). "CE4: Concurrent Engineering of Product, Process, Facility, and Organization." Concurrent Engineering: Research and Applications, 4(2), pp. 187-198.

Levitt, R.E.; Cohen, G.P.; Kunz, J.C.; Nass, C.I.; Christiansen, T.; and Jin, Y. (1994). "The 'Virtual Design Team': Simulating How Organization Structure and Information Processing

Tools Affect Team Performance,” in Carley, K.M. and M.J. Prietula, editors, Computational Organization Theory, Lawrence Erlbaum Associates, Publishers, Hillsdale, NJ, pp. 1-18.

Liston, Kathleen (2000). “Assessing and Characterizing the Use of Visualization Techniques for AEC Decision-Making Tasks.” Ph.D. Thesis Proposal. Stanford University, CA.

Lilien and Rangaswamy (2001). “Tutorial for Decision Tree Analysis.” On-Line Tutorial. Marketing Engineering Applications. <<http://www.mktgeng.com/support/tutorials.html>>

Lu, Ming (2002). “Enhancing Project Evaluation and Review Technique Simulation through Artificial Neural Network-based Input Modeling.” Journal of Construction Engineering and Management. ASCE, Volume 128, No. 5, 438-445.

McNeill, T., Gero, J. S. and Warren, J. (1998). Understanding conceptual electronic design using protocol analysis, Research in Engineering Design, 10: 129-140.

Myers, Michael (1999). “Investigating Information Systems with Ethnographic Research.” Communication of the AIS, Vol. 2, Article 23, pp. 1-20.

Miller, George (1956). “The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information.” Psychological Review 63. 81-97.

Noy, Natalya and McGuinness, Deborah (2001). “Ontology Development 101: A Guide to Creating Your First Ontology.” Technical Report SMI-2001-0880, Stanford Medical Informatics, Stanford University, CA.

O’Brien, William; Issa, Raja; Castro-Raventos, Rodrigo; Choi, Jaehyun; and Hammer, Joachim (2003). “Inducting Subcontractor Process Ontologies: Challenges, Methods, and Illustrative Results.” Proceedings of ASCE Construction Congress 7, Honolulu, Hawaii, March 19-21, 2003, 8 pages.

Paulson, Boyd (1976). “Designing to Reduce Construction Costs.” Journal of the Construction Division. ASCE, Volume 102, No. C04, 587-592.

Popper, Steven; Lempert, Robert; and Bankes, Steven (2005). "Shaping the Future: Scientific uncertainty often becomes an excuse to ignore long-term problems, such as climate change. It doesn't have to be so." *Scientific American*, March 28, 2005, pp. 48-53.

Reda, Rehab and Carr, Robert (1989). "Time-Cost Trade-off Among Related Activities." *Journal of Construction Engineering and Management*, Volume 115, Number 3, pp. 475-486.

Rosenau, Milton (1992). "The Triple Constraint." *Successful Project Management*, Second Edition. Van Nostrand Reinhold, NY, 15-22.

Saaty, Thomas (1990). "Multicriteria Decision Making: The Analytic Hierarchy Process." Volume 1, AHP Series, RWS Publications, Pittsburgh, PA., 502 pages.

Schreyer, Marcus; Hartmann, Timo; and Fischer, Martin (2002). "CIFE iRoom XT Design and Use." Center for Integrated Facility Engineering, Technical Report, Number 144. Stanford University, CA.

Spetzler, Carl and Stael von Holstein, Carl-Axel (1972). "Probability Encoding in Decision Analysis." ORSA-TIMS-AIEE Joint National Meeting. USA, 603-625.

Staub-French, Sheryl (2002). "Feature-Driven Activity-Based Cost Estimating." Ph.D. Dissertation, Department of Civil and Environmental Engineering, Stanford University, CA.

Tsao, Cynthia; Tommelein, Iris; Swanlund, Eric; and Howell, Gregory (2004). "Work Structuring to Achieve Integrated Product-Process Design." *Journal of Construction Engineering and Management*, Volume 130, Number 6, pp. 780-789.

Tversky, Amos and Kahneman, Daniel (1974). "Judgment Under Uncertainty: Heuristics and Biases." *Science*, Volume 185. American Association for the Advancement of Science, USA, 1124-1131.