TOWARDS A MASTER BUILDER INFORMATION FRAMEWORK FOR PROJECT DEVELOPERS

by

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ABSTRACT

This investigation focuses on organizing information in a framework to allow a project developer to act as a "Master Builder." This master builder framework will facilitate coordination, explanation, storage, retrieval and modification of information elements by the project developer and the project team.

This study reviews the development process focussing on the nineteenth century master builder as a goal state. It seeks to provide the electronic framework to support the developer in becoming the modern day master builder. A comprehensive review of building process and product models precedes a review of standard classification schema currently used in practice.

This thesis develops a conceptual Product Model Architecture (PMA) for structuring/ integrating building information; proposes a coding and classification scheme for storing and retrieving this information; and illustrates how it supports the Master Builder concept through a test case. The PMA is developed in detail. Criteria for the architecture are specified before its key elements are defined. These include discipline views, method of representation of intent and hierarchical levels linking components to systems. The use of the PMA is discussed before a classification and coding structure to enable information (stored on frames) to be accessed, and retrieval is also presented. A case study of the use of these frames is presented and the frames are illustrated.
A case study of the use of these frames is presented and the frames are illustrated.

The key to the PMA breakdown lies in the spatial breakdown of building systems. By relating building system disciplines into agreement and conformance with the spatial aspect of the architectural system, a logical and simplified organization is achieved for all information generated in construction. Some of the salient features of the master builder information framework include: a historical database, support of the design process, connectivity of disciplines through a spatial breakdown of the product, provision of levels of abstraction, and user views.

Finally, the thesis evaluates the framework for the PMA and outlines areas for future work.
TABLE OF CONTENTS

LIST OF FIGURES .................................................................................................................. xi
LIST OF TABLES ................................................................................................................... xiv
ACKNOWLEDGEMENTS ....................................................................................................... xv

Chapter 1 INTRODUCTION TO THE STUDY ..................................................................... 1
  1.1 Background ................................................................................................................... 1
    1.1.1 The Property Development Process .................................................................... 2
    1.1.2 Who Develops Projects? .................................................................................... 4
    1.1.3 Current Problems - Information Coordination .................................................. 8
  1.2 Problem Statement ...................................................................................................... 9
  1.3 Research Significance ................................................................................................. 10
  1.4 Research Objectives .................................................................................................. 11
  1.5 Methodology .............................................................................................................. 12
  1.6 Scope of Work ............................................................................................................ 16
  1.7 Thesis Outline ............................................................................................................ 17

Chapter 2 BUILDING INFORMATION REQUIREMENTS AND
    CLASSIFICATION TECHNIQUES ................................................................................... 19
  2.1 Overview .................................................................................................................... 19
  2.2 Introduction to the IBPM ......................................................................................... 19
2.3 Analysis of Process Models to Define Information

Architecture Requirements ............................................. 23

2.4 Product Modeling Introduction ................................... 30

2.4.1 Gielingh's GARM Model ...................................... 30

2.4.1.1 Characteristic and Aspect Data-Modeling Views ........ 31

2.4.1.2 Life Cycle Stage Data-Modeling View .................... 34

2.4.1.3 Decomposition Data-Modeling View ..................... 35

2.4.1.4 Level Discriminator Data-Modeling View ................. 36

2.4.1.5 Extensions to GARM ........................................ 36

2.4.1.6 Advantages and Problems with GARM ................... 36

2.4.2 The Finnish RATAS Model .................................... 38

2.4.3 Turner's Building Systems Model ............................. 40

2.4.4 Martin's Distribution Systems Model ........................ 42

2.4.5 NIDDESC'S Reference Model for Ship Structural Systems ......................................................... 43

2.5 Previous Data Description Techniques ......................... 44

2.5.1 Classification Techniques Used for Organization of Project Information ............................................. 47

2.5.2 The SfB System and its Successors ........................... 49

2.5.2.1 The UDC Classification System ............................. 51

2.5.2.2 The CBC System ............................................. 52

2.5.2.3 The BDC System ............................................. 54

2.5.2.4 The CI/ SfB System ......................................... 55

2.5.2.5 Other International Classification Systems ............ 55
2.5.3 U. S. Developments ........................................ 57
  2.5.3.1 Uniform Construction Index Approach ........ 57
  2.5.3.2 Other Approaches ............................... 58
2.6 Summary .................................................. 59

Chapter 3 THE PRODUCT MODEL ARCHITECTURE .............. 61
  3.1 Overview ............................................... 61
  3.2 Why Use Product Models? ............................ 61
  3.3 Relationship Between Information Architecture and Product
      Model Architecture .................................... 62
  3.4 Criteria for Product Model Architecture ............. 66
  3.5 Developing the Product Model ....................... 68
    3.5.1 Top-down Versus Bottom-up Creation of the Product
          Model Architecture ............................... 68
    3.5.2 Methods of Product Representation ............. 71
    3.5.3 Development Strategy ........................... 72
  3.6 Elements of the Product Model Architecture .......... 73
    3.6.1 The Building Levels ............................. 76
    3.6.2 Discipline Breakdowns .......................... 78
    3.6.3 The Linking of Views ............................ 88
    3.6.4 Connectors in Building Levels .................. 89
  3.7 Rules for Using the Product Model Architecture .... 91
  3.8 Using the Product Model Architecture ................ 93
    3.8.1 The Product Model Architecture's Use in the Design
          Process .......................................... 93
3.8.2 The Product Model Architecture's Use in the Construction Process ........................................ 97
3.8.3 The Product Model Architecture's Use in the Operation Process .......................................... 98
3.9 Application of PMA on a Case Study to Show the Structure for Capturing the Intent of Data .................................................. 99
  3.9.1 Description of the Case Study Application ................................................... 100
  3.9.2 Illustrative Examples for the Product Model Using the Case Study Application .................... 101
3.10 Summary .................................................................................................................. 105

Chapter 4 CLASSIFICATION AND CODING STRUCTURE .................................................. 106
  4.1 Overview ................................................................................................................ 106
  4.2 Selection of a Classification and Coding System ......................................................... 106
  4.3 Design of Code Structure ....................................................................................... 108
  4.4 Proposed Code Format Structure ........................................................................... 108
  4.4.1 Generic Code Format .......................................................................................... 110
  4.4.2 Specific Code Format ......................................................................................... 119
  4.4.3 Frame Structure ................................................................................................ 123
  4.5 Rules for Coding ..................................................................................................... 125
  4.6 Summary ................................................................................................................ 125

Chapter 5 CASE STUDY ................................................................................................... 127
  5.1 Overview ................................................................................................................ 127
  5.2 Linking of Frames .................................................................................................... 127
5.3 The Case Study .......................................................... 128
5.4 Use of the PMA .......................................................... 137
5.5 Meeting the Criteria for an Effective Information Framework . 137
5.6 Benefits of the PMA Based Classification and Coding
   Scheme ........................................................................... 139
   5.6.1 Historical Database .................................................. 139
   5.6.2 Common Search and Retrieval Language for the
       Building Team .................................................................. 140
   5.6.3 Design Support ......................................................... 141
   5.6.4 Multimedia Storage Support ....................................... 141
5.7 Additional Benefits ......................................................... 142
5.8 Summary ......................................................................... 142

Chapter 6 SUMMARY AND CONCLUSIONS .................................. 144
   6.1 General Statement of the Problem ............................... 144
   6.2 Summary ....................................................................... 144
   6.3 The PMA's Comparison to Relevant Product Models ........ 146
       6.3.1 Gielingh’s GARM Model ........................................ 146
       6.3.2 Turner's Building Systems Model .......................... 148
   6.4 Areas Required for Extending the PMA ......................... 149
   6.5 Recommendations for Further Research ....................... 150
   6.6 Conclusion .................................................................... 153
   6.7 Closure ......................................................................... 153
LIST OF FIGURES

Figure 1.1: Evolution of the Standard Building Team .......................... 6

Figure 2.1: Functional Tree of the Integrated Building Process
Model .................................................................................. 21

Figure 2.2: Level F - Provide Facility ............................................. 22

Figure 2.3: Analysis of Generic Similarities in Subfunctions
Required to Provide a Facility .................................................. 24

Figure 2.4: Unique Elements Used to Control the Product ............... 27

Figure 2.5: Layers of STEP ....................................................... 32

Figure 2.6: Product Definition Unit (PDU) Data Modeling Views of
GARM .................................................................................. 33

Figure 2.7: Classification/ Level Discriminators ............................... 37

Figure 2.8: Functional Unit Hierarchy and Connectivity .................. 39

Figure 2.9: Turner's Building Systems Classification ....................... 41

Figure 2.10: NIAM Diagram Showing Hull/ Assembly/ Part
Relationships ........................................................................ 45

Figure 2.11: Three-Faceted Classification and Coding Scheme for
Structural Members ................................................................ 48

Figure 2.12: Example of Classification by UDC.............................. 52

Figure 2.13: CI/ SfB, ISO Standard 6241, and BIC Building
Element Breakdowns ................................................................ 56

Figure 3.1: Relationship of Product Information to the Information
Architecture ............................................................................. 64
Figure 3.2: The Building Information Process as it Relates to the Top-Down and Bottom-Up Approaches ............................................. 70
Figure 3.3: Elements of the Product Model Architecture in Relation to Product Information ................................................................. 74
Figure 3.4: The Building Levels of the PMA .................................................. 77
Figure 3.5: The Product Model Architecture - Relationship Between Discipline Breakdowns Versus the Building Levels ............. 79
Figure 3.6: Architectural System Breakdown ............................................... 81
Figure 3.7: HVAC System Breakdown ......................................................... 82
Figure 3.8: Electrical System Breakdown .................................................... 83
Figure 3.9: Plumbing System Breakdown .................................................... 84
Figure 3.10: Structural System Breakdown .................................................. 85
Figure 3.11: Civil System Breakdown .......................................................... 86
Figure 3.12: Role of Connectors in Building Levels ...................................... 90
Figure 3.13: Use of Attributes in the Iterative/ Cyclical Three Step Systematic Design Process ............................................................ 95
Figure 4.1: Basic Code Structure for the Proposed PMA Scheme .......... 109
Figure 4.2: User Access and Information Type Codes ............................. 112
Figure 4.3: Analysis of Generic Similarities in Subfunctions Required to Provide a Facility ................................................................. 114
Figure 4.4: Code Structure for Discipline Breakdowns .............................. 116
Figure 4.5: Field 12 - Generic Alphanumeric Code Stems ...................... 118
Figure 4.6: Material Codes e - n ................................................................. 121
Figure 4.7: Material Codes for o - y ............................................................. 122
Figure 5.1 Building Level Information for the Hallowell Project .......... 129
| Figure 5.2 | Second Floor Information for the Hallowell Project | 130 |
| Figure 5.3 | Room 228 Information During Design for the Hallowell Project | 131 |
| Figure 5.4 | Room 228 Electrical Layout Information for the Hallowell Project | 132 |
| Figure 5.5 | Electrical Component Information for Room 228 - During Design | 133 |
| Figure 5.6 | Electrical Component Information for Room 228 - During Construction | 134 |
| Figure 5.7 | Material Information for Room 228 - Hallowell Project | 135 |
LIST OF TABLES

Table 2.1: SfB Facet Table Categories .................................................. 50
Table 2.2: SfB Elements, CBC, BDC, and CI/ SfB Code Structures .. 53
Table 3.1: Example of Function, Form, and Factors for HVAC
   Systems at Room Level ................................................................. 102
Table 3.2: Typical Form Attributes for Different Disciplines at
   Level 1 ......................................................................................... 104
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Chapter 1

INTRODUCTION TO THE STUDY

1.1 Background

Management of construction projects today is an attempt to unite the participation of many players involved in delivering a construction project. The lack of centralized information and its control has inhibited planning and execution on the part of facility participants. Information management by a single individual is no longer the standard approach as in the days of the Master Builder. This has resulted in a lack of integration and coordination among facility participants, and is forcing a reevaluation of the standard approach for delivering projects.

Structuring and standardizing models (e.g., contracts, budgets, schedules, etc.) to suit an integrated framework has been cited by Sanvido et al. [1989b] as a means to improving project delivery. Standardized models typically lead to standardized classification and coding schemes. A recent study of a previous metal building supplier has shown that the standardized coding systems for building parts is effective; from both manufacturing and construction viewpoints [Norton et al. 1989]. The primary advantage this technique provides is better integration between the two industries and also faster times of construction.
This investigation focuses on organization of information in a framework such that coordination, explanation, storage, retrieval and modification of information elements can be achieved. Several attempts have been made at logically organizing building construction information [B. Bindslev & K. Bindslev, 1964; Green, 1966; Birgerson, 1967; Ray-Jones and McCann, 1971; Gielingh, 1988; Björk and Pentillä, 1989; Martin, 1989; and Turner, 1989]. Most approaches have tried to categorize information models in mutually exclusive ways. This investigation looks at integration from the viewpoint of product models, group technology coding schemes, and the Integrated Building Process Model (IBPM) [Sanvido, 1990].

The following sections outline the property development process, describe the people who develop projects, define current information coordination problems; and justify the focus on the master builder concept.

1.1.1 The Property Development Process

The property developer is responsible for combining and coordinating all the resources and services that are required to get a facility built. Mr. J. T. Thomas, Jr., partner of Turner-Harwood Ventures identified three main phases that a developer would go through and they are described below.

The first phase is the initiation of a development; i.e., developing a scheme for a potential facility. The steps for this phase are

1. Developing an intention for a facility.
2. Undertaking a feasibility study - assessing the market (i.e. demographics).
3. Acquiring a site.
4. Conducting site exploration (i.e., soil borings).
5. Hiring an architect.
6. Developing sketches and schemes/alternatives for a facility layout.
7. Developing tactics and a plan for execution.

The second phase involves the application for planning permission and the development of a detailed design. The steps for this phase are

1. Refining the scheme.
2. Finalizing design.
3. Obtaining regulatory approval of the building.

The third phase involves the financing, construction, marketing, and disposal of a facility. The steps for this phase are

1. Finalizing arrangements.
2. Tendering and selecting a construction team.
3. Performing construction and marketing the facility (if tenants are not in place).
4. Completing the facility.
5. Letting and occupying the facility.
6. Disposing of the facility:
a) Selling to an institution or property company.
b) Selling to a tenant(s).
c) Retaining in the company portfolio and managing the facility.

These three phases are not meant to be absolute breakdowns of the functions that a developer performs. Rather they provide a picture for understanding the processes and the decisions in which a developer would be involved. This is supported by an earlier study by the author [Khayyal, 1989]. It provides a process model of the development process. Developers using this model would have to customize it to represent the required management activities necessary for controlling their overall development process.

1.1.2 Who Develops Projects?

In the past it was the master builders who developed the practical organization and techniques involved in bringing projects to realization. "The masters responsible had to be able, not merely to plan and design suitable buildings, structurally stable and aesthetically pleasing to their clients, but also to organize the provision of great gangs of men and the acquisition and transport of vast quantities of materials" [Harvey, 1971, p. 20]. It was the master builder who embodied all information generation, integration, decision making, and coordination throughout all phases of a project life cycle. This thesis explains the development process from the master builder perspective. The master builder perspective is obtained by constructing a facility where
everything is concentrated in the mind of one person, who makes all the key
decisions and controls all the information required to provide a facility.

Figure 1.1 presents the evolution of the master builder through three
standard building team organizations. The medieval building team had the
master builder as the driving force for coordinating all activities involved for
provision of a facility. The main players included bricklayers, carpenters,
masons, and plumbers.

The traditional building team used the architect as the master mind for
controlling development. The architect dealt with various design consultants
and a main contractor - who in turn controlled subcontractors. In many places
this building team organization approach is still being practiced.

Presently in the twentieth century, it is the property developer who closely
resembles the master builder of the 1900's. Like master building, property
development encompasses all functions over the entire building life-cycle (i.e.,
marketing, financing, planning and design, construction, merchandising and
property management), and like contractors, developers employ a lot of experts
and consultants. This tends to fragment the development process and makes
each development unique.

Today, corporations interested in building headquarters are abandoning
the traditional method of providing modern office-buildings. The new champion
providing the decision making to oversee large projects is the property
developer. This change has come about due to the experience that developers
have with managing the development process. "Some developers put up four
or five big buildings a year, and have much more experience of the technical
problems likely to beset a complicated construction project" [Corporate,
Figure 1.1: Evolution of the Standard Building Team
1988, p. 22]. The reason for this shift towards the developer has come about due to their strong economic incentives to keep costs down and complete projects on or ahead of schedule. By playing the role of owner and operator, the developer examines a project's economic and financial feasibility, decides on the most efficient design from the list of options and solicits competitive bids for the contracts.

Traditionally, "this master builder encompassed the complete range of knowledge to carry out each stage of a building project from concept to operation" [Sanvido, 1987, p. II-1]. Thus, the reason for focusing on the master builder concept is to provide a key decision maker, namely the master builder, with the tools to better control the project. This yields an integrated approach to controlling the information process required for provision of facilities.

All three types of building delivery systems must perform the processes/functions that are represented by the IBPM. The role of the master, architect, and developer (in Figure 1.1) is shown by the facility champion (described in Chapter 2) in the IBPM. A facility champion is defined as "the individual who initiates the idea, commits and mobilizes the funds and resources required to get the facility developed, and leads in establishing a project team" [Khayyal, 1989, p. B-4]. The property developer (or the facility champion) is the broker, conflict negotiator, and facilitator on the project. His/her major role will be to provide the information, resources and guidance to keep the IBPM network functioning. Thus in the complex twentieth century building team; an information framework is essential. Information problems are now defined.
1.1.3 Current Problems - Information Coordination

A recent case study conducted on two established developers in the Washington, D. C., area (a private and a corporate development firm) showed that developers still build through the trial and error approach - based on their successful experiences. Another finding of the study pointed out that despite the thousands of buildings which have been built, there is still no set procedure that has been devised to show the overall information management process/structure involved.

Building systems are becoming more and more complex resulting in the emergence of many specialists involved in providing facilities. These specialists all generate their own data in many forms. Some of the information elements generated include: meeting notes, change orders, verbal agreements, operating manuals, catalog cuts, inspection/testing reports, codes and regulations, design documents (drawings, specifications, and calculations), municipal authority documents (fire plans, utility connections, operating permits/licenses), insurance documents (bonds, fire, theft, safety), and construction documents (shop, fabrication, erection, and as-built drawings). Management of these different types of data is required in order to achieve effective coordination among the facility players or specialists.

More companies today are using computers to process their information requirements and to increase their productivity rates. The advent of local area networks, facsimile machines, and electronic mail, allows large volumes of information to be generated and transmitted. With this increased volume of technological product data, facility champions/managers will continually be
swamped by data overload if there is no logical way for the organization of information. What is needed to solve this dilemma is a system that will sift through all the information to give a user what he/she really wants to know. This code for building information should be able to take a broad stream of raw data and turn it into actionable knowledge on the part of facility participants; based on topic queries.

1.2 Problem Statement

**Problem Statement:** Developers require vast quantities of information to maintain a single perspective (of the global operations) required to coordinate the managing, planning, design, construction and operations of a building. There is no well documented way for logically organizing the vast quantities of information required to coordinate the parties involved in providing a building. This thesis develops a framework to organize building information. It specifically addresses these questions:

1. What information does a facility champion need to coordinate to get a facility built?
2. What framework is needed to coordinate building information among facility team members?
3. How do facility team members find the required information that describes a building?
1.3 Research Significance

This investigation has the potential to improve productivity as well as change the process by which facilities are currently provided. As stated earlier, there is a trend towards design-build or turnkey projects, and corporations are turning to developers to ensure quality facilities. Yet, nowhere do the words "information gap" resonate so clearly as in property development. As an indicator for gauging this information gap, one can look at project budget overruns. There have been many documented instances where building project budgets have gone out of control. A case in point is the recently completed Morton H. Meyerson Symphony Center in Dallas, Texas. The initial estimate for the building was $49.5 million and the final cost ended up being $81.5 million [McGuigan, 1989, p. 61].

From the standpoint of the owner/developer/master builder, it is convenient and advantageous to settle questions arising from various stages of a project by communicating with a single responsible person. Too often there is a complete difference in how two companies deliver/develop projects, with varying results on quality and cost of construction. In most cases different managers have usually been employed to oversee the different construction subprocesses. But in the case of turnkey projects, a single manager must control the project costs, time schedules, work quality, and so on throughout all stages of the project. By developing a tool for gaining a single perspective on a job, the master builder will be able to play the role of a system organizer.

The PMA and the coding scheme can be used to identify missing information. Given the necessary information elements required for successful
completion of IBPM functions, a status check can be performed to see when information is missing and when it is complete for each function.

Better coordination of the development process can be achieved through use of this information management tool by novice managers as well as facility participants. This tool would also serve as an information system that will contain a historical database for a given building as well as a global window for all information elements.

1.4 Research Objectives

The objective of this research is to define an information framework to assist the project developer in gaining a "Master Builder" perspective of their project.

This will be accomplished by completing the following specific objectives:

1.4.1 Define the information required to control the product (building).
1.4.2 Develop a conceptual product model architecture for structuring/integrating building information.
1.4.3 Refine the conceptual product model architecture using a test case building. This product model architecture is only a concept and will not be implemented.
1.4.4 Develop a coding and classification scheme for storing and retrieving information in the product model architecture using the test case building.
1.4.5 Demonstrate the benefits of this system to the master builder.
1.5 Methodology

The methodology consists of conceptual model building and testing on a case study. Each phase described below corresponds to a specific objective. Details follow.

**Phase one** defined the information necessary for building the master builder information framework as:

a) Simplifying the Integrated Building Process Model to identify generic and unique information elements.

b) Separating the categories of information required to control the product from that required to control the process (for the top level F.0 Diagram, see Figure 2.2 of the IBPM). This allows a focus on product-related information.

c) Identifying the literature relating to work performed on product modeling. A brief description of these works is given in chapter 2.

**Phase two** defined the information framework by defining the product information architecture as follows:

a) Defining a research data collection scheme for supporting the product model architecture.

b) Identifying a representative case study and collecting all available data generated for the project.
c) Analyzing and synthesizing all literature and information collected to categorize the information types for the case study.

d) Developing building system breakdowns using previous works and research team experiences. Validating the building system breakdowns using the case study. Developing a hierarchical classification of building systems.

e) Experimenting with attributes to capture the evolution of information over stages of a project life cycle.

f) Testing the attributes using the case study; applying both process and product information.

g) Proposing a product model architecture for building construction.

Each of these seven tasks is discussed in the manner they were performed.

a) A product model data collection chart was created to aid in capturing the intent of information flows that exist in a project. In addition to this, the IBPM was used to understand information elements produced and utilized by each function required to provide a facility.

b) A case study was selected, and the information elements gathered were mapped onto the product model scheme. Incomplete documentation of the planning and initial design phases made the task of collecting all the information difficult.
c) The information collected was analyzed and categorized based on its type. A dateline was constructed for all memos and documents held by the owner. The time period for this dateline started from the inception of the facility idea to its current point in time—the construction phase (April 1986 - August 1989).

d) Building system breakdowns were developed to understand and single out discipline views in providing facilities. Using this, a building level breakdown was developed to serve as the logical framework for unifying the different information types. The technical discipline breakdowns used to makeup the building systems consisted of: architectural, civil, HVAC, plumbing, electrical, and structural.

e) Information attributes were tested to see how effective various information elements would be in capturing life-cycle data. After several attempts, the Function, Form, Economy, and Time attributes were selected. These attributes are discussed in further detail in the Product Model Architecture section of chapter 3.

f) With the Function, Form, Economy, and Time attributes, several tests were performed on the case study to see how it would support the PMA schema. The tests involved matching
attributes to case study product decisions and they proved to be successful in capturing information elements at various levels of the Building Level breakdown for all disciplines.

g) A product model architecture for building construction was developed.

**Phase three** involved refining the conceptual product model using a test case. This will be accomplished by performing the following activities:

a) Developing criteria for managing construction life-cycle information within a product model architecture.

b) Categorizing information types according to the product model architecture (i.e., building systems).

c) Testing the structure of the PMA using the case study information. Apply process/ product information of the representative case study to the PMA.

**Phase four** developed the coding and classification schemes for storing and retrieving product and process information elements. This phase included completing the following steps:

a) Reviewing literature of various group technology coding schemes.

b) Selecting a code structure that allows for multiple descriptions per digit.
c) Designing the code structure for process and product information utilization.

d) Applying the code structure manually to a representative portion of a case study.

Phase five will concern demonstrating the coding scheme and the product model architecture. This will be illustrated through use of abstraction of information examples for a case study. This phase will include completing the following steps:

a) Showing how abstraction of frames takes place.
b) Explaining the benefits of the PMA data structure.
c) Validating the criteria required for an effective information framework.

1.6 Scope of Work

The scope of this research will be limited to the following elements:

1. Project type - commercial office buildings.
2. Project Size - 100,000 square feet.
5. Project Team Members - Owner, Architect, Engineer, Constructor, Operator. The primary purpose of the team members will be to address the information needs of the Developer.


7. Focus of the conceptual product model architecture - vertical construction only.

1.7 Thesis Outline

This chapter has covered an introduction to the study. It provided background on the need for information organization and it led into the problem definition.

Chapter 2 presents an overview of literature relating to the study (process and product modeling, and product data classification techniques). It examines the IBPM process models and their analysis. Product modeling literature is explained to show current research efforts as well as to show why product models are used. Product data classification techniques are presented to show the advancements made in this field.

Chapter 3 discusses development of the product model architecture for building construction. It presents the generic framework for representing building product information. Chapter 4 defines the development of the code structure. It introduces group technology coding schemes and presents the generic code structure with examples of its use. Chapter 5 provides a case
study application; it presents the data structure abstraction levels using a building case study.

Chapter 6 presents a summary of the study; it provides the conclusion concerning what impact the master builder information system provides. The chapter also addresses requirements needed for implementation, as well as suggestions for further research.
Chapter 2

BUILDING INFORMATION REQUIREMENTS AND CLASSIFICATION TECHNIQUES

2.1 Overview

This chapter describes fundamental concepts of building information requirements and product data classification techniques necessary for building a product model architecture, in three sections. The first section examines the IBPM to determine product modeling aspects of the information elements. The second section is a survey of existing product models which have been developed for the AEC industry. The last section describes coding and classification systems/techniques used for representing construction information.

2.2 Introduction to the IBPM

In order to define the information required to produce a building, one needs to understand the processes required for facility development by the "Master Builder." The IBPM defines the essential functions, inputs, outputs, constraints, and mechanisms required to provide a facility [Sanvido, 1990]. The IBPM is a series of hierarchically decomposing process models developed using the IDEF0 [ICAM, 1981] modeling methodology. The first level

In order to comprehend the magnitude of activities required for coordinating the provision of a facility, the functional tree diagram (see Figure 2.1) of the IBPM defines the broad function areas. Figure 2.2 on the other hand, shows the interrelationships of activities in the first level of abstraction, viz., Manage Facility, Plan Facility, Design Facility, Construct Facility, and Operate Facility. These correspond roughly to the role of the Owner, the Architect, the Designer, the Construction Contractor, and the Property Manager play during the life of a building. The lines and arrows on this figure represent the inputs, outputs, controls, and mechanisms which dictate the information elements/flows, resources, feedbacks, mechanisms, and final products which take place through the various functions.

Drawings, specifications, and schedules are but a few of the information elements or pathways of communication. One of the key information paths is the feedback loops which resemble communication during the thinking process. They also serve as the checks and balances for good quality, cost, time, and safety. The dynamic aspect of the IBPM is its ability to show the passage of changes throughout the course of provision of a facility.

The Master Builder/facility champion/developer needs high quality feedback on the processes in order to control the project successfully. Through use of the IBPM, the master builder can play the role of controller of information
Figure 2.1: Functional Tree of the Integrated Building Process Model
by deciding the content and method of information dissemination. This is a key
function in integrating and controlling the project participants. Thus, the IBPM
serves as the navigating instrument that guides one through the construction
process and the essential feedback circuits.

2.3 Analysis of Process Models to Define Information Architecture
Requirements

Sanvido et al. [1989b] analyzed the upper level of the IBPM models (see
Figure 2.2) to differentiate between the various categories of information in the
construction life cycle. Figure 2.3 is the result of simplification of the elements in
the IBPM. Two types of information are defined. They are process control
information and product description information. Process control information
consists of elements that are generic to all subprocesses of Provide Facility
(Figure 2.2). Product description information is information elements that are
specific/unique to any one subactivity.

There are six generic information elements/arrows that were identified
as controlling the overall facility development process. Sanvido et al. [1989b,
pp. 12-13] describe the process control information elements as follows:

The first two, viz., performance information (P), and optimization
information (O), exist as constraints on the manage function. The
existence of this information and its quality, directly influences
management decisions that control the process. The key element used
to keep the whole process moving is the resources (R), an input of the
manage function. This whole activity is driven by people, the facility team
(F) which starts with the Facility Champion and increases to the complete project organization.

Outputs of the manage function that control subsequent processes are: contracts, obligations and changes (C); resources (R); and a facility team (F). The flow of the C, R, and F elements to the subsequent subprocesses are influenced by decisions made using elements R (as the input), O, and P. The facility experience (E), another output, influences the following projects performed by each team member. The facility team then, for each subfunction, uses resources within the constraints of the contract and optimization information to produce their specific end-products. Three other resultant outputs of subprocesses are facility experience, optimization information and performance information. Definitions of these terms follows:

**Contract:** Legal document between two parties used to arrange for services to be performed and to establish the business relationship.

**Facility Team:** Facility team assembled by the owner to provide the facility. This team starts with the facility champion and expands to include representatives of the planner, designer, constructor, owner, operator, consultants and facilities managers.

**Facility Experience:** The information and knowledge that results from providing the facility that is not included as formally communicated documents, but is resident in other media, e.g., company history and project participants' memories. This improves the abilities of the members of the facility team to provide similar or related facilities in the future.

**Optimization Information:** The information used to integrate expertise of participants in providing the facility. This includes designability, constructibility, operability, and maintainability information.
Performance Information: Information about the progress of activities which, when compared to the plan, is interpreted to assess the status of the project and the appropriateness of the plan.

Resources: Includes all resources provided for the facility by all participants (money, time and man-hours, permanent materials and equipment, energy, information, equipment, temporary materials, tools, and workplace or site).

The product description information, or unique elements, are presented in Figure 2.4, and they show the transformation of facility information from inception to completion of a project. By showing the transfer process of the information elements, one gains an understanding of the functions required to transform an idea for a facility into that of a finished product. Sanvido et al. [1989b, pp. 14-15] define the unique information elements as follows:

Facility Idea: The initial thought or instance that recognizes the need for a facility and its description.

Planning Information: The functional requirements of the facility. These are typically represented by four sets of data:

1. **Program:** A detailed description of the owner's/user's requirements comprising spatial, operational and functional aspects. The program is used to define the proposed facility to the design team in terms of function, form, economy, and time attributes.

2. **Site Information:** A description of the site's attributes such as topography, size, location, and soil characteristics.

3. **Project Execution Plan:** The plan for procuring all resources and services that are required to provide
Figure 24: Unique Elements Used to Control the Product
[Source: Sanvido et al., 1989b, p. 25]
the facility. This includes schedules, contract strategy, milestones, and budgets.

4 **Facility Planning Knowledge:** The information or knowledge that results from planning the facility and the related experience that can be used to support design, construction and operations, of the subject facility, or the planning of other facilities in the future.

**Design Information:** The product of the design function that defines the facility that can be constructed to meet the owner's needs as represented by the facility idea and the planning information. Categories of information include:

1 **Bid and Construction Documents and Criteria:** The formal documents, drawings, specifications, instructions, limitations, procedures, and criteria for constructing the facility. These include bid documents, scope of work, working drawings, limitations of cost and schedule, quality criteria, etc.

2 **Operations and Maintenance Documents:** The formal documents, drawings, specifications, instructions, limitations, procedures and criteria for managing, operating, and maintaining the facility. These include as-built drawings, final test reports, system operating guides, equipment operating and maintenance guides, etc.

3 **Facility Design Knowledge:** The information or knowledge that results from designing the facility and the related experience that can be used to support construction and operations of the subject facility, and the design of other facilities in the future.

**Site:** The physical location of the facility, usually a plot of land.

**Constructed Facility:** The desired building built on the selected site in strict compliance with the design intent, including all installed equipment.
**Construction Information:** The product of the construction function that defines the facility that has been constructed to meet the owner's needs as represented by the facility idea, the planning information, and the design information. Categories of information include:

1. **Post Construction Documents:** These include the vendor suggested maintenance procedures; documents prepared by the constructor which explain operations and maintenance procedures; and edited construction drawings which represent the "as-built" facility.

2. **Facility Construction Knowledge:** The information or knowledge that results from constructing the facility and the related experience that can be used to support operations of the subject facility or the construction of other facilities in the future.

**Operational Facility:** A facility that satisfies the needs of the user, i.e., meets its intended purpose as specified by the facility idea, and enhanced by the planning information, design information, and constructed facility.

**Project Participant's Constraints:** The parameters/limitations imposed by the companies and the project participants on the project, e.g., schedule, manpower loading, support, budget, risk level.

This thesis will focus on both process and product control information, however, the main emphasis will be on the latter. The reason for focusing on both information categories is due to the fact that the coding scheme, for the PMA, must include both information element types, in order for the information framework to be dynamic and complete.
2.4 Product Modeling Introduction

Product models for the AEC industry are defined as data structures which show how components relate to building systems. Successful product models are formed when individual and group needs are met in relation to user viewpoints of products. Product models have been used by manufacturing and other industries for product representations and the integration of information for various applications. They provide a structure for capturing information about products that is meant to support the design, planning, manufacturing/constructing, and operation processes. The information structure is important in product modeling, because "a product is not just a collection of components: the way these components are combined and connected determines how the whole product behaves" [Gielingh, 1988, p. 20]. By structuring information it becomes possible to link and group elements; identify missing information and effectively retrieve it for possible re-use.

Several researchers have presented specific product models. The most relevant were selected for discussion. Descriptions of these models follow.

2.4.1 Gielingh's GARM Model

Gielingh's General AEC Reference Model (GARM) provides a general framework for the organization of product-data which are exchanged by various AEC disciplines. It was originally developed in 1982 as part of the International Standards Organization/ Standard for the Exchange of Product-model data (ISO/STEP) standardization effort. "The goal of this standard is to facilitate
data-exchange between computer-applications for design, production and maintenance of discrete products, including products in the AEC industry" [Gielingh, 1988, p.1]. Figure 2.5 shows the hierarchy and context for which Gielingh's GARM model is used. The specialty area that relates to buildings is covered under the Architecture sub-type of the AEC industry-type layer (shaded areas in Figure 2.5).

In order to explain Gielingh's GARM model a three dimensional representation was made to facilitate in the understanding of the many entities that make up the product model (see Figure 2.6). The Model is based on a generic entity called the Product Definition Unit (PDU); which plays the role of a building block/ cell for production of information elements. Product definition aspects for the classification scheme of GARM include five orthogonal aspects that are each used for representing a data-modeling view. These orthogonal aspects are: Characteristic, Aspect, Decomposition, Life Cycle Stage, and Level Discriminator. The word "orthogonal" is used in the sense that each subdivision, of the five product definition aspects, can be applied to any other subdivision. This provides a network approach for describing entities and information elements.

2.4.1.1 Characteristic and Aspect Data-Modeling Views

This data-modeling entity description is specified in terms of "characteristics" and certain "aspects" of a particular product (see vertical axis). Typically, characteristics apply to any aspect of a product and can be either required, expected or measured depending on the life-cycle stage of the
The GARM Model covers AEC specializations.

Each classification defines broad classes of products, and specializes them to a certain level of detail.

GARM handles each information category as a Functional Unit (PDU type). The categories help to define Functional Units not PDU's. A Functional Unit is the "collector" of all the requirements for the PDU. It can be a design problem or a product to be obtained.

Figure 2.5: Layers of STEP [Source: Gielingh 1988, p. 12]
Figure 2.6: Product Definition Unit (PDU) Data Modeling Views of GARM
product being defined. Aspects on the other hand, are defined by Gielingh, as views of a product definition unit, that are used to define its characteristics. Typical aspects which can relate to each of the characteristics include suitability, durability, strength, etc.

2.4.1.2 Life-Cycle Stage Data-Modeling View

The seven life-cycle stages in Figure 2.6 relate to the seven stages in GARM. Stage discriminators are used to represent product information at discrete points of time in its life cycle. The definitions for these stages are the following [Gielingh, 1988, pp. 68-69]:

**Functional Unit:** Describes function, requirements and constraints of a product, or any physical or non-physical part of a product. Functional Units may be specified by classification codes such as SfB and CSI.

**Technical Solution:** Describes a technical solution for a functional unit [as designed]. A Technical Solution can be an Assembly, a Part, a Feature, a connection, a joint, etc. Generic Technical Solutions can be stored in a library. Each Technical Solution may contain a cluster of Functional Units which specify its components and their functional structure. This decomposition is made explicit on the specific level, and unique on the Occurrence level.

**Planned Unit:** Describes how a technical solution can be realized, using available production techniques. Or, in other words, the Planned Unit describes the Product Definition Unit as it is planned for production.
Physical Unit: Describes the Product Definition Unit as it is realized (manufacturing or built).

Operational Unit: Describes the Product Definition Unit in operation.

Alteration Unit: Describes the Product Definition Unit as it is changed (modified, renovated, maintained, upgraded). A change can be required if:

a. The characteristics of the Operational PDU are changed and do not meet the required characteristics (due to wear, aging, etc.).

b. The required characteristics are changed (new function, new requirements, etc.).

Demolition Unit: Describes the Product Definition Unit as it is demolished.

2.4.1.3 Decomposition Data-Modeling View

"The distinction between the stages is based on clear differences in the type of information about the product, not on the order of processes which produce this information" [Gielingh, 1988, p. 10]. In addition, all seven stages can relate to any decomposition in a building hierarchy (i.e., system, subsystem, part, and detail levels). In turn, each decomposition would have various aspects (i.e., stability, strength) used for defining the product being defined, in one of the life-cycle stages.
2.4.1.4 Level Discriminator Data-Modeling View

For purposes of eliminating redundancy, a level discriminator is introduced (see Figure 2.7 Level Discriminator) to differentiate the levels of detail. At the generic PDU level the product is parametrically defined. The specific PDU level fully defines the product (i.e., has all its parameters defined) and the occurrence PDU describes each instance/occurrence of a PDU (i.e., place and orientation). The data for a PDU is only recorded at this occurrence level, because this abstraction of information reduces duplication of information.

2.4.1.5 Extensions to GARM

GARM is generic but also flexible in that it allows for specific data-structures and defined entities to be added. An example of how an existing product data classification technique can be incorporated is shown in Figure 2.5 with the breakdown of the SfB classification system (this system is covered in section 2.5.2). This system shows three facets which Gielingh's model uses to categorize Functional Units (requirements of a product). Other classification systems incorporated by GARM include: ISO standard 6241, British Building Industry Code (BIC), and the Construction Specifications Institute (CSI).

2.4.1.6 Advantages and Problems with GARM

The principal advantage that GARM has is that it is conducive to the "divide and conquer" strategy. This strategy is used in the design process for
Figure 2.7: Classification/Level Discriminators [Gielingh, 1988, p. 14]
decomposition of systems for defining and selecting the components of a building. PDUs are not predefined which raises this question: How does one unite the different user viewpoints if there is no common denominator for connecting PDUs? Gielingh tries to solve this by stating a rule that the model is only allowed to model relations between Functional Units which belong to the same Technical Solution (see Figure 2.8). However, this does not unite viewpoints across various disciplines involved in the design process (i.e., Technical Solutions [TS] and Functional Units [FU]). Furthermore, the information structure of the final product is made too complex due to the explosive growth of entities. The argument can be made that connectivity of PDU's is dependent on aspect, but even this depends on users' perspectives. There is no rule to control aspect viewpoints by the users and this detracts from having GARM serve as a standard for structuring all significant data exchanges in the AEC industry.

Figure 2.8 attempts to demonstrate the principle of connectivity of Technical Solutions (TS). This example shows the functional network between and within the product; in this case, how a car radio is connected to the components of a car's electrical system. The arrows in the figure show how the ports, and ends (i.e., free and mated) match to interface within the network of one technical solution.

2.4.2 The Finnish RATAS Model

Björk and Pentillä proposed a conceptual structure of a building product model in 1988. The model is referred to as the Finnish RATAS project which
Figure 2.8: Functional Unit Hierarchy and Connectivity [Gielingh 1988, p. 18]

was aimed at data exchange and application of advanced information technology in the Finnish AEC industry. The main concepts used in the model are objects, attributes and relationships between objects. Objects refer to information elements that are described by various classification systems. Attributes associated with all objects include location, orientation, and shape. Relationships between objects are described through two aspects - part of and connected-to. The "part of" aspect connects objects from different abstraction levels. Currently there are five abstraction levels - building, system, subsystem, part, and detail. The "connected-to" aspect links parts and details that occur at the same level.

In summary, the RATAS model defines a building by its objects and the network of relationships between those objects. The shortfall of this model is that it only defines buildings from an "after the fact" standpoint. The model does
not work in conjunction with the design process - there is no time element or rules for connectivity of systems. The advantage the model provides is its entity relationship approach to building a data base of building objects. This makes user queries simple and straightforward.

2.4.3 Turner's Building Systems Model

The objective of Turner's work was to develop a high-level conceptual schema for data modeling of engineered products. One AEC aspect of the PDES effort involved work by Turner in the development of a Building Systems Model. Turner's model shows system breakdowns as they are classified by systems and sub-systems. An AEC product model is considered to be a combination of "AEC project phase" and "AEC project type." The AEC project phases correspond to the life cycle stages in GARM. They model time varying aspects of the product. The characteristics of a building are its properties and one or more systems. Building systems breakdown into active systems and passive systems (see Figure 2.9). Another classification for building systems is based on space, fabric, and service-related systems. Further breakdowns for these systems have also been considered. The AEC project types include buildings, ships, process plants, civil projects, and space habitats. This categorizes areas where the model would be applicable.

The modeling methodology used to represent the building systems is the Nijessen Information Analysis Method (NIAM). This method uses symbols to define relationships. The symbols cover objects, roles between objects, and various object and role constraints. Objects consist of tangible or abstract
entities in an enterprise. Objects are represented by Lexical Objects (LOTs) and Non-Lexical Objects (NOLOTs). A NOLOT represents a set of non-representable entities which have common entities. A LOT represents a set of values of an entity (i.e., names and properties). Roles describe relationships between two objects for various sets and subsets of particular occurrences. Object and role constraints describe characteristics of NOLOTs.

The benefit that Turner's model provides is the comprehensiveness it provides in showing relationships of entities. The modeling methodology can effectively be used to show connectivity of systems and subsystems. The problem with Turner's model is shown by the complexity of the modeling symbols - they may be too complicated for manual use by professionals. However, the significance of his work may be of use in the years to come, because computers are moving away from numeric calculation to that of symbolic reasoning (i.e., object-oriented programming).

2.4.4 Martin's Distribution Systems Model

Martin's Distribution Systems Model provides a framework for organizing product information as it relates to distribution systems which are oriented for shipboard systems. Shipboard distribution systems include Piping, HVAC, Electrical, and Raceway systems. This model has been modified for incorporation with both Gielingh's GARM model and Turner's Building Systems model through its allowance of characterization of shape, topology, and geometry of distribution systems. The main aspect of Martin's model is its characterization of systems by the physical configuration characteristics of the
products making up the systems. These physical configuration characteristics include aspects relating to part connectivity; size and orientation; joint/ connection configuration; route geometry; insulation characteristics and geometry; and part attachment configuration. The modeling methodology used for the Distribution System model is the NIAM method.

The benefit of this model is that it can be readily integrated with the construction industry’s distribution systems. The limitations of the model are (1) the diagrams provide a lot of clutter making them difficult to comprehend - too many attributes exists over too many diagrams; (2) there is overlap in definitions for LOTs and NOLOTs which disconnects the attribute definitions; (3) the model only portrays aspects of systems which have been detail designed; (4) the model does not cover specifications or reasoning which lead to the system configurations; and (5) confusion exists in relation to cross-classification/ inheritance of components by different disciplines (i.e., a penetration part being classified by both structural and plumbing systems).

2.4.5 NIDDESC’S Reference Model for Ship Structural Systems

A structural information model was developed by the national shipbuilding research program in 1988 to provide a framework for representing product models of ship structures. This research was conducted by the Navy/ Industry Digital Data Exchange Standards Committee (NIDDESC). The goal of the reference model was to provide a structural information product model for communication, in a digital format, using PDES, and also between CAD/ CAM modeling systems. This model also uses the NIAM modeling methodology
along with an entity-relationship approach to defining a ship's structure. The main features of the product model are the following: hull, systems, sub-systems, unit assemblies, assembly-ids, sub-assemblies, parts, date/time elements, and materials. Each of these features has an entity-relationship structure comprised of rules and symbols for defining their associations to other entities. These features provide the framework for representing the structural information elements, from which all ships can be defined. Figure 2.10 shows the first level abstraction of the relationships that are used to define ships.

The reason for showing a product model for ships is due to the fact that the shipping industry falls under the AEC industry. In addition, the construction industry has much to learn from the highly defined work that is involved in shipbuilding, there are many similarities (from manufacturing as well as the design approach) between the two industries, and many of the concepts and entities used in shipbuilding can be readily applied to construction.

This concludes the summaries on product modeling efforts. The next section focuses on relevant classification techniques used for controlling and organizing information in the construction industry.

2.5 Previous Data Description Techniques

According to Mitchell [1977], there are two types of building descriptions in an architectural design - these are geometric and non-geometric data. Geometric data has commonly been represented through drawings (i.e., elevations, perspectives, sections, and plans) which provide the key aspects of physical elements. The key aspects convey information relating to form/shape,
Figure 2.10: NIAM Diagram Showing Hull/Assembly/Part Relationships [NIDDESC, 1988, p. 19]
location, and dimensions/tolerances. Non-geometric descriptions entail such things as: bills of quantities, schedules (i.e., door, window, color, accommodation), specifications, permits, etc.

The purpose of conveying information through geometric and non-geometric descriptions relates to the roles that each plays in the design process. Mitchell states that the operations performed on geometric and non-geometric data consist of the following [Mitchell, 1977, pp. 137-138]:

**Geometric data:** Sorting elements into sequences and subsets;

Taking *sub-totals* and *totals*, and performing other simple arithmetic tasks;

*Combining* data from different sources (for example applying unit costs to a bill of quantities);

Producing *reports* in various required formats.

**Non-geometric data:** To describe a building *before* form decisions have been made, and thus before any geometric descriptions exist. The initial schedule of accommodation requirements is an example of a non-geometric description in this role.

To record component *selection* decisions. Door, window, and furniture and fitting schedules are examples of this application.

To facilitate tasks of *tabulating*, *aggregating*, and *checking* quantities, costs, area, etc. Bills of quantities, and to a certain extent accommodation schedules, are used in this way.
The subsequent sections cover classification and coding schemes for non-geometric data.

2.5.1 Classification Techniques Used for Organization of Project Information

Classification techniques have become essential for organization of information in various fields. The reason for classification systems is found in the way they show relationships between items/ concepts. Two approaches which have been used for data classification techniques are hierarchical and faceted.

Hierarchical systems have been used widely in many areas. A prime example is the Dewey decimal system used in libraries. Hierarchical systems describe general categories which are further subdivided into subcategories. These subcategories are given unique numeric and/ or alphanumeric identification codes. Each subcategory in the hierarchy forms a class/ group of the classification. The limitations that the hierarchical systems provide is the mutual exclusiveness of the breakdowns made in a system. In other words, subcategories at each level in a hierarchy must mutually exclude one another. Additionally, subcategories have to be entirely subdivided by characteristics before they can be divided by another. The benefits of using a hierarchical system in the construction industry are the following:

1. Ease of tracing through the hierarchy.
2. Support of the design process (general to specific details).
3. Potential for comprehensive descriptions of an entity.

Faceted systems are classifications which relate to attribute descriptions of an item. These attributes (facets) can be viewed as being Cartesian in nature, with a code/dimension given for each attribute assigned to an item (see Figure 2.11). The shortcomings of using facets stems from a lack of mutual exclusiveness and inadequate descriptions to descisively indicate where an item would be classified.

![Diagram of a cube with facets](image)

<table>
<thead>
<tr>
<th>Code</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rs1</td>
<td>Rectangular steel beam</td>
</tr>
<tr>
<td>Rs2</td>
<td>Rectangular steel column</td>
</tr>
<tr>
<td>Rc1</td>
<td>Rectangular concrete beam</td>
</tr>
<tr>
<td>Rc2</td>
<td>Rectangular concrete column</td>
</tr>
<tr>
<td>Rt1</td>
<td>Rectangular timber column</td>
</tr>
</tbody>
</table>

Figure 2.11: Three-Faceted Classification and Coding Scheme for Structural Members
[Mitchell, 1977, p. 141]
2.5.2 The SfB System and its Successors

The SfB system (the initials SfB derive from the Swedish name for the Institute, *Samarbetskommitten for Byggnadsfrågor*) was invented by the Swedish architect Lars Magnus Giertz. The original intention of this classification system was for it to serve as a standard list of contents for national job specifications, price books and building product catalogues. This is a three-faceted system which was developed between 1946 and 1950 and has since been converted into other systems. The three facets are *Functional element* (i.e., building elements like door, window, etc.); *Form* (i.e., construction forms like bricks, blocks, tiles, fabrics, coatings, etc.); and *Material* (i.e., steel, concrete, wood, etc.). For each product an alphanumeric code is assigned to each facet used to classify it.

"One of the aims of SfB was to produce a system which was simple to use and easy to remember. An alphanumeric system has an advantage over a purely numerical system in that it produces 260 combinations with only two sets of symbols (A0, A1, etc., up to Z9). SfB uses two alphabetical and two numerical sets of symbols" [Green, 1966, p. 208]. The order used for classification of elements is number in bracket (functional element category); capital letter (building product/construction form category); small letter (material resource category); and plain number (this constitutes the numerical breakdown in the material resource category). As an example (see Table 2.1), the symbol (21)Fg2 would refer to WALLS; the classification symbol for external walls is found on reference to the first table category under the main heading Primary Elements (2-). The second table category, construction form, is concerned with
<table>
<thead>
<tr>
<th>FUNCTIONAL ELEMENTS</th>
<th>BUILDING PRODUCT/ CONSTRUCTION FORM</th>
<th>MATERIAL RESOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Substructure</td>
<td>A. Preliminaries</td>
<td>Groups a to d: Administration, plant, labour and operational activities</td>
</tr>
<tr>
<td>(2) Primary Elements</td>
<td>B. Demolitions</td>
<td>a. Administration</td>
</tr>
<tr>
<td>(21) Walls</td>
<td>C. Earthworks</td>
<td>b. Aids, temporary works, plant</td>
</tr>
<tr>
<td>(3) Secondary Elements</td>
<td>D. Formless and basic materials</td>
<td>c. Labour</td>
</tr>
<tr>
<td>(4) Finishes</td>
<td>E. Cast in situ</td>
<td>d. Operations</td>
</tr>
<tr>
<td>(5) Services (piped and ducted)</td>
<td>F. Bricks, blocks</td>
<td>Groups e to o: materials in formed products</td>
</tr>
<tr>
<td>(6) Installations (electrical and mechanical)</td>
<td>G. Large units (structural)</td>
<td>e. Natural stone</td>
</tr>
<tr>
<td>(7) Fixtures</td>
<td>H. Sections/ bars</td>
<td>f. Formed (precast) concrete, etc.</td>
</tr>
<tr>
<td>(8) Loose Equipment</td>
<td>I. Tubes, pipes</td>
<td>g. Clay, in general</td>
</tr>
<tr>
<td></td>
<td>J. Wires, mesh</td>
<td>g2. Heavy burnt clay</td>
</tr>
<tr>
<td></td>
<td>K. Quilts</td>
<td>h. Metal, in general</td>
</tr>
<tr>
<td></td>
<td>L. Foils, papers</td>
<td>i. Wood, in general</td>
</tr>
<tr>
<td></td>
<td>M. Foldable sheets</td>
<td>j. Natural fibres and chips, leather</td>
</tr>
<tr>
<td></td>
<td>N. Overlap tiles, sheets</td>
<td>m. Mineral fibres in general</td>
</tr>
<tr>
<td></td>
<td>P. Thick coatings</td>
<td>n. Plastics etc.</td>
</tr>
<tr>
<td></td>
<td>Q. Acoustical products</td>
<td>o. Glass</td>
</tr>
<tr>
<td></td>
<td>R. Rigid sheets</td>
<td>Groups p to s: Materials in formless products</td>
</tr>
<tr>
<td></td>
<td>S. Rigid tiles</td>
<td>p. Loose fill, aggregates in general</td>
</tr>
<tr>
<td></td>
<td>T. Flexible sheets, tiles</td>
<td>q. Cement, mortars and mass (in situ) concrete</td>
</tr>
<tr>
<td></td>
<td>U. Papers, fabrics</td>
<td>r. Gypsum, special mortars, etc.</td>
</tr>
<tr>
<td></td>
<td>V. Thin coatings</td>
<td>s. Bituminous materials</td>
</tr>
<tr>
<td></td>
<td>X. Components</td>
<td>Groups t and u: fixing and protective materials</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t. Fixing and jointing agents, compounds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>u. Protective materials</td>
</tr>
</tbody>
</table>

Example of classification by SfB: (21)Fg2
BRICKS as products for this example, hence the symbol F. The third table category indicates the material the construction is made of, in this case g for CLAY, and g2 in particular for heavy, burnt clay.

The following sections present other classification system derivates that were based on and/or used with the SfB system.

2.5.2.1 The UDC Classification System

The Universal Decimal Classification (UDC) system [Green, 1966] is an alternative system which has been used to offer further sub-divisions for various sections of the SfB system. The UDC system works in a completely different manner from the SfB system. UDC is based on an artificial subdivision of knowledge into ten classes. The advantage the system provides is its comprehensiveness in covering general background information which may be filed for construction purposes. The drawback in using this system is that its code is much longer, due to the high degree of detail, so its real benefit comes into play for use in large libraries and not by practitioners. Figure 2.12 provides an example of a classification for a technical article dealing with the construction of cavity brick walls using clay bricks (this example is similar to the SfB example presented). The combination of the SfB system and the UDC system has become common in England for cataloguing all building-related information (non-geometric data).
2.5.2.2 The CBC System

The Coordinated Building Communication (CBC) effort, that took place in Denmark in 1963, was an attempt at developing an integrated project management system for all construction participants. The main goal of this effort was to serve as a basis for development of computerized construction information management and document production systems. The system was derived from the SfB system, and it expanded on the SfB applications through an expansion of the code structure (see Table 2.2). The main impact this system provided was its capability to sort information based on facet
<table>
<thead>
<tr>
<th>SfB System - Functional Elements (Breakdown)</th>
<th>CBC Code</th>
<th>BDC Code</th>
<th>CI/ SfB Code</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Functional (Building) Code</td>
<td>Functional (Building) Code</td>
<td>Process Type</td>
</tr>
<tr>
<td></td>
<td>Element</td>
<td>Form</td>
<td>Function/</td>
</tr>
<tr>
<td></td>
<td>(21)</td>
<td>F</td>
<td>Material/</td>
</tr>
<tr>
<td></td>
<td>Site Installations</td>
<td>Site Installations</td>
<td>Substructure</td>
</tr>
<tr>
<td></td>
<td>Site Superstructure</td>
<td>Electrical Centre</td>
<td>Site Superstructure</td>
</tr>
<tr>
<td></td>
<td>Windows, External Doors</td>
<td>Power</td>
<td>Internal Doors, Hatch</td>
</tr>
<tr>
<td></td>
<td>Internal Doors, Hatches</td>
<td>Lighting</td>
<td>Access Floors, Traps,</td>
</tr>
<tr>
<td></td>
<td>Stages</td>
<td>Communications</td>
<td>Stairs, Ramp Finishes</td>
</tr>
<tr>
<td></td>
<td>Balustrades</td>
<td>Transport</td>
<td>Ceiling Finishes</td>
</tr>
<tr>
<td></td>
<td>Suspended Ceilings</td>
<td>Security</td>
<td>Roof Finishes</td>
</tr>
<tr>
<td></td>
<td>Rooflights, Etc.</td>
<td>86 Storage Loose Equipment</td>
<td>86 Circulation Loose Equipment</td>
</tr>
</tbody>
</table>

Note: Examples in bold lettering
arrangements requested by the users. In addition, it provided a way for different documents to be cross-referenced.

2.5.2.3 The BDC System

The Building Data Council (BDC) of Sweden also attempted to achieve coordinated communication and cost control through use of the computer. This system was developed in 1965 and was directly based on the CBC system. The main goal of BDC was to use the bill of quantities as a contract document. This bill of materials constituted the job specification and the list of materials for a given project. The added features this bill of materials had was its ability to be converted for use by the contractor for production planning, materials ordering, supervision and production control. The key feature in the BDC code which enabled this to occur was through manipulation of the location code (see Table 2.2) as it related to product information (i.e., job number, block number, etc., up to activity). The intention of this system was to use a "central catalogue" as a basis for standardizing all building components; during the quantity "take-off" stage. The central catalogue consists of six volumes that contain codes for materials and components, specifications for building elements, and details of workmanship (i.e., quality, methods, etc.) for components and materials. Once all information is quantified for a given project, it is processed to form schedules, bills of materials, and quantity sheets which can be arranged according to any order of the BDC code structure.
2.5.2.4 The CI/ SfB System

The Royal Institute of British Architects (RIBA) and the International Council for Building Research (CIB) backed a data coordination effort that refined the international SfB system in 1968. The Construction Indexing (CI) system developed incorporated some of the same features that the CBC and BDC systems used. The resulting code (see Table 2.2) is the most comprehensive of the SfB related systems, due to the inclusion of process, work stage, and other facets. The system is used by firms "for arrangement, coding and cross referencing of drawings and schedules before using it for the arrangement of specifications or bills of quantities, or for cross referencing to these documents from coded specification notes (annotation) on drawings and schedules" [Ray-Jones and McCann, 1971, p. 26]. The system essentially performs the same activities as the CBC and BDC systems only in a more structured and detailed manner. In addition, the CI/ SfB system can also be computerized.

2.5.2.5 Other International Classification Systems

Two other systems which have been recognized widely are the International Standards Organization (ISO) Standard 6241, and the British Building Industry Code (BIC). These systems provide a hierarchical classification of building elements and have been incorporated with SfB and even with Gielingh's GARM model to form the backbone for information classification. Figure 2.13 presents the structures of these systems.
Figure 2.13: CI/ SfB, ISO Standard 6241, and BIC Building Element Breakdowns
2.5.3 U. S. Developments

There have been a number of efforts involved with breaking down work items for construction projects. Among these efforts are the Uniform Construction Index (UCI) approach, and the construction management approach. Other works exist and are numerous, but these works are proprietary and are customized to particular company operations. A standardized system has yet to be developed for information tracking, coding and classification in construction. Currently the existing systems are used mainly for cost estimating purposes. The following sections provide summaries of the two classification approaches.

2.5.3.1 Uniform Construction Index Approach

The Uniform Construction Index was developed by the Construction Specifications Institute in 1962, and was refined in 1972. This index was meant to serve as a general system for filing product data, and as a format for cost accounting. The format consists of a five-digit code for standard section titles which many companies have incorporated as code numbers for construction specifications. The format is divided into sixteen divisions which are structured based on material and component types of trade classifications (i.e., concrete, masonry, mechanical, electrical, finishes, etc.).

Among the more notable component classification systems is the Building Systems Index (BSI) approach. This system was developed by the General Services Administration (GSA) and has been adapted and extensively
used by the United States Army [Cost Estimates - Military Construction, 1985]. This classification system is similar to the elemental breakdowns of the BIC, ISO 6241, and Cl/ SfB systems, in that it breaks a building down by its elements and provides for several levels of detail.

2.5.3.2 Other Approaches

There have been several other approaches which have been used by the construction industry. Most of the approaches are specialty/company oriented, so their uses are limited. Among the more significant approaches are the American Road Builder's Association (ARBA) approach, the Construction Management (CM) approach, the Ponce Campos and Ricci Approach (PC&R), and Budeiri's Component Task (C-T) Approach [Budeiri, 1984]. All these approaches are significant in that they provide various methods for breaking down work breakdown structures, however, they are very specific in their applications and uses. Of all these approaches, the CM approach is the most widely used, and it revolves around using work packages to structure and classify information. Here, work items or components are packaged into major systems which are used for dividing a project. The reason behind this approach is the capability it provides in being able to integrate schedule and cost factors for physical components in a building. This approach aids the construction manager in that it allows for tracking of material, equipment and labor costs. Two systems which exemplify this approach are Stone and Webster's Integrated Management System (SWIMS) and James Neil's Integrated Project Control System [Budeiri, 1984].
2.6 Summary

This chapter introduced product and process modeling, and coding and classification schemes used in construction. The process models provide a way of showing transformation of relationships for functions and information elements. The process models (IBPM) also describe the complete cycle of a building and information flows. The product models contribute in the way they represent data structure (i.e., connectivity of systems through symbolic relationships and entity relationships), and the consistency of data representations for facilitating communication among various user viewpoints.

The classification and coding schemes presented the different ways that information can be characterized to form a code structure for classification breakdowns. Several classification systems were presented to show their uses, but overall, none of the systems described was comprehensive enough. The codes (i.e., CBC, BDC, SfB, UCI, etc.) only concentrated on contract documentation from the point at which design work has been completed up to the end of the construction period. None of the codes took into consideration the overlap of information flows between design and construction phases. In addition, the codes were developed for specific and exclusive tasks (i.e., cost accounting, information categorization, etc.), so there are limitations to their effectiveness in serving as a complete system.

The development of an information management framework that is comprehensive and standardized (i.e., a common language for communicating and re-using information), involves incorporation of all the different information systems discussed into a combined global system. The global system refers to
an open architecture for separating data-models based on different characteristics (i.e., global division of information) for easier sorting, retrieving, modifying, tabulating, etc., of information elements. This chapter will provide the guidelines for development of the information framework that will be developed in Chapters 3 and 4.
Chapter 3

THE PRODUCT MODEL ARCHITECTURE

3.1 Overview

This chapter presents and discusses a Product Model Architecture (PMA) for building construction. Parts of it were developed in conjunction with members of the Computer Integrated Construction (CIC) research team. The PMA is a generic framework for representing building product information. When combined with process information and other items it forms the overall Information Architecture (IA). The goal of this framework is to integrate the various discipline views at different levels of detail in representing AEC products (buildings). The design phase of a construction project has been emphasized to illustrate the utility of the PMA. This chapter includes a case study application to test the adequacy of the PMA scheme in capturing information.

3.2 Why Use Product Models?

The central source of information in many enterprises is of course the product itself. Product models are used by designers and engineers to represent and organize information describing their products, traditionally
through the use of drawings and specifications. This method is slow and inherently subject to error. It has long been recognized that integration of this information is the key to higher productivity. In recent years, we have seen computers being used for information processing in the construction industry. To achieve integration using computers, it is imperative that we can effectively classify, store, and retrieve data. In general, this is a complex task because of the many users' viewpoints of information [Howard, 1984].

One obvious use of computer-based product models is to analyze alternative designs and to perform "what if" simulations. This is useful in performing all analysis, synthesis, and evaluation of product decisions at the design stage. Eventually, such models can be used to specify integrated software for the construction industry.

3.3 Relationship Between Information Architecture and Product Model Architecture

"An Information Architecture (IA) defines the representation, classification, capture and real time retrieval of data, information, and knowledge in their various forms, to allow multiple users to interactively access data from multiple perspectives" [Sanvido, 1987]. Thus it includes both product-and process-related information in AEC projects. The product information describes the facility form, while process information is essential to control provision of the facility [Sanvido et al. 1989b]. A Product Model Architecture (PMA) is a common scheme for organizing product-related
information from different viewpoints, at different levels of building detail, over a certain stage/phase of the product life cycle.

An integrated IA should cater to the needs of each user from their viewpoint. Henceforth, the term "user" will denote any person interested in the subject building, however, the information provided by the users will only be for the purpose of serving the developer. Example users are the owner, architect, contractor, mechanical engineer, plumber, and electrician. Since each "user" operates within his/her own framework, some provisions have to be made to capture this localized view. An overview of the IA is shown in Figure 3.1. In addition to the product information, the user would need information defining the conditions and constraints external to the users and the building; the resources to be used to achieve the building; knowledge information representing optimization rules, methods, processes, etc.; project information representing contracts, organizations, goals, and scope; and process information to aid in the decision making process. The informational components of the IA are defined as follows:

**External Information** is information defining variables and parameters that impact the construction of the facility which are beyond the control of all project participants (e.g., codes and regulations). For instance, a building planner would be interested in zoning regulations and demographic information regarding the location of the proposed building site.

**Process Information** defines the subsequent functions in the process and identifies inputs, outputs, constraints, and mechanisms for performing the function.
Figure 3.1: Relationship of Product Information to the Information Architecture
**Project Information** is information defining all management-related activities which affect the project as a whole. Typically this information will constitute contracts, a mission statement, the work scope, the organization team, resources, etc.

**Resource Information** for a user is information regarding his/her resource availability (e.g., financial, personnel, equipment and material). In most cases, this information is used only by that specific user. For example, a steel erector for a particular building is normally not interested in the details of employees within the architectural firm that designed the building. In other words, resource information is locally significant.

**Knowledge** available to the user includes that from previous facilities, the current facility or other sources. This knowledge is used in generating alternatives and then choosing among them.

**Product Information** provides the geometric and non-geometric product data descriptions for all building information elements/components. It defines the product model architecture, which specifies a scheme for storing information that is needed by the respective users.

**User** is the member of the facility team accessing facility information from their perspective (e.g., structural design).

Given these components and their relationships, the criteria for the PMA are explained.
3.4 Criteria for Product Model Architecture

Based on the Product Information needs, the Product Model Architecture (PMA) should satisfy certain conditions to be useful in supporting construction projects. These are

1. **Provide a consistent structured way to represent product data:** The PMA should capture information that describes the product (facility) and its components in an organized way. This is achieved by the use of a standardized product model such as those developed by Björk and Pentillä [1989].

2. **Define PMA in an open and conceptual fashion:** To facilitate future revisions, the proposed PMA should be conceptual in nature [Sanvido et al. 1989a]. Thus, it should have a modular arrangement; so that incorporating new knowledge will not be difficult. The PMA should also be capable of accommodating process related information models in the future.

3. **Be comprehensive:** The PMA should be capable of handling all types of information elements [Björk and Pentillä, 1989]. The bulk of the information in construction projects is transmitted through drawings. The PMA should not only handle these, but in addition, capture information contained in documents, visual images, and verbal communications.
4 **Capture intent effectively:** The PMA should provide a means of capturing intent at every stage of the building life-cycle [Sanvido, 1987]. This is important because it helps in connecting activities of all the participants involved in the project. All phases of the project transmit the owner's intent in various forms to other phases.

5 **Provide a link to the process model:** The information defined by the PMA should correspond to the stages of providing a facility, as defined by the IBPM [Sanvido et al. 1989a]. As the facility proceeds from its inception to completion and subsequent use, the facility is defined in various levels of detail. Information evolves from an abstract knowledge to precise measurable data; each phase results in documents which require linking. The PMA should attempt to model this by allowing different levels of details for describing components of a facility. Thus, information at different levels of detail is linked to the stages of development.

6 **Account for process constraints:** The PMA should consider all the constraints that affect the process of providing the facility. These constraints include codes and regulations, standard practices, standard reference specifications, etc. These are regarded as external information for our purposes. The IBPM models provide process constraints affecting each phase of development, from management to operations.
7 **Portray environmental conditions:** The PMA should also take into account the environmental conditions affecting product elements. These include gravity, location, ground, climate, etc. Since the environment of a building is a significant factor in its design, the PMA should account for this information in the model.

These seven desired capabilities are not all inclusive of what should be expected from a product model, but rather, they are the essential capabilities that are required for having an effective product model architecture.

3.5 **Developing the Product Model**

The development of the product model architecture considered the top-down design approach and the bottom-up construction approach to buildings. It also recognizes the traditional method for representing information, namely, Factors, Function, Form, Economy, and Time before, defining the strategy used.

3.5.1 **Top-down Versus Bottom-up Creation of the Product Model Architecture**

One of the key issues in the construction industry is to integrate the design and construction discipline solution approaches. Designers start with an abstract idea (e.g., a building) which considers the whole product.
They develop this from conceptual design, through schematic design, detailed design, working drawings, and shop drawings to selecting the components and materials. Constructors, on the other hand, acquire the components and materials (detail level) and build a building from individual pieces (the synthesis phase). Figure 3.2 shows how the designers use a top-down approach to creation of a design, and the constructors/manufacturers use a bottom-up approach of the design information to assemble a building. Figure 3.2 also shows the information transfer point between the process of analysis and synthesis and where they meet. Once a facility is completed, its success can be measured by how closely the goals match the final product.

It should be noted that there are exceptions to the top-down and bottom-up approaches. For example, when fast track/phased construction delivery systems are used builders would not always have a complete set of detailed plans and specifications from which to work.

The crux of the product model architecture presented in sections 3.6 and 3.8 show how the top-down and bottom-up oriented approaches can be integrated. One thing to note, is that the product model architecture presented here is a model that describes how information about products can be stored and gathered. Its purpose is to serve as an information framework for: supporting an organization of information; as well as the exchange of information by the management, design, planning, construction/manufacturing, and operation subprocesses. Thus, the information framework requires having system levels from which integration of disciplines can be built.
Figure 3.2: The Building Information Process as it Relates to the Top-Down and Bottom-Up Approaches
3.5.2 Methods of Product Representation

It has been widely documented in literature that Function, Form, Economy, and Time are descriptive attributes used to represent design of products in the AEC industry [Peña et al. 1987]. It is not clear whether Function derives Form or the other way around. This relationship varies from client-to-client and project-to-project [Bathgate, 1983]. A relationship between Function-Form sequence and the directional approach to designing has been observed. When the owner's needs for a building are elaborate (e.g., industrial construction), the Function drives the Form. For typical residential construction, Form and Function play equally important roles. Economy and Time attributes play a significant role in the decision-making processes in providing a facility.

Traditional approaches to representing designs vary, but most have been two-dimensional (i.e., paper drawings). This necessitates the use of floor plans (horizontal) and vertical section drawings for most disciplines in the project. More details are obtained from room level drawings than floor level ones and so on. From a strictly representational standpoint, the elemental arrangement is the merging point for all disciplines concerned with a building; in so far as they relate to the spatial breakdown of the architectural system breakdown. By decomposing the building description into its elemental features, a common reference to represent any technical viewpoint (HVAC, Electrical, Plumbing, Civil, Structural, and Architectural) is obtained. Thus, it is possible to structure all discipline elements in a common hierarchy. The ideas of abstraction and aggregation are now
expressed only in terms of the architectural system. One potential problem with such an approach is its usefulness to a designer when he/she is actually performing its design. Some designs are done on a floor-by-floor basis, while others are done on a room-by-room basis. Variations in strategies extend across projects, designers, and disciplines. These can be accommodated by providing a flexible information structure as will be shown later.

3.5.3 Development Strategy

The context used for creation of the product model architecture was based on integration between the two practice-based strategies used in the construction industry (top-down and bottom-up). Representation of the product model architecture occurs through Function, Form, Economy, Time, and Mechanism attributes which are used for linking information elements to the elemental arrangement and breakdown of a building. The common denominator for linking user/data views takes place through a reference to the building's architectural system and the discipline view of the system being designed.

The following section explains the elements used for defining the product model architecture.
3.6 Elements of the Product Model Architecture

The Product Model Architecture is explained schematically in Figure 3.3. It shows the arrangement of "Building Levels" and the "Discipline Breakdowns" as two orthogonal categories. The attributes Function, Form, Economy, and Time tie these two categories together; they provide the links between any one discipline and any one particular building level breakdown. Each object in the "Discipline Breakdown" is a Function for each object in the "Building Level." For example, the Architectural, Structural, HVAC, Electrical, and Plumbing Functions are tied to a given floor, room, etc. Each building element is comprehensively described by the Function, Form, Economy, and Time factors. The benefit this provides for design considerations is that it allows for an understanding of the whole context by which design problems must be solved. The attributes provide the scope for managing information about building elements. From a construction standpoint, the consolidation of these attributes for a given building level allows for a better understanding during assembly of components (i.e., the context that each building element has in relation to the assembly being made). For instance, all discipline functions shared by a floor can be aggregated at a floor level to give a detailed description of the systems and uses for a floor level, room, components, etc. A description of this floor in terms of all these discipline views is then its Form. Function and Form descriptions involve Economy and Time considerations. Mechanisms serve to explain how, who, and by what means design problems are solved.
Figure 3.3: Elements of the Product Model Architecture in Relation to Product Information
It is felt that, in the earlier stages of a facility life, information flow is more of the "Function" type than the "Form" type. Definitions of the attributes are:

**Building Levels** hierarchically define and decompose a building into the different architectural levels of abstraction of a building (i.e., floors, rooms, components). These building levels are used to integrate the various discipline views of a building.

**Function** defines the intended purpose and use. It deals with specification of performance requirements for the building, or components at lower levels. Thus, function implies "what's going to happen in the building" [Peña et al. 1987, p.30].

**Form** relates to the arrangement, design, provision, or configuration of elements to meet functional requirements. It is a representation of design solutions. Form addresses "what is there now" and "what will be there" [Peña et al. 1987, p.30].

**Discipline Breakdown** identifies the technical disciplines in AEC as being: Architectural, Civil, HVAC, Plumbing, Electrical, and Structural. This breakdown was based on work reported in the literature and our case study application.

**Economy** includes consideration of budget and life cycle costs.

**Time** deals with influences of history, schedules, and other temporal considerations.

**Mechanism** refers to the elements, means and methods used to perform a process or operation. The mechanism element was not
addressed in detail so as to retain the generic emphasis of the product model architecture. Typically, it would be a customized operation based on the organization team assembled for provision of a particular facility being built. In the future this element may be performed by expert systems or specialized computer applications.

The following sections discuss the building level and discipline breakdown elements used to define the product model architecture. Subsequently, linking of views and connectors are defined.

3.6.1 The Building Levels

The "Building Levels" represent the architectural view of buildings in so far as the spatial breakdown of buildings - in a hierarchical fashion - is concerned (see Figure 3.4). This type of decomposition enables us to tie in discipline views at different levels of detail according to the way in which design is performed.

Project information is at the highest level of abstraction; it describes the mission, scope, organization team, contracts, and resources used for a building's creation. Every project has a site and a building.

The site corresponds to civil systems like site drainage, storm drainage, etc., and to other conditions which exist outside the boundaries of a building. It defines the boundaries of the project and the environmental conditions that affect the building (i.e., rain, snow, wind, etc.). Sites may
Figure 3.4: The Building Levels of the PMA

* System Level
** Subsystem/ Assembly Level

Note: The spatial breakdown of the Building levels represents the Architectural view.
belong to more than one building or project, and they may have their own systems. The site connects the building to a project.

At the next level of spatial arrangement is the whole building itself. It consists of Floors, Vertical Connectors (i.e., elevators, stairs, utility shafts, etc.), and an External Envelope (or skin). Floors are the vertical separators within a building. Vertical Connectors exist for each discipline. They are connections between Floors for that discipline. For example, HVAC penetrations are areas provided for ducts and pipes to cross from one Floor to the next. The External Envelope includes the external walls (vertical skin) and the roof (horizontal skin).

At the next level of abstraction, a Floor is divided spatially into Rooms, Service Spaces, and Horizontal Connectors. A Room is an enclosure consisting of elemental features such as walls, floor, ceiling, and the objects within it. Typical objects associated with a room are its Components (i.e., furniture, doors, equipment/fixtures, internal surfaces, windows, etc.). Horizontal Connectors provide a link between Rooms (for each discipline). Service spaces include telecommunications closets, mechanical closets, janitorial closets, etc.

3.6.2 Discipline Breakdowns

Figure 3.5 shows the relationship between the discipline breakdowns and the building levels. The link between these two orthogonal categories is made through the Function, Form, Economy, Mechanism, and Time attributes. The mechanism attribute, however, is the driving force between
Figure 3.5: The Product Model Architecture - Relationship Between Discipline Breakdowns Versus the Building Levels
the two orthogonal categories, because in most cases it will be the disciplines which play the role of performing processes by various means and methods. Figures 3.6-3.11 represent the physical building elements of the six discipline types which define the product model architecture entities in Figure 3.5. These building elements correspond to current practice. They show how systems and subsystems are currently designed and built. Systems are defined as groupings of objects/components which are combined in an organized/related fashion such that they relate to a specific function/process. Subsystems/assemblies are defined as groupings of objects which are based on specific aspects of a functional process (i.e., production process).

Industry practice and processes used for development of today’s facilities include firms such as: landscape, geotechnical, and paving contractors for Civil systems; structural engineering firms for Structural systems; mechanical contractors for HVAC systems; plumbing contractors for Plumbing systems; electrical contractors for Electrical systems; and trade contractors and architectural firms for Architectural systems. These firms and their corresponding disciplines represent the data views through which the product model architecture is viewed. Definitions for the discipline breakdowns are

**Architectural discipline** defines the programming, spatial features (i.e., form), aesthetics, orientations, and arrangements for a building and its elements.
Figure 3.6: Architectural System Breakdown
Figure 3.7: HVAC System Breakdown
Figure 3.8: Electrical System Breakdown
Figure 3.9: Plumbing System Breakdown
Figure 3.10: Structural System Breakdown

- BUILDING
  - Vertical
    - Walls
      - Shear Walls
      - Tube Walls
      - Tube in Tube
      - Frame & Shear Walls
      - Load Bearing
    - Columns
      - Concrete Stirrups
      - Steel Section
      - Built In Rolled Section
    - Shallow Footing
      - Isolated Piers
      - Piles
  - Deep
    - Piers
    - Piles
  - Slabs
    - Two-way
      - Flat Plate
      - Slab Support
      - Slab Support Bearing Walls
      - Slab Support Joist
    - One-way
      - Slab-beam Girder
      - Slab-beam Bearing Walls
    - Tie
  - Structural Roof
  - Beams
  - Ties

System level
Subsystem level
Site Furniture/Art/Structures
- Site Drainage
  - Catch basins/manholes
  - Septic Tanks
  - Utility Vaults
  - Wells
  - Storm drainage
  - Etc.

Site Topography
- Contour Elevations
- Roads & Walks
  - Etc.

Utility Connections
- Utility line Layouts
- Manhole Locations
- Orientation of Pipes
- Water Mains

Landscape Information
- Plant Types
- Planting Details
- Ground Cover Details
  - Etc.

Soil Information
- Areas for soil control measures
- Soil Types
- Bale sediment traps

Traffic Flow
- Speed
- Noise
- Direction
- Car/Pedestrian

Previous Site Usage
- Areas for demolition/excavation

Building Atmosphere
- Building Shape & Orientation
- Maneuverability & Access Space
  - Geometry of Parking Area
  - Loading/Unloading Configuration
  - Location

Surrounding Environment
- Annual Climatic Conditions
  - Snow loads
- Acids
  - Rain, Wind, Sunlight
- Earthquakes

Figure 3.11: Civil System Breakdown

Note: This figure is beyond the scope of research (outside the building). It was presented to give an idea of the factors that might make-up the functional categories of the External Environment for a Building/Site.
Structural discipline determines the structural form, materials, strength, variability of loads, and structural integrity/safety of a given building or component. The basic divisions of the structural system include horizontal components, vertical components, and foundation systems.

Civil discipline describes the site and environmental conditions affecting a building.

Plumbing discipline defines a building's fluid, gas, and fire supply systems as well as the drainage (storm and sanitary) and venting required. Typically, this is a network of piping, valves, fittings, and accessories in a building that supplies water to all plumbing fixtures.

HVAC discipline determines the heat gain for air conditioning; the heat loss for heating; the required air changes per hour for ventilation; the size and shape of duct to deliver the volume of air to various HVAC areas designated in a building; the control systems/wiring; fixtures; and components required for having a complete functional system.

Electrical discipline determines the electric loads required to operate equipment in a building (i.e., lights, fixtures, motors, heaters, signal systems, etc.).

The building elements are discipline-oriented to support integration and segregation including proprietary ownership of information. Thus, the disciplines on a project can maintain company libraries based on projects developed, as well as maintain privity of company operations while sharing
the design information. The facility champion can thus store all shared information centrally for a given project. These discipline breakdowns interface to the product model architecture through the architectural system, the design method, and organization used for a given project.

3.6.3 The Linking of Views

The linking of views occurs at the building level and the room level; through component connections (see Figure 3.6). The key connection points between the disciplines (Figures 3.7-3.11) and the architectural system (Figure 3.6) follow. The HVAC, electrical, and plumbing system components connect to equipment/fixtures in rooms while the structural elements connect to any applicable level. For example, a luminaire designed by the electrical discipline would be connected/linked through the Equipment/Fixture level in the Architectural breakdown. The Civil system is exclusive to the Architectural system in that it only deals with the Site and external environment for a given facility. However, the HVAC, Plumbing, Electrical, Structural, and Architectural disciplines can relate to the Civil systems where affected (i.e., a case by case basis). The main thing to note is that the systems do not link at every level, since no component/facility form solution is predefined from the outset.
3.6.4 Connectors in Building Levels

The idea of connectors is used to better define interfaces between various objects of the PMA, and to represent horizontal and vertical integration between product elements and building systems. It also helps in preserving the tree structure of the PMA. Figure 3.12 shows the role of connectors in the hierarchy of "Building Level" objects. Every object in this hierarchy can have a view for each discipline.

Level 0 represents project information related to the building and the site (i.e., budgets, contracts, resource costs, organization team, etc.).

The site (Level 1) represents the physical surroundings of the building. This includes environmental features that affect the Form and Function of the building. The building level (Level 1) is used in representing Form and Function that affect the whole building. The building level is associated with a project through a site connection.

Floor level (Level 2) descriptions are more specific than building level ones, but more generic than those for room level. Vertical connectors serve to connect floors. Architecturally these are the elevators, escalators, stairs, etc. From an electrical designer's perspective, these are wiring (or other) connections between floors, and so on.

Level 3 carries room level information about Form and Function for every discipline. A room will have some (or all) of electrical, HVAC, plumbing, structural, or architectural views. The Horizontal Connectors provide links between spatial objects at a Floor level (e.g. Rooms). The horizontal connectors assign rooms to systems; connectors represent
Figure 3.12: Role of Connectors in Building Levels
physical connections only and not system logic. Examples of such connectors might include: piping, ductwork, electrical wiring, and doors.

The lowest level (Level 4) is one where all the details occur. For instance, equipment, components, furniture, window, door, or other details fall under this category.

In summary, the higher level objects reference the lower ones which carry increasingly detailed descriptions of the product. This approximates the "top-down" design procedure used by designers. It also provides the designer flexibility in storing information at whichever level he/she chooses. Then, the higher levels are defined by abstraction, and the lower levels by specialization. It can be argued that designers think in terms of "zones" (which could relate rooms at one floor directly to those at another floor). But, it is felt that this method of structuring data is more conducive to implementation, and it provides a logical framework for user queries.

### 3.7 Rules for Using the Product Model Architecture

Several rules are important for maintaining the integrity of the PMA;

1. In the course of development of the design, the architectural discipline governs. Hence, conflicts between architectural and other disciplines are resolved by the chief architect. Thus all products must conform to the elemental configuration of the architectural system. The design team must coordinate with
the architect concerned all predefined spatial allotments for system raceways/areas for defined uses (i.e., holes and void spaces). The exception to this occurs when the structural discipline deems the architectural design to be infeasible, in which case the architectural concept is overridden in order to maintain the integrity of the facility structure.

2. Higher levels of abstraction govern over lower levels.

3. All changes related to the design of a facility must be authorized, updated, and recorded by the controllers of information based on the building level breakdown. The list for controllers, as they relate to the building levels is the following:
   - Project level: Owner.
   - Building level: Project manager.
   - System level: Discipline engineer (i.e., architectural, plumbing, HVAC, etc.).
   - Subsystem/assembly level: Trade contractor.
   - Component level: Affected manufacturer.

4. Where a common element has both architectural and structural form elements (i.e., columns) the rule for data storage is that all load bearing structures are classified under the structural system.
5. The rule for controlling structural discipline coordination with affected disciplines is that the structural engineer is responsible for designing all systems affecting designs which relate to support systems of other disciplines (i.e., load bearing equipment foundations, penetration parts - pipe sleeves, etc.).

6. The rule for storage of information elements - where there is a multiple number of building levels involved - is that they be stored at the highest level where all information elements are shared (i.e., lowest common denominator) in relation to the building level hierarchy.

3.8 Using the Product Model Architecture

This section discusses the Product Model Architecture's use in the design, construction, and operations processes.

3.8.1 The Product Model Architecture's Use in the Design Process

In the IBPM, the design phase follows the planning phase. Design comprises all the functions required to define and communicate the owner's needs to the builder [Norton, 1989]. These activities translate the program and project execution plan (PEP) [Al-Muallem and Guvenis, 1989] into bid and construction documents and operations and maintenance documents that allow the facility to meet the owner's needs. As such, it is this particular
phase of the project where many key decisions are made. It is also the one phase with the most information exchanges.

The design procedure in construction projects involves a proper consideration of Function, Factors, and Form (see Figure 3.13). Function refers to the intended use or purpose and is either the owner's need or a derivation thereof. For example, the HVAC Function of a room could be simply stated as 70 degrees Fahrenheit, 50 percent relative humidity, 1.5 total air changes per hour, and class 100 air classification (for clean rooms). Note that, the building owner would not usually express his needs with such details, but some project participant has translated his/ her intent into a function at the room level. Factors are the variables involved in the design (i.e., elements relating to quality, safety, cost, performance, etc.). The process of analysis leads to an enumeration of variables. Economy and Time are also crucial factors in the design procedure. Their mutual relationship can be studied through time/ cost tradeoffs. Knowledge is used throughout the design process. It is especially significant in the process of synthesis. It allows the user to select between alternative solutions and to combine them if necessary. Synthesis is the process of combining together parts or elements so that the system performs, behaves, or responds according to a given set of specifications. Form is the result of synthesis and is a configuration that has been selected to serve a definite purpose (Function). The Form is compared against the original Function in a process called evaluation. The evaluation process can terminate with the design being either accepted or rejected. If the design is accepted it becomes a
Figure 3.13: Use of Attributes in the Iterative/Cyclical Three Step Systematic Design Process
[Sources: Asimow, Jones, Archer, and Markus in Cross, 1984]
product attribute, and if it is rejected it goes through the analysis, synthesis, and evaluation loop repeatedly until all functions are satisfied.

In summary, the product modeling concept begins with a breakdown of the Building Levels (the PMA). Using the "divide and conquer" strategy as the design process, the architectural discipline can decompose the elemental features/ components of a building as they relate to the Building Levels. These Building Levels would then be assembled - component wise - based on the discipline breakdowns through conformance to the Architectural system - the common denominator for all activities and entities in the development/ design process. The decisions that go into creating the development/ design process could be based on Functions/ goals/ requirements for a facility followed by the Factors which would be based on Economy, Time, Experience, and Design calculations to arrive at a Design Solution/ Facility Form. The representations for these processes would be done through frames for storing information. Frames refer to field values, in database terminology, and are essentially the data structures which are used to represent and describe objects and events. Frames were chosen for on their future potential for displaying hypertext technology [Conklin, 1987], and are used here as graphical sheets for representing various building information elements/ fields. For purposes of staying within the scope of the research topic, implementation issues are not addressed.
3.8.2 The Product Model Architecture’s Use in the Construction Process

By structuring building component information according to the building level breakdown and in relation to the spatial and elemental features of the architectural system, several uses can be obtained from a construction/manufacturing standpoint. Three hypothetical construction uses of the PMA are postulated.

The first use is that of a component indexing reference, based on the elemental decomposition of a building. Here, a list of components can be obtained for each room, floor, service space, etc. The benefit this provides is an increased capability to order and allocate components during the construction process. Additionally, work packaging or aggregation of components at a room level can be performed. A case in point would be the grouping and fabrication of plumbing units (i.e., pipes, fittings, welding, etc.) offsite in a controlled and productive environment where manufacturing operations can be performed on small clusters of components. In other words, small assemblies could be made in an environment conducive to efficiency of operations. Once the assemblies are made, they could then be allocated to the rooms in which they belong (based on a code); this would reduce construction time, and improve quality and labor productivity. A further application of the component index could be for Quality Assurance/Quality Control (QA/QC) checklist and punchlist purposes.

The second use may be that of an initial quantity take-off listing, of the building materials and components, from which contractors could expand
on. In other words, contractors would not have to estimate material and component quantities from drawings, thus eliminating the duplication effort that currently exists today. Since the product model architecture allows for the data structuring of all building elements, a detailed listing of all items could possibly be available for analysis and estimating purposes once design is completed. Contractors would then have to add material, labor, overhead costs, and other cost factors such as waste materials and complexity of construction technology/methods, in order to arrive at a bid price for a project.

A third use may be that of construction sequence planning - of work packages - based on groupings of manufactured components. Activities of work crews could be planned and assigned based on component types.

These three uses are not all inclusive of what may be a benefit to the construction process. More can be developed, but these are implementation aspects that have to be addressed.

3.8.3 The Product Model Architecture's Use in the Operation Process

From the standpoint of the product model architecture serving as a historical database, several uses are clearly seen for the operation process. The location of building elements can be identified easily through use of a coding scheme based on the PMA. This application would aid in the serviceability of equipment, and for troubleshooting system breakdowns. An operator would be able to know what equipment is located in any given part of a building.
Another use for the operation process would be the understanding of the intent behind design decisions. Operators could access the discipline from which a component was designed, and they could call up the factors that went into selection/design of a given component (i.e., how a component came to be there - factors). This feature would help in conducting outcome research on buildings. By understanding why components or designs do not work, and the factors that went into creating them, knowledge can be gained as to how to design/select better. Additionally, the effects of time and use of a building can be logged, which could lead to improved processes, methods, materials, and designs (optimization knowledge). The PMA could also be used as a facility space planning tool, whereby components could be tracked based on changes made; as a result of varying uses of a building. Before building the coding structure, an example use of the PMA is discussed.

3.9 Application of PMA on a Case Study to Show the Structure for Capturing the Intent of Data

For purposes of identifying the systematic breakdown of disciplines (Architectural, Plumbing, Structural, Civil, Electrical, and HVAC) as they relate to Function, Form, Economy and Time through various phases of a project's life cycle, a representative building was chosen for a case study application. The case study application also shows how the three-step systematic design process would be utilized. From this, a data structure is
provided for showing the intent behind product data decisions; throughout the design and construction cycle.

3.9.1 Description of the Case Study Application

The building selected is a 23-million dollar, 100,843 square foot, multi-purpose building situated on a large university campus in Pennsylvania. The project is a five-story building comprising classrooms, administrative offices, greenhouses, laboratories, a library, a 200-seat auditorium, and supporting facilities, including animal holding rooms, cold rooms, instrumentation rooms, constant temperature rooms. The building proved to be reasonably complex and a good example of a representative commercial building. Additionally, the building had both structural steel and concrete as structural building materials. The majority of systems incorporated in the building were very modern. For example, the telephone and communication systems were sophisticated enough to provide for networking computers and related electronic equipment, and the HVAC system was controlled by an efficient temperature regulating system (both heating and cooling).

In the CIC research research team's attempts to analyze the facility life-cycle information, we encountered many difficulties relating to the quantity and quality of information for the various stages of the building's life cycle. There were occasional gaps in the information, and there was no single source for information. However, success was found in developing
system breakdowns by discipline (i.e., Figures 3.6-3.11); supporting the PMA.

3.9.2 Illustrative Examples for the Product Model Using the Case Study Application

In an effort to validate the PMA, a match of its organization to that of a representative building was made. A complete set of drawings was available for the detailed design stage of the case study project. The drawings were then successfully mapped on to the levels of abstraction (Building, Floor, Room, etc.) for each discipline. Since drawings carry Form information, it was concluded that Form frames could be used to capture the same information. Capturing Function information at different levels of abstraction (for any discipline) presented problems. Because function deals with requirements, it is difficult to associate it with any particular level of abstraction. Two examples were chosen to illustrate our approach.

Table 3.1 provides practice based examples of Function, Factors, and Form elements for HVAC systems at a room level. The information source for obtaining the attribute data elements is from Bathgate [1983]. In our usage, Function specifies requirements, Factors are the variables, and Form is the design decision. For an HVAC system, Function can be specified in terms of temperature ranges, relative humidity, air quality, and air change rate per hour. Note that, some of these function elements may not be explicitly specified for any one project (especially at the room level). Factors affecting the design process include room location with respect to the sun,
Table 3.1 Example of Function, Form, and Factors for HVAC Systems at Room Level

<table>
<thead>
<tr>
<th>FUNCTION</th>
<th>FACTORS</th>
<th>FORM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired Temperature Range (Deg. F)</td>
<td>Room orientation and location within building</td>
<td>Number of glass panes, Glass types</td>
</tr>
<tr>
<td>Relative Humidity (% RH)</td>
<td>Internal Heat production (Equipment used and number of occupants-- BTU's/Hr)</td>
<td>Wall materials (insulation, reflectivity, thermal inertia, condensation control, and coefficients)</td>
</tr>
<tr>
<td>Air Quality classification (ppm)</td>
<td>Dimensions of room-- length, height, width (volume in CFM)</td>
<td>Heating/Cooling system capacities</td>
</tr>
<tr>
<td>Air change rate per hour (Total CFM/Hr)</td>
<td>External heat production (sun exposure, intensity of radiation, sun angle, shading features, etc.) for a room</td>
<td>Duct sizing, layout and HVAC equipment</td>
</tr>
<tr>
<td></td>
<td>Infiltration/Exfiltration due to wind, wind shielding</td>
<td>Operation information for HVAC design within the room</td>
</tr>
<tr>
<td></td>
<td>HVAC cost factors/energy budget tradeoffs</td>
<td></td>
</tr>
</tbody>
</table>
anticipated internal heat production, room dimensions, cost, and performance of the alternative HVAC equipment. The Form captures a designer's ideas to meet the function. For an HVAC system, it would be choice of HVAC equipment, layout, and dimensions of the ducts, wall construction materials, sizing, location of windows, etc.

Some form attributes (and considerations) for level 1 of the "Building Level" hierarchy are shown in Table 3.2. When referring to the site and the external environment, the civil systems are an important consideration. Site and soil characteristics, landscaping, site equipment, and demolition areas are of interest. A person from the architectural discipline would be interested in the location of the site, shape, geometry, and orientation. For a plumber, important aspects are the location and details of utility connections to the building. An electrical systems designer would also be interested in the external utility (service) connection at this level. The HVAC person is concerned with external climatic conditions because they affect the design of the heating/cooling systems within the building. He/she will also be interested in sunlight conditions, wind characteristics, etc.

A prototype application for the PMA was built. This was done to demonstrate its feasibility in capturing discipline specific information at the different Building Levels. The CIC team took a specific room and combined two building disciplines (Architectural and HVAC), to show the mapping of one level of abstraction, and information related to both disciplines at that level.
Table 3.2 Typical Form Attributes for Different Disciplines at Level 1 (Site)

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Civil</td>
<td>Site Characteristics (Topography, Soil, etc.), Site Equipment Location, Site Geometry/Features, Demolition Areas.</td>
</tr>
<tr>
<td>Architectural</td>
<td>Site Location, Shape/Geometry, Orientation</td>
</tr>
<tr>
<td>Plumbing</td>
<td>Water utility connections</td>
</tr>
<tr>
<td>Electrical</td>
<td>Electric utility connections</td>
</tr>
<tr>
<td>HVAC</td>
<td>External climatic conditions, Temperature ranges, Wind characteristics</td>
</tr>
</tbody>
</table>

The main issue discovered from conducting this work is the fact that current documents do not show storage patterns for building data. Users of information have to continually search for the information they desire. This searching of information consists of checking all available information sources for a given project (i.e., schedules, drawings, specifications, general conditions, etc.). Information is currently structured on the most convenient media used to represent it. What this section attempted to show was that it is possible to restructure information independent of media, based on the frame structure and storage pattern presented in Table 3.1 and 3.2. The next chapter gives us a way to code these frames based on the PMA structure.
3.10 Summary

This chapter defined the reason for a product model architecture and its relationship to the information architecture. Criteria for the product model architecture were developed before its development strategy was presented. The elements of the PMA were defined as Building Levels, Discipline Breakdowns. Linking of views and Connectors were discussed. Rules for the PMA preceded discussion on the use of the PMA. Finally, an example of the use of the PMA was presented.
Chapter 4

CLASSIFICATION AND CODING STRUCTURE

4.1 Overview

This chapter introduces a classification and coding scheme for the product model architecture. This scheme combines several of the ideas expressed in Chapter 2. The selection of the classification and coding structure is discussed, and the format and examples of its use are presented. It should be noted that the design of the code structure is specifically suited to account for the overall IA scope. The coding scheme in this study is only a general format for the context in which a more detailed scheme would need to be developed for implementation purposes.

4.2 Selection of a Classification and Coding System

According to Culbreth, systems for coding are generally of three types [Culbreth, 1984, pp. 65-75]:

1. Hierarchical codes (monocodes)
2. Attribute codes (polycodes)
3. Hybrid codes (semi-polycodes)
These coding systems usually take the form of either numeric or alphanumeric digits. The choice between the two forms usually rests on the population of possible choices requiring codes. The alphanumeric code is capable of accommodating more values/variables than the numeric.

Monocodes have been defined as "an integrated code of fewest characters to distribute evenly a classification of a population of items where each code character is qualified by the preceding code and, in turn, qualifies the succeeding code" [Hyde, 1981 in Culbreth 1984, p. 66]. An example of an industry accepted monocode for construction is the UCI index with its sixteen divisions and five digit format.

Attribute codes or polycodes are a "chain-type structure where each digit is of fixed significance and a certain digit value in a specific position always represents the same feature" [Rohan 1977 in Culbreth 1984, p.69]. This code type is similar to the facets used in the SfB system.

Hybrid codes or semi-polycodes are a combination of monocodes and polycodes and have been used effectively in the areas of group technology. Group technology has been defined as "a way of identifying and bringing together related parts so that design and manufacturing can take advantage of their similarities" [Houtzeel et al. in Maxwell, 1985, p.3]. The advantage of using group technology techniques is found in the way parts/components/physical items are identified such that design and manufacturing can take place. In other words, unique classifications are made for all items such that specific applications can be utilized by the different users (i.e., design, construction, etc.).
Group technology applications have been developed mainly for manufacturing systems. However, cases where hybrid code structures have been utilized outside of manufacturing include the electronics industry [Maxwell, 1985] and reinforced concrete structures for the construction industry [Sacchetti, 1989]. Based on the successful applications of these two research efforts, the author has followed the same parallels in applying the hybrid code system format, since it has been proven to work effectively.

4.3 Design of Code Structure

The hybrid code structure design is based on the organization and logic of data which make-up the product model architecture. However, process models, product model attributes, and a part of the SfB system were incorporated to make the code structure comprehensive enough to suffice the overall IA requirements. The next section explores the basic code structure and how it is used.

4.4 Proposed Code Format Structure

The coding scheme is made up of twenty fields, and is numeric and alphanumeric in nature. The first fourteen fields are used as a generic or standard section of code. The remaining six fields are designated for the specific section of the code structure. The subsequent sections define the generic and specific code formats. Figure 4.1 provides an overview of the basic code structure for the proposed PMA scheme (the shaded circles are the focus
Figure 4.1: Basic Code Structure for the Proposed PMA Scheme
of this research). Generic and specific code formats of this scheme are described in the next two subsections.

4.4.1 Generic Code Format

The first fourteen fields are given the following definitional parameters.

1. Project Type
2. Information Type
3. Work Stage/ Process Phase (Information Architecture Module)
4. Product Information (Information Architecture Module)
5. Project Information (Information Architecture Module)
6. Knowledge/ Alternatives (Information Architecture Module)
7. Resource Information (Information Architecture Module)
8. External Information (Information Architecture Module)
9. IBPM Process Identification
10. IBPM Arrow Identification
11. Discipline Identification
12. Building Level Identification
13. Assembly Identification
14. Site Information

Each of these parameter fields is defined as follows:
1. Project Type: this provides a generic listing of building types for the given user, e.g., (A) Administrative; (B) Hospitals; (C) Educational; (C1) Primary; (C2) Secondary; (C3) University; (D) Industrial, etc. The specific section of this field would be an alphanumeric which provides a unique identifier for any given project.

2. Information Type: this classification consists of eight information sets which are used to define the broad information types that define the six modules of the information architecture. The information types are a subset of process information and the IBPM elements. Definitions for these information elements are included in chapter 2. The information sets serve as related collections of one or more data items. This work involves coding only the product information category. The other information types relate to specific aspects of the information architecture (see Figure 4.2).

3. Work Stage/ Process Phase: this category relates data to the time frame according to the five stages of development outlined in the IBPM [Sanvido, 1990]. The five stages are as-managed (M); as-planned (P); as-designed (D); as-constructed (C); and as-operated (O). These stages serve to discriminate/isolate information types as they correspond to the five stages of development.

4. Product Information: this classification provides the geometric and non-geometric product data descriptions for all building
Figure 4.2: User Access and Information Type Codes
information elements/ components. It defines the product model architecture, which specifies a scheme for storing information that is needed by the respective users. In Figure 4.3 product information is defined as being part of the elements which make up the Facility Idea, Planning Information, Design Information, and Construction Information arrows of the IBPM. Thus, product information is coded as (D) for field 2. Note that Figure 4.2 is based on the information elements categorized in Figure 4.3. Additionally, Figure 4.3 shows the inclusion of a limitations/ constraints and controls category which was not accounted for in the IBPM information analysis chart in chapter 2.

5. Project Information: this classification serves to define all information elements which pertain to a project as a whole (i.e., specifications). Usually, this information consists of contracts, and plans for monitoring and executing projects. A subcategory of this field is the site information field.

6. Knowledge/ Alternatives: this classification provides the user knowledge or rules learned from previous facilities, the current facility or other sources. This knowledge is used in generating alternatives and then choosing among them.

7. Resource information for a user is information regarding his/ her resource availability (e.g., financial, personnel, equipment and material). In most cases, this information is used only by the specific user. This classification provides information pertaining
Figure 4.3: Analysis of Generic Similarities in Subfunctions Required to Provide a Facility
[Adapted from Sanvido et al. 1989b, p. 23]
to resources which is locally significant to the project team members.

8. **External Information** is information defining variables and parameters that impact the construction of the facility which are beyond the control of all project participants (e.g., codes and regulations).

9. **IBPM Process Identification**: this classification category classifies all functions in the IBPM (see Appendix A for a complete listing of all the function code values). It also serves as a search pattern for traversing among the different information architecture elements.

10. **IBPM Arrow Identification**: this identifies specific arrows which represent specific information processes and data items. These arrows represent the information flows in the IBPM. As an example, function box D.5.1, in the IBPM, has an arrow labeled post-design drawings as an output; this means that final drawings (plans, details, sections, elevations, schedules, etc) are transmitted to the next process.

11. **Discipline Identification**: this category identifies the technical disciplines in AEC as being: Architectural, Civil, HVAC, Plumbing, Electrical, and Structural (definitions were provided in section 3.6.2). Figure 4.4 provides the code structure for the six disciplines (i.e., 1 = Architectural, 2 = HVAC, etc.) and their respective breakdown systems and subsystems. This breakdown was based on work reported in the literature, industry
<table>
<thead>
<tr>
<th>1 - ARCHITECTURAL</th>
<th>2 - HVAC</th>
<th>3 - ELECTRICAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 - Building</td>
<td>20 - System Type</td>
<td>30 - Primary Power</td>
</tr>
<tr>
<td>11 - Floors</td>
<td>21 - Equipment/ Fixtures</td>
<td>31 - Secondary Power</td>
</tr>
<tr>
<td>111 - Rooms</td>
<td>211 - Heating Specific</td>
<td>301 - Distribution</td>
</tr>
<tr>
<td>1111 - Envelope</td>
<td>212 - Cooling Specific</td>
<td>311 - Emergency Power Sources</td>
</tr>
<tr>
<td>1112 - Furniture</td>
<td>213 - Ventilation Specific</td>
<td>302 - Lighting</td>
</tr>
<tr>
<td>1113 - Equipment/ Fixtures</td>
<td>214 - Common Equipment</td>
<td>303 - Elevators/ Escalators</td>
</tr>
<tr>
<td>1114 - Doors/ Windows</td>
<td>22 - Controls and Instrumentation</td>
<td>312 - Distribution</td>
</tr>
<tr>
<td>112 - Horizontal Connectors</td>
<td>221 - Components</td>
<td>304 - Communication</td>
</tr>
<tr>
<td>12 - Vertical Connectors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>121 - Penetrations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 - Envelope/ Skin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>131 - Above Ground</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1311 - Roof</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1312 - External Walls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>132 - Below Ground</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 - PLUMBING</td>
<td>5 - STRUCTURAL</td>
<td>6 - CIVIL</td>
</tr>
<tr>
<td>40 - Supply System</td>
<td>50 - Horizontal</td>
<td>60 - Site Furniture/ Art/ Structures</td>
</tr>
<tr>
<td>41 - Drainage System</td>
<td>501 - Structural Roof</td>
<td>61 - Site Drainage</td>
</tr>
<tr>
<td>411 - Sewer</td>
<td>502 - Beams</td>
<td>62 - Site Topography</td>
</tr>
<tr>
<td>4111 - Sanitary</td>
<td>5021 - Structural</td>
<td>63 - Utility Connections</td>
</tr>
<tr>
<td>4112 - Storm Water</td>
<td>5022 - Ties</td>
<td>64 - Landscape Information</td>
</tr>
<tr>
<td>412 - Waste</td>
<td>503 - Slabs</td>
<td>65 - Soil Information</td>
</tr>
<tr>
<td>42 - Fire Protection</td>
<td>5031 - One-Way</td>
<td>66 - Previous Site Usage</td>
</tr>
<tr>
<td>421 - Fire Suppression</td>
<td>5032 - Two-Way</td>
<td>67 - Building Atmosphere</td>
</tr>
<tr>
<td>4211 - Suppression</td>
<td>51 - Foundation</td>
<td>671 - Traffic Flow</td>
</tr>
<tr>
<td>4212 - Detection</td>
<td>511 - Deep</td>
<td>672 - Surrounding Environment</td>
</tr>
<tr>
<td>4213 - Alarm</td>
<td>512 - Shallow</td>
<td>673 - Maneuverability &amp; Access Space</td>
</tr>
<tr>
<td>422 - Stand Pipes</td>
<td>52 - Vertical</td>
<td>674 - Building Shape &amp; Orientation</td>
</tr>
<tr>
<td></td>
<td>521 - Columns</td>
<td></td>
</tr>
<tr>
<td></td>
<td>522 - Walls</td>
<td>68 - Building Layout</td>
</tr>
<tr>
<td></td>
<td>523 - Suspended Cable</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.4: Code Structure for Discipline Breakdowns
practice, and the case study application. For specific codes, values representing the organizations/ facility team/ mechanisms can be used for identifying the companies hired for performing work portions.

12. Building Level Identification: this classification provides the distinction for which the information elements are associated to the Architectural Building level hierarchy - building spatial system. For specific codes, a generic stem is used to differentiate among the various levels of detail. Figure 4.5 shows the basis for this breakdown with the alphanumeric code distinctions given in bold letters. These code distinctions should precede any coding given to an item so as to quickly give a user a frame of reference, in relation to what part of the building the information affects.

13. Assembly Identification: This classification identifies groupings of objects/ components as they would be identified by a trade (i.e., unit assemblies). The coding scheme for this function consists of the UCI division number (i.e., five-digit codes for trade/ work divisions), whereby physical components are logically grouped into actual construction phases. Sub-classifications for this category might include connection methods (i.e., welding, nailing, etc.) and packaging information.

14. Site Information: this classification identifies all information elements which define the site for a project. An example of the
Figure 4.5: Field 12 - Generic Alphanumeric Code Stems
possible categories for this information was provided in chapter 3 - Figure 3.11.

4.4.2 Specific Code Format

The specific codes used in the PMA code structure scheme, were based on the classification and coding schemes presented in chapter 2. Fields 15-20 are used to store specific information, based on the characteristics applicable in Module 4 - Product Information. The definitional parameters for these specific code formats are:

15. Component Identification
16. Material Identification
17. Part Identification
18. Frame Identification
19. Date/ Time
20. Revision Number

Definitions for these fields are:

15. Component Identification: this classification identifies the clusters of components/ sub-assemblies which make-up a functional object or assembly and their location in relation to the building level or more specifically the Room Identification. Components may be listed by either a manufacturer's serial number or by a bar code number, or
the Uniform Construction Index's five digit code. A sub-classification for this field may include dimension aspects of the component.

16. Material Identification: this classification element is a subelement of the component identification and is used for describing components which are impractical for numbering/coding (i.e., floor tiles, bricks, bulk quantities, etc.). The coding scheme used for materials consists of the third facet used in the SfB system (presented in Figures 4.6 and 4.7). Along with the material descriptions, quantities are provided in the unit of measure commonly used for describing the item. The only rule for classifying materials is that they be coded only by the dominant material of which they are made. In addition, the materials identification may contain a subclassification for dimensions.

17. Part Identification: this classification pertains to common elements which are used for composition of a component (i.e., rebar, screws, bolts, nuts, etc.). Parts are considered to be manufactured from one element of original material. A subclassification for this field could include tolerances.

18. Frame Identification: this classification provides a unique number for each frame created so that queries can be made based on an indexing system. Values for this field are from 1-n.

19. Date/Time: this key attribute provides the mechanism for searching all information elements contained in the frame structure (see Figure 4.1). Thus, if an owner wants to know what information elements
### e. Natural Stone
- e1 Granite and igneous
- e2 Marble
- e3 Lime stone (other than marble)
- e4 Sandstone
- e5 Slate

### f. Formed (Precast) Concrete, etc.
- f1 Sand lime concrete
- f2 Heavyweight concrete (precast)
- f3 Terrazzo (precast) etc.
- f4 Lightweight concrete (precast)
- f5 Lightweight aggregate concrete (precast)
- f6 Asbestos-based materials (preformed)
- f7 Gypsum (preformed)
- f8 Magnesium based materials (preformed)

### g. Clay, in General
- g1 Adobe, cob, pise
- g2 Fired clay
- g3 Falence
- g6 Heat-resistant material, refractory ware fireclay

### h. Metal in General
- h1 Cast iron
- h2 Steel
- h3 Steel alloys including stainless steel
- h4 Aluminium alloy including aluminium
- h5 Copper
- h6 Copper alloy
- h7 Zinc
- h8 Lead
- h9 Tin, chromium, etc.

### i. Wood (Including Rot-Proofed) in General
- i1 Timber (unwrot)
- i2 Wrot soft wood
- i3 Wrot hardwood
- i4 Laminated wood, plywood

### J. Natural Fibres & Chips, Leather
- j1 Wood fibre, wood particles
- j2 Paper
- j3 Vegetable fibres
- j6 Animal fibres and leather
- j7 Mixed natural/synthetic fibres
- j8 Wood wool

### m. Mineral Fibres in General
- m1 Mineral fibres

### n. Plastics, etc.
- n1 Asphalt (preformed)
- n2 Impregnated fibre & felt
- n4 Linoleum
- n5 Rubbers (natural & elastomers)
  - a rubbers general
  - b natural rubbers
  - c chloroprene polymers
  - d isobutylene polymers
  - e polysulphides
  - f other rubbers
- n6 Plastics in general including synthetic fibres
  - a thermoplastics general
  - b polyvinylchloride (PVC) general
  - c unplasticized PVC
  - d plasticized PVC
  - e other vinyl polymers, PVA
  - f LD polyethylene
  - g other olefin polymers - polypropylene
  - h styrene polymers
  - i acrylic polymers
  - k other thermoplastics
  - o thermosets general
  - p phenolics
  - q melamines
  - r urea formaldehyde
  - s polyesters
  - t epoxides
  - u polyurethanes
  - y composites
  - z plastics and rubbers described together
- n7 Cellular plastics
- n8 Reinforced, laminated plastics

---

**Figure 4.6: Material Codes e-n**

[Construction Indexing Manual, 1968, pp. 82-83]
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>o1</td>
<td>Clear, Coloured</td>
</tr>
<tr>
<td>o2</td>
<td>Translucent, coloured, foamed</td>
</tr>
<tr>
<td>o3</td>
<td>Opal, Opaque, coloured, foamed</td>
</tr>
<tr>
<td>o4</td>
<td>Wired (all types)</td>
</tr>
<tr>
<td>o5</td>
<td>Multiple glazed</td>
</tr>
<tr>
<td>o6</td>
<td>Heat, X-ray absorbing, rejecting</td>
</tr>
<tr>
<td>o7</td>
<td>Mirrored</td>
</tr>
<tr>
<td>o8</td>
<td>Toughened (clear &amp; opaque)</td>
</tr>
<tr>
<td>o9</td>
<td>Cellular, foamed in general</td>
</tr>
<tr>
<td>p</td>
<td>LOOSE FILL, AGGREGATES IN GENERAL</td>
</tr>
<tr>
<td>p1</td>
<td>Natural fills, aggregates</td>
</tr>
<tr>
<td>p2</td>
<td>Artificial (processed) aggregates (heavy)</td>
</tr>
<tr>
<td>p3</td>
<td>Artificial (processed) aggregates (light)</td>
</tr>
<tr>
<td>p4</td>
<td>Ash</td>
</tr>
<tr>
<td>p5</td>
<td>Shavings</td>
</tr>
<tr>
<td>p6</td>
<td>Powder</td>
</tr>
<tr>
<td>p7</td>
<td>Organic, mineral fibre loose fills</td>
</tr>
<tr>
<td>p8</td>
<td>Plastic fills</td>
</tr>
<tr>
<td>q</td>
<td>CEMENT, MORTARS &amp; MASS (IN SITU) CONCRETE</td>
</tr>
<tr>
<td>q1</td>
<td>Lime</td>
</tr>
<tr>
<td>q2</td>
<td>Cement-Portland cement in general</td>
</tr>
<tr>
<td>q4</td>
<td>Mortar, heavyweight concrete in situ</td>
</tr>
<tr>
<td>q5</td>
<td>Terrazo etc: concrete w/ special aggregates</td>
</tr>
<tr>
<td>q6</td>
<td>Lightweight concrete: lightweight concrete in situ and in general</td>
</tr>
<tr>
<td>q7</td>
<td>Lightweight aggregate concrete in situ &amp; in general including sawdust concrete</td>
</tr>
<tr>
<td>q9</td>
<td>Asbestos-based materials in general</td>
</tr>
<tr>
<td>r</td>
<td>GYPSUM, SPECIAL MORTARS, ETC.</td>
</tr>
<tr>
<td>r1</td>
<td>Clay mortar, chemically resistant mortar, fire-resistant mortar</td>
</tr>
<tr>
<td>r2</td>
<td>Gypsum</td>
</tr>
<tr>
<td>r3</td>
<td>Magnesium based materials</td>
</tr>
<tr>
<td>r4</td>
<td>Synthetic bonded mortars plastics binders</td>
</tr>
<tr>
<td>s</td>
<td>BITUMINOUS MATERIALS</td>
</tr>
<tr>
<td>s1</td>
<td>Bitumen, pitch, tar basic materials, also paints and emulsions</td>
</tr>
<tr>
<td>s4</td>
<td>Mastic asphalt: small or no aggregate</td>
</tr>
<tr>
<td>s5</td>
<td>Rolled asphalt, bitumen macadam, tar macadam: large aggregate</td>
</tr>
<tr>
<td>t</td>
<td>FIXING AND JOINTING AGENTS, COMPOUNDS</td>
</tr>
<tr>
<td>t1</td>
<td>Welding material</td>
</tr>
<tr>
<td>t2</td>
<td>Soldering material</td>
</tr>
<tr>
<td>t3</td>
<td>Adhesives, bonding agents, animal glues</td>
</tr>
<tr>
<td>t4</td>
<td>Putty, mastics, jointing materials, etc.</td>
</tr>
<tr>
<td>t5</td>
<td>Fastenings in general</td>
</tr>
<tr>
<td>t6</td>
<td>Permanent fastenings</td>
</tr>
<tr>
<td>t7</td>
<td>Ironmongery, hardware in general</td>
</tr>
<tr>
<td>u</td>
<td>PROTECTIVE MATERIALS</td>
</tr>
<tr>
<td>u1</td>
<td>Anti-corrosive materials, treatments in general</td>
</tr>
<tr>
<td>u2</td>
<td>Concrete admixtures in general workability aids</td>
</tr>
<tr>
<td>u3</td>
<td>Materials, treatments for prevention of insect attack, etc., and rot-proofing materials in general</td>
</tr>
<tr>
<td>u4</td>
<td>Flame-retardent materials, treatments in general: means for improving fire resistance</td>
</tr>
<tr>
<td>u5</td>
<td>Surface treatment materials, treatments in general</td>
</tr>
<tr>
<td>u6</td>
<td>Water-repellent materials, treatments in general</td>
</tr>
<tr>
<td>v</td>
<td>MATERIALS FOR PAINTS, ETC.</td>
</tr>
<tr>
<td>v1</td>
<td>Stopping, paint fillers, etc.</td>
</tr>
<tr>
<td>v2</td>
<td>Pigments, stains, etc.</td>
</tr>
<tr>
<td>v3</td>
<td>Oils</td>
</tr>
<tr>
<td>v4</td>
<td>Varnish: varnish &amp; lacquers finishes other than paints</td>
</tr>
<tr>
<td>v5</td>
<td>Paint: complete paint systems other than varnish, emulsion &amp; cement paints</td>
</tr>
<tr>
<td>v6</td>
<td>Emulsion paints</td>
</tr>
<tr>
<td>v8</td>
<td>Cement paint, lime wash</td>
</tr>
<tr>
<td>v9</td>
<td>Metallic paints</td>
</tr>
<tr>
<td>w</td>
<td>OTHER CHEMICALS</td>
</tr>
<tr>
<td>w1</td>
<td>Rust-removing agents</td>
</tr>
<tr>
<td>w2</td>
<td>Solvent, thinner, drying agent, emulsifying agent, etc.</td>
</tr>
<tr>
<td>w4</td>
<td>Water</td>
</tr>
<tr>
<td>w5</td>
<td>Acids and Alkalies</td>
</tr>
<tr>
<td>w6</td>
<td>Fertilizers, sprays, etc.</td>
</tr>
<tr>
<td>w7</td>
<td>Soaps, detergents, cleaning powders</td>
</tr>
<tr>
<td>x</td>
<td>PLANTS</td>
</tr>
<tr>
<td>x1</td>
<td>Trees</td>
</tr>
<tr>
<td>x2</td>
<td>Shrubs</td>
</tr>
<tr>
<td>x3</td>
<td>Non-woody plants</td>
</tr>
<tr>
<td>x4</td>
<td>Special plants</td>
</tr>
<tr>
<td>x5</td>
<td>Turf grasses and plants</td>
</tr>
<tr>
<td>y</td>
<td>MATERIALS IN GENERAL</td>
</tr>
</tbody>
</table>

Figure 4.7: Material Codes for o-y
are generated during a given period of time, the frames created could be listed. The syntax used to represent this attribute is: YYYYMMDD. HHMMSS. The syntax is explained as follows: YYYY = year; MM = month (01-12); DD = day (00-31); HH = hours (00-23); MM = minutes (00-59); and SS = seconds (00-59).

20. Revision Number: this classification provides a status check on the most recent occurrence of a change, so that the chance of errors made by users are reduced. Values for this field are from 1-n.

4.4.3 Frame Structure

The frame concept developed by Minsky [1975] is the data structure being used for representing and describing an object or an event. The frame structure consists of field names and field values which provide the representation mechanism for all product elements (i.e., Function, Form, Economy, Time, and Factors - defined in chapter 3). Figure 4.1 shows the structure for the frame and its generic elements. Based on the discipline and activity, the propriety of attributes for each frame would change on a case-by-case basis. It is, however, possible to identify universal attributes for frames at each level based on field value identifications for each module in the IA (i.e., Identification numbers for Process, Product, Project, Knowledge/ Alternatives, External Information, and Resource Information). The exact usage of these attributes would depend on the field identifications utilized. From this, generic and specific codes could be used as query attributes for finding relevant frames. Thus, similar field values would indicate frames which contain other frames.
The frame structure used is divided into six areas of information storage (see Figure 4.1). The first area is made up of generic and specific code fields for each module in the information architecture. For this work, only the product and process modules are covered. The Factors attribute makes up the second area and this serves to capture the intent behind the decision making; this information may be stored in the form of design calculations, spreadsheet programs (i.e., listing variables and selections), rules (parameter, logic, and cost driven, or static in nature), constraints, etc. The Function attribute constitutes the third area, and this serves to capture the intended purpose and/or requirements for the product abstraction level being planned/ designed/ constructed/ operated. The Form attribute constitutes the fourth area, and this describes the make-up of the solution for the product (be it graphic or written). The Economy and Time attributes make-up the fifth and sixth areas respectively, and these provide information which relate the cost and duration perspectives for the functions/forms being represented.

As an example of a frame, consider the Electrical discipline at the Room level. The function can be stated in terms of lighting requirements, telephone needs, etc. The Form attribute/frame would include layout of wiring, fixture locations, and electrical equipment located within the room. Economy and Time values might include total cost prices and durations for installment. The Factors attribute could contain information regarding reasons behind selection of equipment and fixtures. It is important to note that the attributes can take on any format for representing product data.
4.5 Rules for Coding

Two rules are used to control coding of information elements. The first rule for controlling coding of building information elements is that the phase of development dictates the degree of information storage. In other words, at the conceptual design phase only the Building level may be stored, for the schematic design phase the System level would be stored, etc. In terms of responsibility for coding, the chief architect codes all items at the system level, and the discipline heads code all items below the system level.

The second rule is that information is only stored once; at the level above which it is shared. This rule is used to eliminate redundancy in data storage. In the case where occurrences of products take place across several building levels, only generic codes are specified. The specific codes are used for recording occurrence of products/information at specific levels of detail.

4.6 Summary

This chapter discussed the proposed PMA classification and coding scheme, and selected the hybrid code structure. The twenty digit code was developed. Fourteen fields are generic, and six are specific. Each of the fields is defined here. The structure of the data storage is the frame, and coding rules are mentioned.

It is important to note that this chapter only provides a procedure/guideline in which a user can develop a tailored coding system which allows for a fit within the overall generic code framework. The benefit of this coding
schema is its allowance for design methodology (abstraction of details based on spatial systems) and its basis for a storage structure of information elements. A disadvantage of this coding schema is found in the number of fields that exist. However, it is felt that through implementation - a menu-driven feature can possibly eliminate the redundancy of re-keying repetitive codes for various users.

Demonstrations and benefits of this coding and classification scheme are presented in chapter 5.
Chapter 5

CASE STUDY

5.1 Overview

A case study was used to illustrate the adequacy of the PMA data structure scheme at capturing information. This chapter will show how to use frames at different levels of abstraction for describing building details. It describes the benefits gained from use of the PMA and the classification and coding scheme, and evaluates the criteria required for having an effective information framework.

5.2 Linking of Frames

The case study used for representing frame abstraction levels is a 2.9-million dollar, 50,000 square foot, four-story multi-purpose building comprising administrative offices, laboratories, and supporting facilities. The building is located in central Pennsylvania, and is owned and operated by an organization which owns many buildings. The case study data was collected from drawings, specifications, and files of the subject project. Information used from these data sources was mapped onto frames using the product model architecture. The data on the frames was then coded according to the scheme presented in
chapter 4. The examples presented in this chapter are sample frames for each of the Building levels.

Linkage of the frames occurs through the codes and revision numbers used. Whereby frames would be clustered based on the generic and specific codes, and the IBPM process phases used; for each building level abstraction. Thus, changes or evolutions of product decisions can be tracked as they evolve through life cycle facility development, through the various code values.

Examples of the information elements might be photographs, memos, drawings, contracts, etc., which are contained on a frame. In this case where fields do not apply for descriptions of the information elements, dashes will be used to indicate that the field is not being used. The frames could not be filled in completely because the design information was extracted from detailed drawings, thus no Factors are given (intent is missing).

5.3 The Case Study

Figures 5.1 to 5.7 show storage of data for a Building, Floor, Room, Electrical Discipline, Component, and Material. Through use of the generic and specific codes on these frames, a simple and consistent method for making information accessible is obtained. Figure 5.1 has a generic product information code (C3 • D • 1 • 10 • -) which means the following:

- **C3** Project Type - University building (field 1).
- **D** Information Type - Product information (field 2).
- **1** Discipline Identification - Architectural (field 11).
Figure 5.1: Building Level Information for the Hallowell Project
Figure 5.2: Second Floor Information for the Hallowell Project
**Figure 5.3: Room 228 Information During Design for the Hallowell Project**
Figure 5.4: Room 228 Electrical Layout Information for the Hallowell Project
Figure 5.5: Electrical Component Information for Room 228 - During Design

| B4.0: | 4’
| B4.1: | 0’
| B3.0: | 2’
| B3.1: | 2’

- **Luminaires in Room 228**
  - Form (con'd)
  - 50 Footcandles at Working Plane
  - 4’ x 4’ Fixture Dimensions: 2 x 4’
  - 2 Lamps T-12 36W: RS
  - 6 Luminaires
  - Lutron Ballasts No. 245
  - Catalog No. 32561

- **Factors**
  - Generic: C3 • D • 302 • 1113
  - Specific: 1606 • D • RM228
  - Process ID: D.5.1

- **Revision No.**
  - 0

- **Date/Time**
  - 19980306.100754
### Luminaires in Room 228

<table>
<thead>
<tr>
<th>Generic</th>
<th>1606 • D • RM228 • 32561 • C.2.1.3</th>
</tr>
</thead>
</table>

| Specific   | Frame ID 26.2 | Revision No. 20 |

<table>
<thead>
<tr>
<th>Function</th>
<th>Form</th>
<th>Economy</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Change</td>
<td>No Change</td>
<td>$40/ Fixture</td>
<td>Rough Wiring - 3 Hrs.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.15/ Ft. of Cable</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$5/ Switch</td>
<td>Fixture Installment - 3 Hrs.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Cost $260</td>
<td></td>
</tr>
</tbody>
</table>

**Factors**

**Time**

- Rough Wiring - 3 Hrs.
- Fixture Installment - 3 Hrs.

**Economy**

- Lutron Fixture
- Mfg. Serial # 00123823

**Date/Time**

- 19900331.122633

---

**Figure 5.6: Electrical Component Information for Room 228 - During Construction**
Figure 5.7: Material Information for Room 228 - Hallowell Project
Building Level Identification - Building (field 12).
- Assembly Identification (CSI five digit codes) - None (field 13).

This figure also has a specific product information code (1606 • D • • B3 • • • • • •) meaning that the project number is 1606, and that it pertains to zone B3 of the building level. A process identification (D.2.1) is also used to show it is a conceptual design. The date, revision number and frame identification are unique identifiers. Functional requirements are specified for the building. A building elevation is part of the form, and a target of $40 per square foot or $2,000,000 is set as a goal. The project duration time is set for twenty-four months. These information elements are stored at this level only.

The next level, the second floor (shown in Figure 5.2), then has functional requirements for that floor only. A footprint (schematic design - process code D.3.1) is shown for the form. No new cost/time information is available. Figure 5.3 shows information relating to room number 228, which was done during the detailed drawing phase. An electrical layout for the same room is shown in Figure 5.4, and one luminaire is defined in detail as a frame in Figure 5.5. One should note that the generic and specific codes expand as the detail level increases. Figure 5.6 shows additional information generated during construction in the economy and time cells; additionally, a generic assembly code is given to show an interior lighting fixture assembly (16510). There have been no function and form changes. Figure 5.7 shows an example of material information pertaining to room 228; here a material identification (r2) is used to show the resource type.
5.4 Use of the PMA

Information is inherited between the abstraction levels based on the code digits used for storing the information elements on frames. In other words, having a single digit for the discipline identification would connote storage at the building level, having two digits would connote storage at the system level, three digits at the subsystem level, four digits would signify a component type/category, and five digits or more would be a specific bar code or manufacturer serial number for components. This breakdown combined with the six discipline breakdowns provides the overall structure for inheritance of product information items.

5.5 Meeting the Criteria for an Effective Information Framework

The product model architecture was meant to satisfy the following seven conditions (explained in more detail in Chapter 3) to effectively support the developer in managing construction projects:

1. Provide a consistent structured way to represent product data.
2. Define PMA in an open and conceptual fashion.
3. Be comprehensive.
4. Capture intent effectively.
5. Provide a link to the process model.
6. Account for process constraints.
7. Portray environmental conditions.
Each of these criterion is explained in the subsequent paragraphs.

The first criterion is achieved through the logical breakdown for classifying building product information - i.e., the building's spatial decompositions as seen from the architectural view. Additionally, discipline breakdowns are provided for structuring building product information between disciplines so that they may be linked to the product model architecture.

The second criterion is met through the modular arrangement which constitutes the information architecture. The six modules are: process information; product information; project information; knowledge/alternatives; external information; and resource information. These modules combine to support multiple hierarchies in the PMA. By structuring information in multiple hierarchies, information can be broken up into several ways through orthogonal decompositions.

The third criterion has not been fully tested since it is primarily an implementation issue. Only the software and hardware systems can determine the capability for handling all types of information elements (photographs, verbal communications, documents, etc.). However, the data structure for supporting all information types has been achieved. All disciplines and all levels of detail are accounted for in the PMA.

The fourth criterion involves capturing intent effectively. This is achieved through the attributes provided in the frame structure. The attributes (Function, Factors, Form, Economy, and Time) provide a vehicle which respects the ways of thinking and working among various disciplines.

The fifth criterion is achieved through a process code which is based on the IBPM. The five stages of providing a facility relate directly to the stages in
the IBPM. This code can be especially useful in the operations stage of a facility for communicating critiques.

The sixth criterion is accounted for by the external information and IBPM modules. The external information module was not developed (outside the scope of research), however, the IBPM provides generic constraints which affect provision of facilities.

The seventh criterion relating to environmental conditions is represented by the civil discipline breakdown as it applies to site information. This also was not developed in detail, and is only presented to show a possible breakdown for information elements relating environmental conditions.

5.6 Benefits of the PMA Based Classification and Coding Scheme

The classification and coding scheme has several advantages for the project developer/master builder providing facilities. The following sections provide descriptions of how the PMA based classification and coding scheme can benefit the construction industry.

5.6.1 Historical Database

Through implementation, the PMA should provide a master builder database of all building objects and information elements used to describe the building product in the process of providing a facility. The PMA provides a structure for storing information such that a life-cycle database environment can be established. The benefit this provides an owner is the means by which he/
she can inherit and manage information for a project/building, facilitating operation, construction and retrofit.

5.6.2 Common Search and Retrieval Language for the Building Team

The generic and specific codes which define the code structure can be used for tracking information items. Using the code attributes and through use of the PMA scheme, two different ways are provided for accessing the information elements requested by the users. This information framework system should make extraction of useful information faster than the traditional method. Currently, users have to search through various media to find the answer to various questions that arise by the various viewpoints of the project participants. In this system however, the division of information is based on discipline breakdowns and building levels. Through implementation, a project index can be developed (through use of fields and entity relationship diagrams) so that objects can be cross-referenced. Queries can be made based on sorting of the generic and/or specific code fields, this way every user can receive the information in the manner by which he/she prefers/desires/needs.

Through use of the PMA scheme and the code structure a common language is obtained between and among all facility team members. Through use of this language a vocabulary is established for making distinctions and it is the distinctions that the facility team draws upon that make the product/facility. This could lead to effective communication among the participants and a reduction of the risk of errors and misunderstandings.
5.6.3 Design Support

The classification and coding scheme can be used by designers for archiving drawings, retrieving standardized design components (for re-use), and detecting missing information. By querying components, drawings, projects, etc., designers will be able to retrieve any predefined object stored in the past. Through development of the Knowledge database, alternatives can be used for comparison purposes, of previous and current projects, based on given Function, Form, Economy, Time, and Factor perspectives. These queries can serve to ensure that certain factors used in design (i.e., insulation, sound, and light parameters) are not missed. In other words, a checklist of information requirements for various design types can be used based on previous project experiences.

5.6.4 Multimedia Storage Support

Through use of the frame concept allowance is made for the incorporation of various multimedia sources. Examples of multimedia types could be such things as: photographs, computer-aided drawings, digitized text, voice recordings, scanned images/text, computer applications, spreadsheets, graphs, etc. Users benefit from this storage of multimedia by the fact that building related ideas/information can be represented in their full context; through correspondence to perceptual objects stored on frames. This then enables a user to manipulate ideas/information and their relationships by directly manipulating frames.
5.7 Additional Benefits

These frames when combined with an information model structure can be used by a project developer for providing the following advantages:

1. Information structuring - organized linking of building product information.
2. Global views of building information elements - based on mixed code queries.
3. Modularity of information - by allowing information to be referenced from several places, concepts can be expressed with less clutter and duplication.
4. Consistency of information - in the sense that all frames can be accessed through code links entered (generic and specific). The codes provide a filter so that a user can shift the view or abstraction of detail.

5.8 Summary

This chapter attempted to show that frames can be used to convey and store graphical and textual information or knowledge about data in the form of entities, attributes, and relationships. The concept behind using frames as the storage media is that objects, ideas, facts, and evidence can be directly associated with perceptual objects of a facility as represented on a frame. The
storage media is defined as the frame structure and the storage code is described by the PMA and the coding structure.

The advantage of the frame concept is to specify a medium from which information can be captured comprehensively and effectively. The attributes that make up the frame structure comprehensively represent information used by various disciplines. This should aid all users affected by building information, since it is well represented information which is the key resource in decision making. The flexibility that the frame structure provides is found by the way the attributes allow a user to preserve data in its full context.

The disadvantage of the PMA is that it does not allow for multiple inheritance, whereby information can be organized in different ways depending on differing viewpoints. In other words, data can be viewed only from the single dimension of the affected disciplines; no cross-referencing of information across disciplines can take place. Additionally, there is no mechanism for tracing connections between frames, so if changes are made to functions or other attributes, there would be no way for making real-time changes on the data. Furthermore, there is the problem of disorientation on the part of the user in the sense that he/she may not be able to find what he/she does not know exists. This is due to the fact that intent and other information types may be dispersed across many frames.
Chapter 6

SUMMARY AND CONCLUSIONS

6.1 General Statement of the Problem

The purpose of this thesis is to develop and illustrate a master builder information framework for project developers. Specifically, a generic framework for representing and organizing building product information is presented along with a coding scheme for finding and coordinating information among various users. The thrust of this effort is to integrate discipline views with the levels of detail in representing AEC products so that integration is achieved between the top-down and bottom-up approaches used in the construction industry.

6.2 Summary

In this thesis study three questions were specifically addressed, they are:

1. What information does a facility champion need to coordinate to get a facility built?
2. What framework is needed to coordinate building information among facility team members?
3. How do facility team members find the required information that describes a building?

These questions were answered by achieving the following five objectives:

1. The first objective involved identifying the information required to control the product, this was achieved through a comprehensive review of existing product models, and an analysis of the IBPM.

2. The second and third objectives concerned development of the conceptual product model architecture. The product model architecture combines various discipline views through a common hierarchy of a building's architectural features. This hierarchy serves in providing different levels of building detail. Information is represented by the generic attributes of Function, Form, Economy, Factors, and Time using frame like data structures. Overall, the PMA provides a logically organized information management structure which allows for integration between system disciplines as well as abstraction of building level details in representing building products/ information; through a series of data structure frames.

3. The fourth objective entailed development of a coding and classification scheme for storing and retrieving information in the
PMA. This scheme consists of twenty fields comprising generic and specific classifications.

4. The fifth objective involved demonstrating the master builder information framework system. This was achieved by showing how abstraction of building levels can be represented using frames.

It is felt that an environment for integration and coordination among facility participants has been established. Integration is achieved by organizing and linking the product information to the process information through use of the PMA and the IBPM.

6.3 The PMA’s Comparison to Relevant Product Models

Of all the product models discussed in Chapter 2, only two were relevant for comparison. These two are Gielingh’s GARM model and Turner’s Building Systems Model. They are the only models which address buildings as a whole, from a life-cycle point of view.

6.3.1 Gielingh’s GARM Model

The most comprehensive existing product model is Gielingh’s GARM model. In comparison to this work there appear to be several differences.
The first difference is in the number of entities used for representing the products, GARM allows for an explosive growth of entities which makes the information structure of the product very complex. The PMA allows for only six attributes which are represented by the following attributes: Function; Form; Economy; Time; Mechanism; and Factors.

The second difference is seen by the way data views are used for defining characteristics of products. GARM allows for views of products based on aspects (i.e., strength) whereas the PMA allows for views based on disciplines. Both ways work, Gielingh uses a bottom-up approach (in relation to views of products) and the PMA takes a top-down approach. However, the top-down approach is advantageous because it classifies aspects based on the processes and hierarchical categories of the IBPM, whereby the functions allow for mutual exclusion. The mechanisms in the IBPM define the disciplines and from there characteristic aspects (of the applicable discipline) are provided by the Factors frame (criteria used for design of products).

A third difference is found in the classification of life cycle stages used between the two models. Gielingh provides for seven life cycle stages and the PMA allows for five - based on the IBPM. The merits of both are evident but the IBPM is process oriented, more detailed, and easier to follow based on the levels of abstraction provided, additionally the model has been validated.

The fourth difference concerns the issue of redundancy, GARM solves this by having level discriminators (generic, specific, and occurrence). The PMA deals with the issue of redundancy by only storing information once - where it occurs in relation to the spatial breakdown of a building. In other words, information is stored at the level above which it is shared. Additionally, all
changes made are linked through frames using the generic and specific codes. Whereby the generic codes store information applicable to more than one level of building detail, and the specific codes relate occurrence of products/information as it applies to a specific level of detail (i.e., a particular room).

The fifth and most significant difference is found in the manner by which the two models unite different user viewpoints. The PMA provides a common denominator for the integration of disciplines through the architectural view of buildings. GARM on the other hand, only connects functional units which belong to the same technical solution, and no basis is given for integrating technical solutions among different disciplines.

6.3.2 Turner's Building Systems Model

In relation to Turner's building systems model the only benchmark for comparison relates to the classification of building system breakdowns. Turner's model classifies systems and subsystems based on divisions of active and passive systems, whereas the PMA classifies the systems based on industry practice (architectural, structural, HVAC, plumbing, electrical, and civil disciplines). There are benefits to both methods, but from an implementation point of view the practice oriented method seems to be more conducive to industry acceptance.
6.4 Areas Required for Extending the PMA

The limits of the PMA consist of the following items:

1. The structural breakdown is based on geometry and not function for linkage to the building levels breakdown.

2. The PMA can only be used for building construction projects.

3. The PMA does not account for any type of approval authority/ status attribute(s).

4. Characterizations of Form (i.e., representation formats for shape, topology, geometry, etc.) are not covered, and are considered to be an implementation issue.

5. The PMA does not deal with coordination among disciplines (i.e., sequential design development priorities by the disciplines).

6. The PMA does not cover connection methods between objects.

7. The frame structure in the PMA is not suitable for use in the conceptual design stage.
6.5 Recommendations for Further Research

As a result of this study, the author considers the following areas related to implementation of the PMA, to be of major importance in terms of future research and study efforts:

1. Breakdowns of each remaining information architectural module.
2. Computer implementation of the PMA and coding scheme.
3. Full-scale testing of the PMA and classification and coding scheme.
5. Development of contractual methods/ guidelines for effective utilization of the PMA.
6. Classification of mechanisms available/ required for provision of facilities.
7. Examination of implementation barriers for introducing and transferring the product model architecture to industry.
8. Evaluation of applications of other modeling methods to complement the product model architecture.

These areas are by no means exhaustive. They are, however, important problems for continued research. The following paragraphs will present the concepts behind each of the areas mentioned above.

All the information architecture modules need to be defined in order to achieve a comprehensive product model. In order for the information system to
be really effective all information elements need to be defined so that there are
less problems with integration.

Computer implementation of the PMA and classification and coding
scheme needs to be constructed. By working out implementation issues, further
refinements can be made to the PMA and coding scheme, thus providing a
better system.

Testing of the information system needs to be performed once
implementation is completed so as to work out any particular circumstances
which may affect effectiveness of the overall system.

System discipline breakdowns refer to decompositions of all the systems
involved in providing a facility. This research narrowed the disciplines down to
six, and this showed very good results. But further research is needed to obtain
a recognized standard of system breakdowns by discipline. If all parties
involved in the building process were to agree on the classification of building
elements, then integration among disciplines would be facilitated. This work
would involve development of good definitions, which would need to be
consented to by the AEC industry, so that no misunderstandings are prevalent.

Another area of research relates to introduction of new contractual
methods/ guidelines that are needed to control usage of the PMA. An example
of this might be in the area of design. Designers of systems for a facility would
need to have control over any design changes that are made, and this would
necessitate the use of security measures in an integrated database. This way,
facility participants would be given the capability of read only, read and write,
etc., depending on who is accessing the database. In essence, new contracts
would probably need to be written in a manner which will prescribe the activities
of the parties affected in providing a facility, so that errors and omissions are avoided. Thus, by following a guideline on methods and procedures, all affected parties would be aware of their responsibilities. At the same time accountability can be secured for all product decisions made; at all stages of a facility life cycle. This is important because the minute duties are shared between project participants, and questions arise about who is responsible for what.

Mechanism refers to the people who will be executing the functions required in providing a facility - as they relate to the PMA. A systematic study needs to be performed to assess impacts of staffing the necessary system disciplines so that strengths and weaknesses can be understood. Through an understanding of what it takes (how and who - organizationally) to make a project successful, processes can be performed more effectively. These mechanisms can also relate to computer applications, such as expert systems which solve various problems.

Research is required to look at potential problems that may be encountered in the use of this scheme by industry so that a smoother transition can be made. An assessment of possible obstructions in getting the idea accepted and implemented in the shortest time possible, and in the most effective way possible is essential. One aspect of this research would be to select the prototype companies which would be suitable as test cases for the product model architecture.

The last area of research refers to applications of other modeling methods to complement the product model architecture. This includes incorporating features from other models which will contribute in fully defining
the AEC product model architecture. One model that is being considered is the Systems Distributions Model [Martin, 1989].

6.6 Conclusion

The main intent behind this work is to identify and organize geometric and non-geometric product data required for designing, manufacturing, constructing, and operating of the structured components which make up a facility so that it can be stored. The PMA combined with the coding scheme provides a structure from which users/disciplines can conceive of a database as being the core of what they are doing rather than a collection of documents. This is important, because it is becoming increasingly crucial to recognize that there should be a database accompanying a facility throughout its life cycle. Through the use of the frame concept and the PMA, a foundation is established for transforming the AEC industry’s point of view on the whole design process, from one that is primarily document-oriented towards one that is building-oriented, whereby a facility is described by its real objects in a manner that is as close as possible to the real object itself.

6.7 Closure

This thesis attempted to provide an integrated information management system to support the property developer in gaining a Master Builder perspective of the project, in so far as product information is concerned. This research has outlined the problem of integration between the top-down and
bottom-up approaches - it is theoretical work, and prototype implementation would need to be the subsequent step to take. The PMA provides a rational information structure, and the code structure provides a translation mechanism for storing, accessing/retrieving, and modifying information elements. Through use of the frame structure, a paperless environment is brought one step closer. From this research, it can be concluded that the construction industry needs to start looking at buildings through a code for disciplines. This research provides one datum and one perspective on how it might be done, it provides an information system which is based on the needs of the disciplines. By structuring information it becomes possible to link and group elements; identify missing information and effectively retrieve it for possible re-use.

Through development of a "Master Builder" database - a single database which will serve all facility team purposes - it is envisioned that a decision support system for facility development can be created. This work devised a micro-scale solution that may have macro-scale consequences. It was a holographic approach, in the sense that it entailed viewing the problem in three dimensions (spatial breakdown), at many different levels of detail and from various viewpoints, exploiting and uniting the perspectives of a host of disciplines. The construction industry is technologically immature when compared to other industries such as oil and manufacturing, and this needs to change. Hopefully this information framework can serve as a prototype/blueprint for implementation.
REFERENCES


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Appendix

IBPM FUNCTION CODES

M  MANAGE FACILITY

M.1 - Establish Management Team
   M.1.1 - Determine Internal Capabilities/ Operations
   M.1.2 - Develop Preliminary Facility Work Scope
   M.1.3 - Structure & Staff the Management Team

M.2 - Develop Work Scope and Needs
   M.2.1 - Understand Owner Needs
   M.2.3 - Define Facility Work Scope & Needs
   M.2.4 - Develop Strategy for Resource & Service Acquisition

M.3 - Plan/ Control Facility
   M.3.1 - Understand Work Scope and Performance Criteria
   M.3.2 - Develop Facility Management Plan
   M.3.3 - Administer Contracts & Purchase Order Agreements
   M.3.4 - Implement & Supervise Work (Contracts)
   M.3.5 - Monitor Facility & Progress
   M.3.6 - Analyze Performance of Facility

M.4 - Acquire Services to Provide Facility
   M.4.1 - Identify Services Needed
   M.4.2 - Identify Sources of Services
   M.4.3 - Prepare Invitation to Bid and Submit Proposal
   M.4.4 - Review Proposals & Select Agent/ Contractor
   M.4.5 - Execute Contracts and Agreements

M.5 - Acquire/ Provide Resources for Facility
   M.5.1 - Identify Resource Needs
   M.5.2 - Identify Sources of Resources
M.5.3 - Prepare Purchase Requisitions & Submit Proposals
M.5.4 - Review Proposals, Select Vendor, & Execute Purchase Orders
M.5.5 - Receive and Inspect Resources
M.5.6 - Distribute/ Store Resources & Manage Inventory

P PLAN FACILITY

P.1 - Assign Planning Team
P.2 - Study/ Define Needs
  P.2.1 - Study User Requirements
  P.2.2 - Evaluate Existing Facilities
  P.2.3 - Determine Needs
  P.2.4 - Generate Alternatives
P.3 - Study Feasibility of Alternatives
  P.3.1 - Study Economic Feasibility
    P.3.1.1 - Estimate Funding Requirements
    P.3.1.2 - Conduct Cost/ Benefit Analysis
    P.3.1.3 - Allocate/ Secure Funds
  P.3.2 - Study Technical Feasibility
    P.3.2.1 - Study/ Determine Technical Properties
    P.3.2.2 - Study Availability of Resources & Technology
    P.3.2.3 - Study Execution Possibility
  P.3.3 - Study Environmental Feasibility
    P.3.3.1 - Study Impact on Vicinity
    P.3.3.2 - Study Impact on Utilities
    P.3.3.3 - Study Impact on Community
    P.3.3.4 - Study Environmental Impact on Facility
  P.3.4 - Communicate Results/ Decisions
P.4 - Develop Program
  P.4.1 - Gather Information
  P.4.2 - Define Scope
  P.4.3 - Develop Design Criteria
  P.4.4 - Develop Site Criteria
P.4.5 - Communicate Program
P.5 - Develop Project Execution Plan (PEP)
  P.5.1 - Identify Required Services
  P.5.2 - Study Construction Market Conditions
  P.5.3 - Develop Project Plan
  P.5.4 - Develop Contracting Plan
  P.5.5 - Communicate Project Execution Plan
P.6 - Select & Acquire Site
  P.6.1 - Identify Candidate Sites
  P.6.2 - Evaluate and Select Site
  P.6.3 - Acquire Site
  P.6.4 - Investigate Site (For Design)

D  DESIGN FACILITY

D.1 - Understand Functional Requirements
  D.1.1 - Assimilate and Analyze Information
  D.1.2 - Establish Project Objectives
  D.1.3 - Establish Design Parameters
D.2 - Explore Concepts
  D.2.1 - Perform Preliminary Concepts
  D.2.2 - Prepare & Develop Concepts
  D.2.3 - Coordinate Concepts
  D.2.4 - Evaluate and Select Concepts
D.3 - Develop Systems Schematics
  D.3.1 - Develop Standard Systems Schemes
  D.3.2 - Coordinate to Find Compatibilities
  D.3.3 - Develop Integrated Schematics
D.4 - Develop Design
  D.4.1 - Perform Systems Development and Layouts
  D.4.2 - Perform Studies and Reviews
  D.4.3 - Develop Outline Specifications
  D.4.4 - Acquire Design Approval
D.5 - Communicate Design to Others
   D.5.1 - Develop Post-Design Drawings
   D.5.2 - Develop Post-Design Specifications
   D.5.3 - Perform Document Reviews
   D.5.4 - Deliver Post-Design Documents & Acquire Approval

D.6 - Maintain Design Information and Models
   D.6.1 - Collect Data
   D.6.2 - Store Data
   D.6.3 - Retrieve Data
   D.6.4 - Update Information
   D.6.5 - Transmit Information

C  CONSTRUCT FACILITY

C.1 - Acquire Construction Services
   C.1.1 - Identify Qualified Parties
   C.1.2 - Provide Work Scope Information
   C.1.3 - Prepare and Submit Proposals
   C.1.4 - Review Proposals and Select Constructor
   C.1.5 - Execute Contracts/ Agreements

C.2 - Plan and Control the Work
   C.2.1 - Develop the Construction Plan
      C.2.1.1 - Determine the Scope of Work and Coordinate the Planning
      C.2.1.2 - Select Work Methods
      C.2.1.3 - Estimate the Work
      C.2.1.4 - Schedule the Work Activities
      C.2.1.5 - Analyze the Plan
   C.2.2 - Implement the Plan
   C.2.3 - Monitor Performance
   C.2.4 - Analyze Performance

C.3 - Provide Resources
   C.3.1 - Mobilize
C.3.2 - Acquire Resources
C.3.3 - Receive and Inspect the Resources
C.3.4 - Store the Resources and Manage the Inventory
C.3.5 - Repair and Maintain the Resources
C.3.6 - Allocate the Resources

C.4 - Build the Facility
C.4.1 - Plan the Daily Work
C.4.2 - Distribute the Resources
C.4.3 - Do the Physical Work
   C.4.3.1 - Identify the Location for the Work
   C.4.3.2 - Set Up the Work Area
   C.4.3.3 - Prepare the Resources
   C.4.3.4 - Perform the Work
   C.4.3.5 - Clean Up the Work Area
C.4.4 - Inspect and Approve the Work
C.4.5 - Turn Over the Completed Work

O OPERATE FACILITY

O.1 - Manage Operations
   O.1.1 - Review Data
   O.1.2 - Plan Operations
      O.1.2.1 - Understand Operations Plan and User Needs
      O.1.2.2 - Schedule Operations
      O.1.2.3 - Determine User Needs
      O.1.2.4 - Assign Operations Execution Team
   O.1.3 - Acquire Operations Services & Resources

O.2 - Monitor Facility Condition and Systems
   O.2.1 - Select Critical Points/ Areas to Monitor
   O.2.2 - Select Monitoring Mechanism
   O.2.3 - Collect Data
   O.2.4 - Reduce to Information in Correct Format

O.3 - Evaluate Conditions & Detect Problems
O.3.1 - Evaluate Information Against Standards
  O.3.1.1 - Understand User Standards
  O.3.1.2 - Classify/ Sort Information
  O.3.1.3 - Compare Information With Critical or Expected Conditions
  O.3.1.4 - Determine if the Information is Within the Tolerances

O.3.2 - Locate and Identify Problems
O.3.3 - Notify Problem Solving Mechanism

O.4 - Develop Solutions
  O.4.1 - Understand the Problem
  O.4.2 - Determine the Necessary Information and Skills
  O.4.3 - Assemble Necessary Information and Skills
  O.4.4 - Develop/ Design Solutions
  O.4.5 - Analyze Implications
  O.4.6 - Present Alternatives

O.5 - Select Plan of Action
  O.5.1 - Understand Alternatives and Their Implications
  O.5.2 - Select Alternatives
  O.5.3 - Commit Services and Resources

O.6 - Implement Plan
  O.6.1 - Distribute Resources
  O.6.2 - Do the Work
  O.6.3 - Inspect the Work