AN INTERACTIVE KNOWLEDGE BASED FORMWORK SELECTION SYSTEM FOR BUILDINGS

by

Awad S. Hanna
Victor E. Sanvido

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CIC
COMPUTER INTEGRATED CONSTRUCTION

Computer Integrated Construction Research Program
Department of Architectural Engineering
The Pennsylvania State University
University Park, PA 16802
FOREWORD

The Computer Integrated Construction (CIC) Research Program at Penn State was started in 1987 with a large grant from the National Science Foundation. This grant enabled a twenty member research team to develop the fundamental process models defining the scope of the activities required to provide a facility. The Consortium for the Advancement of Building Sciences (CABS), the sponsor of this project, was formed in 1988 at Penn State. Half of the founders of this group of concerned industry representatives had been involved in the CIC Research Program as an Industry Advisory Board. This report describes their first funded project. The project sought to demonstrate the benefits of representing expert knowledge for a narrow field (selecting formwork systems) in an organized manner through a newer type of software - the expert system - and make it available to many engineers.

In this report, Awad Hanna, the principal author has investigated the formwork systems available to the industry, found some new systems unpublished in the literature, and provided an excellent description of them. He has explained expert systems to the novice, and showed how to collect the knowledge of experts. WALLFORM and SLABFORM are developed to select vertical and horizontal formwork systems respectively. The system has been tested against case studies and experts. The system has been successfully implemented in select contractor offices.

It is envisioned that this cornerstone piece of basic research provided by Awad, will lead to many future applications in the areas of formwork selection, formwork design, and the complementary problems of site layout and equipment selection.

Other complimentary work will be detailed in subsequent technical reports issued by the CIC research program.

Victor Sanvido
Assistant Professor of Architectural Engineering
Director of CIC Research Program
ABSTRACT

The selection/design of a formwork system for a project is influenced by the building design, site constraints, the contractor's experience with different systems, and their availability. Typically the selection of a formwork system is made by a senior member of the contractor's organization. The decision is heavily based on that individual's experience. This experience may limit the selection of a system to one that is not the optimum. This report presents a tool to assist the formwork selector/designer in making that decision. This tool was developed by systematically capturing the expertise of people involved in all phases of the life of the formwork, from design through erection and concrete placement to its removal. The end result of this research is (1) a conceptual model which models the decision-making process of the expert; (2) a formwork selection knowledge base; (3) a rule-based computer tool that can help the designer in selecting the optimum formwork system; (4) a parametric guideline for formwork selection.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>List</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>xv</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xvii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>xviii</td>
</tr>
<tr>
<td>GLOSSARY</td>
<td>xix</td>
</tr>
</tbody>
</table>

## CHAPTER ONE: INTRODUCTION

1.1. Formwork Systems  
1.1.1. Definition of a Formwork System  
1.1.2. Economical Selection of a Formwork System  
1.1.3. Types of Formwork Systems  
1.2. Introduction to Expert Systems  
1.3. Problem Statement  
1.3.1. Need for Formwork Selection Research  
1.3.2. Current Selection Procedures for Formwork Systems  
1.3.3. Problems with the Current Procedures  
1.3.3.1. Solution Limited to Experience  
1.3.3.2. Scarcity of Expertise  
1.3.3.3. Lack of an Integrated Formwork System Selection Method  
1.3.3.4. Different Viewpoints Between the General Contractor and the Subcontractor  
1.4. Applicability of Problem Statement to Expert System Methodology  

Page 1
1.4.1. The Problem Domain is Subjective 14
1.4.2. The Task Requires Expertise 14
1.4.3. Experts are Available 14
1.4.4. The Problem is Bounded 15
1.5. Source of Knowledge for the Formwork Selection Problem 15
  1.5.1. Formal Documents 15
  1.5.2. Documented Case Studies 17
  1.5.3. Expert Interaction 18
1.6. Objectives and Expected Benefits of Research 18
  1.6.1. Objectives 18
    1.6.1.1. Develop a Formwork Conceptual Model 19
    1.6.1.2. Develop a Formwork Selection Knowledge Base 19
    1.6.1.3. Develop a Rule-Based Expert System Software for Formwork Selection 20
    1.6.1.4. Conduct a Parametric Study to Identify the Controlling Parameters 20
  1.6.2. Expected Benefits of Research 20
1.7. Research Methodology 21
  1.7.1. Develop a Formwork Conceptual Model 22
    1.7.1.1. Define the Formwork Life Cycle 22
    1.7.1.2. Select a Modeling Methodology 22
    1.7.1.3. Develop Formwork Tree 23
    1.7.1.4. Develop Formwork IDEF0 Model 23
    1.7.1.5. Identify Formwork Systems 24
  1.7.2. Develop a Formwork Selection Knowledge Base 24
    1.7.2.1. Identify the Role of the Knowledge Engineer 24
1.7.2.2. Identify the Domain Experts/Sources of Knowledge
1.7.2.3. Prepare Questionnaire
1.7.2.4. Conduct Interviews
1.7.2.5. Identify the Factors Affecting Formwork Selection
1.7.2.6. Conduct a Comparative Analysis
1.7.3. Develop a Rule-Based Expert System for Formwork Selection
1.7.3.1. Select Expert System Shell
1.7.3.2. Build a Prototype System
1.7.3.3. Test the Prototype System
1.7.3.4. Develop the Complete Expert System
1.7.4. Conduct Field Study to Identify Controlling Parameters
1.7.4.1. Conduct Field Test
1.7.4.2. Validate Test Case
1.7.4.3. Conduct a Parametric Study
1.8. Research Scope and Limitations
1.9. Organization of Report

CHAPTER TWO: A CONCEPTUAL FORMWORK MODEL
2.1. Modeling Definition/Purpose
2.2. Types of Models
2.2.1. Pure Physical Models
2.2.2. Physical Geometric Models
2.2.3. Mathematical Models
2.2.4. Simulation Models
37
2.2.5. Schematic Models
37
2.3. The IDEF0 Modeling Methodology
37
2.3.1. Types of IDEF0 Models
38
2.3.2. Basic Steps in Creating IDEF0 Diagrams
for the Formwork Situation
40
2.4. An Integrated Concrete/Formwork Life Cycle
42
2.5. Modeling the Concrete Structure
46
2.6. Provide Concrete Structure (A-0)
46
2.6.1. Design Structure (A1)
49
2.6.2. Construct Structure (A3)
50
2.6.3. Choose Formwork System (A13)
52
2.6.4. Build Structure (A32)
53
2.6.5. Provide Formwork (A321)
54
2.6.6. Provide Concrete (A322)
56
2.6.7. Remove Formwork (A3213)
57
2.7. IDEF0 Models to Support Expert System Development
58
2.7.1. Choose Formwork System IDEF0 Model
60
2.7.2. Provide Formwork IDEF0 Model
60
2.7.3. Remove Formwork IDEF0 Model
60
2.8. Reading IDEF0 Models and Their Diagrams
63
2.9. Summary
64

CHAPTER THREE: FACTORS AFFECTING THE SELECTION OF
FORMWORK SYSTEMS FOR CONCRETE
BUILDINGS.
65
3.1. Introduction
65
3.2. Parties Involved in Formwork Selection and Their Responsibilities 67
3.2.1. Owner's Role 67
3.2.2. Designer's Role 67
3.2.3. Contractor's Role 70
3.3. Forming Systems 70
3.3.1. Horizontal Forming Systems 71
3.3.1.1. Conventional Wood Systems 71
3.3.1.2. Conventional Metal Systems 71
3.3.1.3. Flying Truss Systems 73
3.3.1.4. Column-Mounted Shoring Systems 73
3.3.1.5. Tunnel Forming Systems 76
3.3.1.6. Joist-Slab Forming Systems 76
3.3.1.7. Dome Forming Systems 81
3.3.1.8. Summary of Horizontal Formwork Systems 81
3.3.2. Vertical Forming Systems 82
3.3.2.1. Conventional Wall Forming Systems 82
3.3.2.2. Ganged Forming Systems 82
3.3.2.3. Slip Forming Systems 84
3.3.2.4. Jump Form Systems 87
3.3.2.5. Self Raising Forming Systems 87
3.4. Summary 90

CHAPTER FOUR: EXPERT SYSTEMS 92
4.1. Definition of Expert Systems 92
4.2. Components of Expert Systems 94
4.2.1. Knowledge Base 94
4.2.2. Working Memory or Database 96
4.2.3. Inference Engine 96
4.2.4. User Interface 96
4.2.5. Knowledge Acquisition Module 97

4.3. Control Strategies 98
4.3.1. Forward Chaining 98
4.3.2. Backward Chaining 98

4.4. Knowledge Representation 100
4.4.1. Semantic Networks 100
4.4.2. Frames 101
4.4.3. Blackboard Representation 101
4.4.4. Predicate Calculus 104
4.4.5. Rule Based Representation Scheme 104

4.5. Summary 107

CHAPTER FIVE: KNOWLEDGE ACQUISITION 108
5.1 Introduction to the Problem of Knowledge Acquisition 108
5.1.1. Sources of Knowledge 108
5.1.2. Nature of Expertise 109

5.2. Knowledge Acquisition Techniques 110
5.2.1. Interviews 110
5.2.2. Protocol Analysis 111
5.2.3. Machine Induction Technique 112

5.3. Description of the Knowledge Acquisition Process for the Formwork Selection System 113
5.3.1. Familiarization Stage 114
5.3.1.1. Literature Review 114
CHAPTER SIX: FACTORS AFFECTING THE SELECTION OF
A FORMWORK SYSTEM

6.1. Introduction

6.2. Building Design: Slab Type
   6.2.1. Two-Way Flat Plate
   6.2.2. Two-Way Flat Slab
   6.2.3. Waffle Slab
   6.2.4. Two-Way Slab Supported By Beams
   6.2.5. One-Way Slab, Beam, and Girder
   6.2.6. One-Way Slab Supported by Beams or Bearing Walls
   6.2.7. One-Way Joist (Ribbed) Slab

6.3. Building Design: Lateral Load Supporting Systems
6.3.1. Type I Structure (Rigid Frame System) 140
6.3.2. Type II Structure (Shear Walls) 140
6.3.3. Type III Structure (Framed-Shear Wall Systems) 143
6.3.4. Type IV Structure (Framed Tube) 143
6.3.5. Type V Structure (Tube-in-Tube Systems) 143

6.4. Building Design: Building Shape 148

6.5. Job Specifications 149
6.5.1. Concrete Finish 149
6.5.2. Speed of Construction 150

6.6. Local Conditions 151
6.6.1. Area Practice 151
6.6.2. Weather Conditions 152
6.6.3. Site Characteristics 154

6.7. Supporting Organization 154
6.7.1. Available Capital (Cost) 155
6.7.2. Hoisting Equipments (Cranes) 157
6.7.3. Home-Office Support 157
6.7.4. Supporting Yard Facility 158

6.8.1. Choosing the Proper Formwork System Using the Comparison Tables 167
6.8.2. Example Project 167
6.8.3. Use the Table 6.4 168

6.9. Summary 169

CHAPTER SEVEN: EXPERT SYSTEM DEVELOPMENT FOR THE SELECTION OF FORMWORK SYSTEMS 170
7.1. Languages and Tools For Building Expert Systems
   7.1.1. General Purpose Programing Languages (GPPL)
   7.1.2. General Purpose Representation Languages (GPRL)
   7.1.3. Domain Independent Expert System Framework
7.2. Shell Selection/Function
   7.2.1. Selection of an Appropriate Tool for the System Development
   7.2.2. Choice of EXSYS Professional for Systems Development
   7.2.3. Overview of EXSYS Professional
7.3. Representing Formwork Knowledge
   7.3.1. Develop the Search Tree
   7.3.2. Prepare the Tabular Knowledge Base
7.4. Building the Prototype
   7.4.1. Extract Rules/Subgoals from Tabular Knowledge Base
   7.4.2. Transform Rules into Format Compatible with EXSYS
   7.4.3. Develop the Prototype System
   7.4.4. Test the Prototype System
7.5. Development of the Complete Expert System
7.6. Development of the Formwork Selection System
   7.6.1. Development of WALLFORM (Decision Tree Approach)
   7.6.2. Development of SLABFORM (Subgoals Approach)
7.7. System Features Inherited from EXSYS
   7.7.1. Control Strategy/Chaining Mechanism
CHAPTER EIGHT: SYSTEM VALIDATION AND PARAMETRIC ANALYSIS

8.1. Method of Testing

8.2. System Validation/Testing

8.3. Test Case #1
  8.3.1. Tutorial Run with Test Case #1
    8.3.1.1. System Requirements/Loading
    8.3.1.2. Description of Analysis Using the Expert System Software
    8.3.1.3. System Performance and Expert Evaluation for Test Case #1

8.4. Test Case #2
  8.4.1. Project Description
  8.4.2. System Performance Via Expert Evaluation

8.5. Test Case #3
  8.5.1. Project Description
  8.5.2. System Performance Via Expert Evaluation

8.6. Parametric Analysis

8.7. Expert's Evaluation of System
8.8. Summary

CHAPTER NINE: SUMMARY AND CONCLUSIONS

9.1. Problem Domain/Appropriateness as a Knowledge Based Expert System 215

9.2. Summary and Issues of System Development 216

9.3. Current Status of the System 217

9.4. Contributions to Knowledge 217

9.5. Areas for Future Research

9.5.1. Extension to the Current Research 219

9.5.2. Necessary Related Research 220

9.5.3. Other Areas for Future Research 222

9.6. Conclusions 222
LIST OF FIGURES

1.1 Basic Components of an Expert System 6
1.2 Sample Expert System Rule 8
2.1 IDEF0 Model Structure 39
2.2 Sample IDEF0 Showing Relationship of Elements 41
2.3 Decomposition of the Provide Concrete Structure Activity into Subactivities 43
2.4 Integrated Concrete Formwork Life Cycle 44
2.5 The Provide Concrete Structure Context 47
2.6 Logical Flow Chart for Erecting Forms 55
2.7 IDEF0 Model of "Choose Formwork System" 59
2.8 IDEF0 Model of "Provide Formwork" 61
2.9 IDEF0 Model of "Remove Formwork" 62
3.1 Standard Distribution of Costs for Cast-in-Place Concrete 68
3.2 Conventional Wood System 72
3.3 Conventional Metal System 74
3.4 Flying Truss System 75
3.5 Representation of One of Several Systems Available for Column-Mounted Shoring System 77
3.6 Tunnel Forming System 78
3.7 Dome Form for Waffle Slab 79
3.8 Conventional Wall System 83
3.9 Standard Ganged Form 85
3.10 Slipform System 86
3.11 A Typical Jumpform Cycle 88
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.12 A Typical Self-Raising Form Cycle</td>
<td>89</td>
</tr>
<tr>
<td>4.1 Expert System Architecture</td>
<td>95</td>
</tr>
<tr>
<td>4.2 Semantic Net Representation Scheme</td>
<td>102</td>
</tr>
<tr>
<td>4.3 Frame Representation Scheme</td>
<td>103</td>
</tr>
<tr>
<td>4.4 Blackboard Representation Scheme</td>
<td>105</td>
</tr>
<tr>
<td>5.1 The Knowledge Acquisition Process</td>
<td>115</td>
</tr>
<tr>
<td>6.1 Factors Affecting the Selection of a Formwork System</td>
<td>134</td>
</tr>
<tr>
<td>6.2 Two-Way Slab System</td>
<td>136</td>
</tr>
<tr>
<td>6.3 One-Way Slab System</td>
<td>139</td>
</tr>
<tr>
<td>6.4 Type I Structure-Rigid Frame Systems</td>
<td>141</td>
</tr>
<tr>
<td>6.5 Type II Structure-Shear Walls</td>
<td>142</td>
</tr>
<tr>
<td>6.6 Type III Structure-Framed Shear Wall</td>
<td>144</td>
</tr>
<tr>
<td>6.7 Type IV Structure-Framed Tube</td>
<td>145</td>
</tr>
<tr>
<td>6.8 Tube V Structure-Tube-in-Tube</td>
<td>146</td>
</tr>
<tr>
<td>7.1 Appropriate Use of Expert System Shells</td>
<td>173</td>
</tr>
<tr>
<td>7.2 Basic Structure of EXSYS Professional and Its Relation with the User, Knowledge Engineer, and Domain Expert</td>
<td>175</td>
</tr>
<tr>
<td>7.3 Example of Extract Rule from the Tabular Knowledge Base</td>
<td>179</td>
</tr>
<tr>
<td>7.4 The Use of Tabular Knowledge Base to Develop Expert System Subgoals</td>
<td>180</td>
</tr>
<tr>
<td>7.5 Sample Qualifiers for Adequacy of Hoisting Equipment</td>
<td>182</td>
</tr>
<tr>
<td>7.6 Sample Rule Developed Using Qualifier # 13, 14, and 17</td>
<td>183</td>
</tr>
<tr>
<td>7.7 Decision Tree for WALLFORM</td>
<td>188</td>
</tr>
<tr>
<td>7.8 Subgoal Development for the Horizontal Forming System</td>
<td>191</td>
</tr>
<tr>
<td>7.9 Sample Rule for Modular Building Design</td>
<td>192</td>
</tr>
<tr>
<td>8.1 Parametric Analysis for the Vertical Forming System</td>
<td>211</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.1</td>
<td>Suitability of Formwork Systems to Structural Elements</td>
</tr>
<tr>
<td>1.2</td>
<td>Divisions of Formwork Cost for General Contractor and Formwork Subcontractor</td>
</tr>
<tr>
<td>3.1</td>
<td>Dimensions of Forms for One-Way Joist Construction</td>
</tr>
<tr>
<td>6.1</td>
<td>Structural Systems and Building Height</td>
</tr>
<tr>
<td>6.2</td>
<td>Slipform: Example Projects</td>
</tr>
<tr>
<td>6.3</td>
<td>Effect of Reuse on Concrete Formwork Cost Based on One Use Equal to 1.00</td>
</tr>
<tr>
<td>6.4</td>
<td>Factors Affecting the Selection of Horizontal Forming Systems</td>
</tr>
<tr>
<td>6.5</td>
<td>Factors Affecting the Selection of Vertical Formwork Systems</td>
</tr>
</tbody>
</table>
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GLOSSARY

This glossary provides some basic definitions for terms used in this report. The glossary is divided into two basic sections: (a) formwork terms; and (b) expert system terms. Definitions are taken from Formwork for Concrete (4); and Building Expert Systems (19).

A. FORMWORK TERMS

FORM ANCHOR

Form anchors are devices used to secure formwork to previously placed concrete of adequate strength; normally embedded in concrete during placement. There are two basic parts: the embedded anchoring device and the external fastener which is removed after use.

BEAM SIDE

Side (vertical) panels or parts of a beam form.

CAMBER

A slight (usually) upward curvature of a truss, beam, or form to improve appearance or to compensate for anticipated deflection.
FALSEWORK

The temporary structure erected to support work in the process of construction. In discussion of concrete construction, the term may be used much the same as formwork to include shores or vertical posts, forms for beams or slabs, and lateral bracing.

FORM

Term used interchangeably with formwork (see formwork), but also used in a more restricted sense to indicate the supporting members in direct contact with the freshly placed concrete.

FORMWORK

The total system of support for freshly placed concrete, including the mold or sheathing which contacts the concrete as well as all supporting members, hardware, and necessary bracing. The term Falsework is also used with essentially the same meaning.

GANGED FORMS

Prefabricated panels joined to make a much larger unit (up to 30 x 50 ft.) for convenience in erecting, stripping, and reusing - usually braced with wales, strongbacks, or special lifting hardware.

RUSTICATION

A groove in a concrete or masonry surface.
RUSTICATION STRIP

A strip of wood or other material attached to a form surface to produce a groove or rustication in the concrete.

SHEATHING

The material forming the concrete face of forms; also called lagging, or sheeting.

SHORE

Temporary vertical support for formwork and fresh concrete or for recently built structures which have not developed full design strength. Also called prop, tom, post, strut.

SHORING

System of vertical or inclined supports for forms; may be wood or metal posts, scaffold-type frames, or various patented members.

SLIP FORM

Also referred to as sliding form. A form which moves, usually continuously, during placing of the concrete. Movement may be either horizontal or vertical. Slip forming is like an extrusion process with the forms acting as moving dies to shape the concrete.

SNAP TIE

Patented concrete wall form tie, the end of which can be twisted or snapped off after the forms have been removed.
STRIP

To remove formwork; also a long thin piece of wood, metal, or material.

STRONGBACK

A frame attached to the back of a form to stiffen or reinforce it; additional vertical wales placed outside horizontal wales for added strength or to improve alignment; also called stiffback.

STUD

Vertical supporting member to which sheathing is attached.

TIE

A concrete form tie is a tensile unit used to hold concrete forms securely against the lateral pressure of unhardened concrete, with or without provision for spacing the forms a definite distance apart, and with or without provision for removal of metal to a specified distance back from the finished concrete surface.

WALE

Long horizontal member (usually double) used to hold studs in position; also called a ranger.
YOKE

A tie or clamping device around column forms or over the top of wall footing forms to keep them from spreading because of the lateral pressure of concrete; also part of structural assembly for slip forming which keeps the forms from spreading and transfers form loads to the jacks.
B. EXPERT SYSTEM TERMS

ARTIFICIAL INTELLIGENCE

The subfield of computer science concerned with developing intelligent computer programs. This includes programs that can solve problems, learn from experience, understand language, interpret visual scenes, and, in general, behave in a way that would be considered intelligent if observed in a human.

BACKWARD CHAINING

One of several control strategies that regulate the order in which inferences are drawn. In a rule-based system, backward chaining is initiated by a goal rule. The system attempts to determine if the goal rule is correct. It backs up to the if clauses of the rule and tries to determine if they are correct. This, in turn, leads the system to consider other rules that would confirm the if clauses. In this way the system backs into its rules. Eventually, the back-chaining sequence ends when a question is asked or a previously stored result is found.

BLACKBOARD

A data base accessible to independent knowledge sources and used by them to communicate with one another. The information they provide each other consists primarily of the intermediate results of problem-solving.
CERTAINTY FACTOR

A number that measures the certainty or confidence one has that a fact or rule is valid.

DATA BASE

In a knowledge based system, data base is the memory contains a set of facts that describe the current situation and contains all the attribute-value relationship that have been established during the consultation.

DEDUCTION

A process of reasoning in which the conclusion follows from the premises given.

DOMAIN EXPERT

A person, who through years of training and experiences, has become extremely proficient at problem-solving in a particular domain.

DOMAIN KNOWLEDGE

Knowledge about the problem domain, e.g. knowledge about geology in an expert system for finding mineral deposits.

END-USER

The person who uses the finished expert system; the person for whom the system was developed.
EXPERT SYSTEM

A computer program that uses expert knowledge to attain high levels of performance in a narrow problem area. These programs typically represent knowledge symbolically, examine and explain their reasoning processes, and address problem areas that require years of special training and education for humans to master.

EXPERT-SYSTEM-BUILDING-TOOLS

The programming language and support package used to build the expert system.

EXPLANATION FACILITY

That part of an expert system that explains how solutions were reached and justifies the steps used to reach them.

FORWARD CHAINING

An inference method where the IF-portion of rules are matched against facts to establish new facts.

FRAME

A knowledge representation scheme that associates an object with a collection of features (e.g., facts, rules, defaults, and active values). Each feature is stored in a slot. A frame is the set of slots related to a specific object. A frame is similar to a property list, schema, or record, as these terms are used on conventional programming.
GOAL-DRIVEN

A problem-solving approach that works backward from the goal.

HEURISTIC

A piece of knowledge capable of suggesting plausible actions to follow or implausible ones to avoid.

INFERENCE CHAIN

The sequence of steps or rule applications used by a rule-based system to reach a conclusion.

INFERENCE ENGINE

That part of a knowledge-based system or expert system that contains the general problem-solving knowledge. The inference engine processes the domain knowledge (located in the knowledge base) to reach new conclusions.

KNOWLEDGE

The information a computer program must have to behave intelligently.

KNOWLEDGE ACQUISITION

The process of extracting, structuring, and organizing knowledge from some source, usually human experts, so it can be used in a program.
KNOWLEDGE BASE

The portion of a knowledge-based system or expert system that consists of facts and heuristics about the domain.

KNOWLEDGE-BASED SYSTEMS

A class of computer programs that use knowledge and inference and procedure to solve problems.

KNOWLEDGE ENGINEER

The person who designs and builds the expert system. This person is usually a computer scientist experienced in applied artificial intelligence methods.

KNOWLEDGE ENGINEERING

The process of building an expert system.

KNOWLEDGE REPRESENTATION

The method used to encode and store facts and relationships in a knowledge base. Semantic networks, object-attribute value triplets, production rules, frames, and logical expressions are all ways to represent knowledge.

NODE

A point (representing such aspects as the system state or an object) in a graph connected to other points in the graph by arcs (usually representing relationships)
PATH
A particular track through a state graph.

PREDICATE CALCULUS
An extension of propositional calculus. Each elementary unit in predicate calculus is called an object. Statements about objects are called predicates.

PRODUCTION RULE
The type of rule used in a production system, usually expressed as IF condition THEN action.

PRODUCTION SYSTEM
A type of rule-based system containing IF-THEN statements with conditions that may be satisfied in a data base and actions that may change the data base.

RULE
A formal way of specifying a recommendation, directive, or strategy, expressed as IF premise THEN conclusion or IF condition THEN action.

RULE-BASED METHODS
Programming methods using IF-THEN rules to perform forward or backward chaining.
RULE-BASED SYSTEM

A computer program that represents knowledge by means of rules.

SEARCH

The process of looking through the set of possible solutions to a problem in order to find an acceptable solution.

SEARCH SPACE

The set of all possible solutions to a problem.

SLOT

An attribute associated with a node in a frame system. The node may stand for an object, concept, or event; e.g., a node representing the object employee might have a slot for the attribute name and one for the attribute address. These slots would then be filled with the employee's actual name and address.

TREE STRUCTURE

A way of organizing information as a connected graph where each node can branch into other nodes deeper in the structure.

USER

A person who uses an expert system, such as an end-user, a domain expert, a knowledge engineer, a tool builder, or a clerical staff member.
CHAPTER ONE
INTRODUCTION

1.1. Formwork Systems

The selection/design of a formwork system for a project is influenced by the building design, site constraints, the contractor's experience with different systems, and their availability (1). Typically the selection of a formwork system is made by a senior member of the contractor's organization. The decision is heavily based on that individual's experience. This experience may limit the selection of a system to one that is not the optimum (1). This report presents a tool to assist the formwork selector/designer in making that decision.

The life cycle of any concrete building passes through several basic stages. These are conceptual and feasibility studies, design and engineering, estimating, scheduling, procurement, construction, and finally occupancy, operation, and maintenance (2). In the second stage, design and engineering, there is a distinct difference between design and engineering. Design may be defined as the process during which the concept or idea is developed, refined, and implemented into detailed instructions (3). On the other hand, engineering is defined as the process during which the elements' shape and size (dimensions) are determined. The selection of a formwork system is categorized under the design process.
1.1.1. Definition of a Formwork System

A formwork system, from the contractor's point of view, is defined as "the total system of support for freshly placed concrete including the mold or sheathing\(^1\) which contacts the concrete as well as supporting members, hardware, and necessary bracing." It should be noted that the term falsework also has essentially the same meaning as formwork (4).

1.1.2. Economical Selection of a Formwork System

In most reinforced concrete buildings, the contractor evaluates different schemes to get the optimum formwork system and achieves an efficient construction sequence. The contractor may also choose between building forms on the job site by setting up a special fabrication area, or building many forms in a central yard facility and transporting them to the site. He may also choose between building the forms himself, buying, or renting them. Many contractors find that renting forms for specific usage allows them more flexibility in controlling the volume of work they are able to perform. A fair cost estimate for different schemes is required to determine which is most economical. The decision about whether to invest company funds in a particular system is always crucial. In addition to cost, this decision is also influenced by safety, quality, and time considerations.

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\(^1\) A glossary of key terms is provided. These terms are underlined and organized in alphabetical order.
1.1.3. Types of Formwork Systems

There are several forming systems used in the construction of reinforced concrete buildings. Stick forms and improved stick forms are still the most common and popular formwork systems. Their popularity stems from their flexibility in forming different shapes and elements. However, stick forms always result in high labor and material cost (4).

The most significant improvement in recent years in formwork systems is the "Ganged Panel Form." This type was developed in response to the progress of crane development, the need for massive concrete placements, and the greater demand for reducing project time and labor cost. Large ganged panels are usually assembled on the ground and then hoisted into position. Additional cost is saved when using the ganged forms because they can be stripped as one unit.

Flying forms consist of sheathing that is supported by trusses, beams, or scaffolding units which generally need to be handled mechanically. The vertical supporting system of the flying forms can be (1) truss-supported slab forms; (2) slab forms supported by column or wall mounted hardware; or (3) decks supported by metal frame shoring. Jacks are usually provided to facilitate stripping by lowering the deck (4).

Slip or sliding forms are a special type of formwork that is used frequently for special structural systems such as shear walls. These systems consist of wall formwork about 5 ft. high, with working platforms on each side, which are continually concreted and
continually raised by hydraulic jacks which are fixed to steel tubes in the finished wall (4).

Self-raising forms are used in the construction of high, uniformly shaped concrete structures. In self-raising forms, the forms pull themselves up in sequence with the casting operation. Unlike slipforms, which shape the structure in a continuous, unbroken extrusion-forming process, self-raising forms are used in stages, one lift at a time. Self-raising forms, as the name suggests, are not flown by crane - they raise themselves (6).

Based on a literature search, Table 1.1 shows the basic types of formwork systems that are best suited for each structural system.

1.2. Introduction to Expert Systems

Some confusion may occur when the term "Expert System" is used, so it should first be defined. The simplest definition would be: "A computer program that uses expert knowledge to attain a high level of performance in a narrow problem domain. These programs typically represent knowledge symbolically, examine and explain their reasoning processes, and address problem areas that require years of special training and education for a human to master" (7). Figure 1.1 illustrates the basic components of an expert system. The structure of an expert system consists of the following four logical parts (8):

1. A knowledge base that contains facts, algorithms, and a representation of heuristics.
Table 1.1 Suitability of Formwork Systems to Structural Elements

<table>
<thead>
<tr>
<th>STRUCTURAL ELEMENTS</th>
<th>FORMWORK</th>
<th>Foundation</th>
<th>Column</th>
<th>Wall</th>
<th>Beam</th>
<th>Slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stick</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>Improved Stick</td>
<td>M</td>
<td>P</td>
<td>P</td>
<td>M</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Ganged Panel</td>
<td>N</td>
<td>N</td>
<td>P</td>
<td>N</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Flying</td>
<td>N</td>
<td>N</td>
<td>P</td>
<td>N</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Slip</td>
<td>N</td>
<td>N</td>
<td>P</td>
<td>N</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>Self-Raising</td>
<td>N</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>N</td>
<td></td>
</tr>
</tbody>
</table>

P = Primary Use
M = May be used
N = Not Suitable
Figure 1.1 Basic Components of an Expert System (8)
2. A **global database** which contains dynamic data that can be applied to any problem in a specific domain.

3. A **control structure** of the **inference engine**, which uses input data and facts, and attempts to search through the knowledge to find a solution.

4. A **man/machine interface**.

The above process may be illustrated by using one of the rules for the formwork selection problem. Input facts might include information such as architectural design (modular column design, opened or closed facade), and structural design (flat slab or flat plates). A rule is a way of representing knowledge that specifically describes an IF-THEN relationship. This is illustrated in Figure 1.2.

1.3. **Problem Statement**

1.3.1. **Need for Formwork Selection Research**

Shrinking construction markets and shorter construction periods are driving more and more contractors to execute critical path activities and large cost items with their own forces (4). Typically the first thing which a general contractor performs in-house is the structural concrete frame. The reasons for this are (1)

1. This is a large cost item.
2. It controls the pace of the project.
3. It is a phase of the work where labor is exposed to risky or unsafe conditions.
IF : Structural slab systems are flat-plates or flat slabs;

AND : Initial or make-up cost requires that there should be at least ten uses of the forms;

AND : The interior and exterior columns of the building are in lines;

AND : The building has an open facade through which the form can be passed;

AND : Prefabricated components which might impede form removal, such as plumbing stacks, are not used.

THEN : Structural slab systems can be handled expeditiously with flying forms.

---

Figure 1.2 Sample Expert System Rule (9).
4. The quality of the structure can also dictate the quality of workmanship acceptable on the project to the trades that follow.

As noted below, the current procedures of formwork selection, which are driven by the above mentioned reasons, are highly dependent on the experience, intuition and judgment of recognized experts. As a result, a knowledge-based expert system could become a feasible and potentially useful tool in the development of a rational and systematic selection process. A review of the literature indicates that, to date, no one has attempted to develop such an expert system.

1.3.2. Current Selection Procedures for Formwork Systems

The selection/design of a formwork system for a project is influenced by the building design, site constraints, the experience of the contractor with a specific system, and the availability of the formwork system. Typically, the selection/design of a formwork system is made by a senior member of the contractor's organization. The decision is heavily based on that individual's experience. Published literature does not provide an organized procedure for selecting a formwork system.

1.3.3. Problems with the Current Procedures

As mentioned above, the selection of a formwork system to shape and support the freshly cast concrete is largely based on the experience of the person selecting the system. This fact may often
result in a faulty or expensive system. Some of the problems resulting from current procedures may be summarized as follows.

1.3.3.1. Solution Limited to Experience

In many situations, the selection of a particular system is biased because it is based on the individual's experience. This experience may be limited, thus constraining the selection to one that is not the optimum.

1.3.3.2. Scarcity of Expertise

The expert "Knowledge Czar" is not always available and is costly to hire. This fact imposes some limitations especially for small/medium size contractors.

1.3.3.3. Lack of an Integrated Formwork System Selection Method

Most of the published literature treats formwork selection as a set of separate elements rather than an integrated system. It explains the selection criteria for individual structural elements (i.e., foundation, column, etc), and does not treat formwork as an integrated system.
1.3.3.4. Different Viewpoints Between the General Contractor and the Subcontractor

Usually, a general contractor does not select the formwork system for a given project. The general contractor prices the formwork as a sub-item of concrete cost ($/sq. ft.) without much consideration of the system. Only the subcontractor, who is responsible for the concrete work, conducts an in-depth analysis of the different systems and selects one. Some general contractors do in fact perform concrete work, hence may share the same viewpoint.

Table 1.2, which is based on a field study by the writer, differentiates between the division of cost categories for the general contractor and the formwork subcontractor. It shows that the labor cost for the formwork subcontractor is less than that for the general contractor. This could reflect the cost reduction achieved by the optimum selection of a formwork system. Also, it is interesting to note that the margin for the formwork subcontractor is higher than that for the general contractor, because it is his only business and his specialization commands a higher profit for higher productivity. However, the general contractor can earn almost as high a dollar amount per unit because his lower margin is applied to the total price of concrete work and not just to a subsystem.
Table 1.2  Divisions of Formwork Costs for General Contractor and Formwork Subcontractor

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>General Contractor</th>
<th>Subcontractor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor</td>
<td>55%</td>
<td>45%</td>
</tr>
<tr>
<td>Materials</td>
<td>22%</td>
<td>22%</td>
</tr>
<tr>
<td>Insurance &amp; Taxes</td>
<td>18%</td>
<td>18%</td>
</tr>
<tr>
<td>Margin</td>
<td>5%</td>
<td>15%</td>
</tr>
</tbody>
</table>

\(^2\) This table has been taken from (59).
1.4. **Applicability of Problem Statement to Expert System Methodology**

Several researchers have pointed out that the nature of the construction industry makes expert systems especially applicable to construction engineering and management (10). They noted that in the construction industry, one depends heavily on empirical rules and procedures derived from experience rather than on a scientific knowledge base. Furthermore, researchers have pointed out that many tasks in the construction industry have high training requirements for experience-based, rather than conceptual knowledge - hence, the use of long-term programs for training the crafts and for the gradual accumulation of responsibility in the project engineering and project management tasks.

Since conventional wisdom may be further advanced than scientific knowledge in construction, and since it is hard to train new employees when the knowledge has not been formalized, expert systems may have an unusually large role to play in communicating the knowledge of more experienced practitioners to newer employers.

The problem of selecting a formwork system is therefore felt to be a legitimate candidate for expert system application for the following reasons.
1.4.1. The Problem Domain is Subjective

1. The domain is characterized by the use of expert knowledge, judgment, and experience (11).
2. Conventional programming (algorithmic) approaches to the problem are not satisfactory (11).
3. There are recognized experts that do solve the problem.
4. The solutions developed by professional "experts" have proven to be better than those developed by experienced individuals with just field supervision experience.
5. The solution of this problem has a very high expected payoff.

1.4.2. The Task Requires Expertise

1. The task requires symbolic reasoning.
2. The task requires the use of heuristic (rule of thumb) strategies and a large search space.
3. Knowledge is not required from a very large number of areas.

1.4.3. Experts are Available

1. There exists an expert to work with the project.
2. The expert's knowledge and reputation are sound, so that the system will have credibility and authority.
3. The expert has built up expertise over a long period of project task performance.
4. The expert is able and willing to communicate and cooperate.

1.4.4. The Problem is Bounded

1. The task of formwork selection is neither too easy (taking less than a few minutes), nor too difficult (taking more than a few hours).
2. The task is sufficiently narrow and self-contained. The task is limited to a choice among approximately ten different formwork systems for different structural elements (foundations, columns, etc).

1.5. Source of Knowledge for the Formwork Selection Problem

The sources of knowledge which will be applied to the formwork selection problem are three-fold:

1.5.1. Formal Documents

There are four basic documents which this writer will use to determine comprehensive guidelines for formwork operations in building construction. These are: (1) ACI 318-86, "Building Code Requirements for Reinforced Concrete" (12,13); (2) ACI Standard
347-78 "Recommended Practice for Concrete Formwork" (14); (3) Formwork for Concrete by M.K. Hurd, which was prepared under the review and guidance of ACI Committee 347, Formwork for Concrete (4); and (4) ANSI Standard A10.9 (1983), American National Standards Institute (15).

ACI 318-86 deals with construction practice and provides a general guideline for the design of formwork, removal of formwork and shores, and the placement and curing of concrete. However, no quantitative values are specified for any of these guidelines (12, 13).

ACI 347-78 provides more extensive and detailed recommended practices for formwork. This document covers: (a) preparation of contract plans and specifications; (b) design criteria for vertical and horizontal forces and lateral pressure; (c) design considerations, including capacities of formwork accessories; (d) preparation of formwork design drawings; (e) construction and use of forms, including safety considerations; (f) materials for formwork; and (g) formwork for special structures (14).

"Formwork for Concrete" (4), ACI special publication SP-4, provides a comprehensive description of the concrete formwork topic and discusses the objectives in formwork building, overall planning, materials and accessories, and calculating loads and pressures. In this document, the first four chapters deal with the planning of formwork as an integral part of overall job planning. Formwork design is covered in chapters 5, 6, and 7. Chapter 8 provides several different examples of large-scale drawings and methods of preparing suitable notes. It also provides simple rules and checklists for the
draftsman. Chapters 10 through 17 deal with formwork for special structures.

The ANSI Standard A10.9 (1983) provides both quantitative and qualitative provisions for the design of formwork. Many of the detailed provisions of this document are based on the ACI 347 Standard (15).

In addition to these four documents, there are other documents which provide design guidelines for formwork. These include state and local building codes, and guidelines prepared by contractors and formwork manufacturers.

1.5.2. Documented Case Studies

Another source of knowledge was found in the magazine articles. They typically describe successful case studies of certain formwork systems. Four of these technical magazines were relevant to this research. These are (1) Concrete Construction; (2) Concrete International; (3) Engineering News Record; (4) Construction Methods and Equipment. In addition, several papers developed by contractors were used to examine successful case studies. Several rules were obtained by reviewing these articles. Some of these rules are explicit and the others can be inferred from the project description.
1.5.3. **Expert Interaction**

A third way in which the writer will compile the available knowledge is by means of experience or by learning from various experts. The rules obtained from human experts will embody the unpublished knowledge that they have acquired through their experience with particular problems. These "heuristics," or rules-of-thumb, incorporate knowledge such as how to handle incomplete or inconsistent data, or how to select the best solution among several possible alternatives under a particular set of conditions. The degree of success achieved by the system is dependent on the ability of the experts whose knowledge is encoded in the knowledge base (16).

It should be noted that this research study was sponsored by the Consortium for Advancement of Building Science (CABS), which gave the writer an opportunity to elicit the knowledge from experts in formwork design that work for several of the member companies. This writer conducted several unstructured interviews in the Washington D.C. area. These led to subsequent structured interviews.

1.6. **Objectives and Expected Benefits of Research**

1.6.1. **Objectives**

In multistory reinforced concrete building construction, the selection of the formwork to shape and support freshly cast concrete is largely based on the experience of the person selecting the system. Typically, there are one or two "experts" in a company. After the
formwork design is selected, it is then checked by a professional engineer-of-record to ensure that the integrity of the structure and the safety of the workers is maintained. The problems with this procedure were discussed in sections 1.3.3.1 to 1.3.3.4. Because of these problems, the objectives of this research are fourfold:

1.6.1.1 Develop a Formwork Conceptual Model

The writer will develop a conceptual model which models the key decisions made as the formwork cycles through a structure. The intended model will be developed as a functional and informational model. The model will be a useful tool for any decision-making process involving formwork design. It is the basis for structuring the knowledge base.

1.6.1.2 Develop a Formwork Selection Knowledge Base

The writer will collect, organize, and develop the knowledge base required to develop the formwork selection system. This knowledge base will include the different forming systems along with rules for their potential uses and limitations. The knowledge base will then be organized in a format suitable to be inputted to the selected shell. An expert system shell is a fully developed expert system that has had its knowledge base removed.
1.6.1.3. Develop a Rule-Based Expert System for Formwork Selection

The writer will develop a rule-based computer tool that can mimic the thoughts of a formwork design expert. The software to be used is an expert system shell (EXSYS PROFESSIONAL) which interactively questions the user to determine certain key factors and information. Such information may include the shape of the building and its components (design), site characteristics, adequacy of crane service, schedule and the desired quality of concrete, etc.

1.6.1.4. Conduct a Parametric Study to Identify the Controlling Parameters

This writer will perform a parametric study which changes some of the controlling parameters (i.e. building height, size, etc) and determine the corresponding appropriate formwork system. If there is any apparent relation between one or more of these parameters and the formwork system that is selected, appropriate graphic plots will be prepared and presented.

1.6.2. Expected Benefits of Research

The product of the research will be of great value to contractors because it will:

1. Archive the expertise of the formwork system selector/designer.
2. Provide a useful tool in the form of a conceptual model that facilitates the decision-making process for formwork selection.

3. Increase the performance of the formwork selector/designer.

4. Accelerate the decision-making process for selecting the formwork system.

5. Provide training for new staff who use the software.

6. Provide a starting point for additional decision support systems associated with concrete placement, rebar placing, and steel erection.

1.7. Research Methodology

The proposed research methodology was developed for each of the four objectives mentioned in Section 1.6. These were:

1. Develop a formwork conceptual model.

2. Develop a formwork selection knowledge base.

3. Develop a rule-based expert system for formwork selection.

4. Conduct a parametric study to identify the controlling parameters.
1.7.1. Develop a Formwork Conceptual Model

The purpose of this section was to identify the basic steps that are necessary for the knowledge engineer to build the knowledge base. Five steps comprised the major activities for this section:

1.7.1.1. Define the Formwork Life Cycle

Develop a flow model showing the interaction between the formwork life cycle and the life cycle of the concrete structure. Sources of input included experts, researchers, and literature. The purpose of this step was to focus on the formwork as an entity. The formwork life cycle was divided into:

1. The design life cycle: which includes formwork planning, scheduling, costing, system choosing, designing, and drawings; and
2. The physical life cycle: which includes manufacturing, hoisting, erecting, pouring concrete, shoring and reshoring, stripping, cleaning and maintenance, and reuse or storage.

1.7.1.2. Select a Modeling Methodology

The proposed model utilized the IDEF0 modeling methodology to represent each stage of the formwork life cycle. Special emphasis was given to the design life cycle, which included the formwork selection activity. The IDEF0 modeling methodology, adapted from
Integrated Computer Aided Manufacturing (ICAM), was established and used to model a manufacturing process in its entirety (17). The IDEF0 graph (ICAM Definition) is a hierarchy of process boxes with input, control, and output represented by arrows.

1.7.1.3. Develop Formwork Tree

The concrete building life cycle was presented as a hierarchical tree. Formwork design and physical life cycle activities were further decomposed into more detail in order to focus on the formwork activities. The advantage of using this tree was to show the relation between formwork activities, the focus of this research effort, and the other activities required to build a concrete structure. It also showed other potential research area in the concrete structure domain.

1.7.1.4. Develop Formwork IDEF0 Model

Three major formwork activities were selected from the hierarchical tree explained above and represented by the IDEF0 modeling methodology. These activities show different stages in the formwork life cycle. These activities were: choose formwork, provide formwork, and remove formwork.
1.7.1.5. Identify Formwork Systems

Data defining the different types of formwork available to contractors was collected from contractors and formwork manufacturers. The questionnaire shown in Appendix A (Section A.1) was mailed to companies shown in Appendix A (Section A.2). Data from three contractors was collected by interviews, recorded and organized. This step was essential to form the basis for identifying the different formwork systems available to the contractor.

1.7.2. Develop a Formwork Selection Knowledge Base

The credibility of any expert system stems from the accuracy and completeness of its knowledge base. Literature indicated that 80% of an expert system's development time was consumed in the collection and organization of the data base (19). As a result, this objective involved seven subactivities which represent the heart of this research.

1.7.2.1. Identify the Role of the Knowledge Engineer

The Knowledge Engineer, by definition, is the one who transfers the problem-solving expertise from the knowledge source to a program. Civil Engineers active in expert systems do not ordinarily utilize specialist knowledge engineers to assist them in knowledge base development (20). In this study, the writer served as the
knowledge engineer. The writer's fifteen years of practical and academic experience made him a good candidate to perform the role of the knowledge engineer. Also, in the last two years, the writer was active in studying the basics of expert systems and the knowledge acquisition process.

The knowledge engineer performs two basic tasks:

1. Collected the "static" knowledge found in textbooks, journals, and other written reference sources.
2. Extracted the "private" knowledge possessed by the human experts and organized it in an efficient manner. This private knowledge included rules-of-thumb that have become known as heuristics.

1.7.2.2. Identify the Domain Experts/Sources of Knowledge

In order to build a pool of expertise from which heuristics could be extracted later in the process, a group of external experts in formwork design were interviewed. Appendix A (Section A.3) shows that the source of formwork design expertise was organized into four groups: (1) General Contractor; (2) Concrete Subcontractor; (3) Design/Consulting Firm; and (4) Formwork Subcontractor.

The process of identifying the domain expert was a progressive one. It started by interviewing three formwork experts in Washington D.C. area. Those experts in turn introduced the knowledge engineer to other experts.

The knowledge engineer also had the opportunity to attend two major events concerning the formwork domain. These were the
Fourth International Conference for "Forming Economical Concrete Buildings," and "World of Concrete 89." These two events gave the knowledge engineer the opportunity to interview nine formwork experts working for major formwork subcontractors.

1.7.2.3. Prepare Questionnaire

Based on a field study performed by this writer, it was noted that some of the knowledge required would be inaccessible to the writer. For example, the slipform system is most prevalent on the Northeast, Southeast, Hawaii, and Puerto Rico, and is less popular in the Northeastern part of the U.S.A. Thus, it was necessary to prepare a written questionnaire and send it to several companies to extract the knowledge that the writer could not obtain through direct interviews with the experts. The questionnaire included:

1. A set of instructions explaining how to answer the questions.

2. A tentative set of questions.


The result of this questionnaire was completely disappointing, and no single answer was received from the fifty-four questionnaires sent. As a result, this writer decided to upgrade this step by conducting interviews for these systems instead of sending questionnaires. This was accomplished by visiting the "World of Concrete 89," in which most of the formwork manufacturers exhibited their products while supported by experts who answered questions about their forming systems. The main drawback of this
step was lack of statistical data to support the confidence factors when implementing the expert system. It should be noted that the same questionnaire was used when conducting the "in-person" interviews.

1.7.2.4. **Conduct Interviews**

Unstructured and structured interviews were conducted to extract the knowledge from the selected experts. The unstructured interviews focused on the formwork selection problem in general terms. Broadly focused questions were asked which led to a more organized sets of questions that were used in structured interviews. Structured interviews involved detailed questioning of experts to develop answers to detailed questions. Activities included preparing interview kits, preparing and conducting interviews, and formulating interview records. This step is explained in detail in Chapter Five.

1.7.2.5. **Identify the Factors Affecting Formwork Selection**

A broad set of factors/parameters were identified through the interviews, case studies, and literature research. These parameters were categorized, consolidated, and reviewed by two human experts.

1.7.2.6. **Conduct a Comparative Analysis**

Based on interviews, case studies, and literature review, data relevant to formwork systems were collected, organized and
tabulated. A comparative analysis among the different systems to show the advantages and disadvantages, usage and limitations of each, was conducted. The result is presented in a tabular format in Chapter Six to show the relation between the different formwork systems and the factors affecting the selection of these systems.

1.7.3. Develop a Rule-Based Expert System for Formwork Selection

The process of building a rule-based expert system for formwork selection involved five major steps. The proposed method for performing each step is explained below.

1.7.3.1. Select Expert System Shell

The process of building a rule-based system started with the selection of the shell most appropriate for the knowledge base. The selected shell for this research was "EXSYS PROFESSIONAL," produced by EXSYS, Inc. In selecting the shell, four major considerations were important to this writer. First was the "user friendliness" of the system - because the intended users of the system had little or no experience in programming. Second was the flexibility of the system - the ability to modify and expand the system. Third was the availability of a robust, well-tested system to the contractor on a single floppy desk which could run on high density drive IBM machines or compatibles. Fourth was the availability of the shell.
EXSYS is available for application at Penn State's Civil Engineering Department and this writer is familiar with the system.

1.7.3.2. Build a Prototype System

The second step in building a prototype is to develop a "demonstration prototype" - that is, a small demonstration program that handles a portion of the entire problem that will eventually be addressed. This type of program is often used to test ideas about problem definition, scope, and representation of the problem. Many references indicated that the approximate number of rules for the prototype was between 20 and 60 (14, 15) The prototype system developed for this research contained 23 rules.

1.7.3.3. Test the Prototype System

The prototype system was a complete system but on small scale. The emphasis in this step was to assure that the system was capable of providing the right selection and arranging the selected systems in correct sequences. The methodology for this step covered the following:

1. Evaluation and testing of the prototype system.
2. Analysis of the problems of and restructuring of the prototype system.
3. Incremental improvement and modification of the prototype system.
Testing involved evaluating the performance and the utility of the prototype system and revising it if necessary. Once the prototype system ran from start to finish on two or three examples, it was tested with a variety of examples to determine weakness in the knowledge base. This evaluative test did uncover problems with the representation scheme, such as missing concepts and relations. Such problems forced this writer to recycle through the various development phases.

In evaluating the prototype system the following issues were checked:

1. The agreement between the decision that the system made and the expert's decision.

2. The consistency, completeness, and correctness of the inference rules.

3. The adequacy of the explanation facility for describing how and why the system reached a certain conclusion.

Once the system was capable of selecting and ranking possible formwork systems, features were added by incrementally increasing the number of rules. These newly added rules were informational rules. They belonged to each forming system and were not part of the rules used in the selection process.

1.7.3.4. Develop the Complete Expert System

In building an expert system, revision is often necessary. Restructuring of concepts and refinement of the implemented system were necessary. Refinement of the prototype normally involved
recycling through the implementation and testing stages. The iterative processes of restructuring and refinement were continued until the expected behavior or results were obtained. The result of the revised prototype which this writer developed was the complete system, which should be assessed by the human expert. Ultimately, the successful complete expert system had to be verified against all reasonable test cases.

1.7.4. **Conduct Field Study to Identify Controlling Parameters.**

The purpose of this section is twofold: the first is to validate the implemented expert system via "real world" test cases; the second is to study the effect of changing certain parameters on the selected formwork system.

1.7.4.1. **Conduct Field Test**

Once the total system had been built the following activities were performed:

1. Test cases were chosen and management was contacted to obtain all the pertinent information. The test cases were in the Washington D.C. area because most of the new buildings are made of reinforced concrete; it is a very competitive market and the expertise is available.
2. The system was run. The formwork system selected by the expert system was printed and compared to the system selected by the human expert.

3. The expert system was modified as necessary and the modified expert system maintained. The ultimate validation was the satisfaction of the human expert.

1.7.4.2. Validate Test Case

The writer ran the test case before two human experts, one at a time. The following activities were performed:

1. A test case building or group of buildings was selected and the expert selected the formwork system.
2. The expert system was used to do the same selection.
3. Results were discussed and differences noted. Comments were recorded and added the system as appropriate.

1.7.4.3. Conduct a Parametric Study

A parametric study was conducted, using the expert system software, and choosing some hypothetical situations concerning different building features. Some of the controlling parameters (i.e. height, area, structural system, etc.) were changed, and the corresponding appropriate formwork system was determined. The relationship between some of these parameters and the selected formwork system was arranged in the matrix shown in Chapter Eight.
1.8. Research Scope and Limitations

The domain of application is the selection of a formwork system for the concrete structure of a building. The formwork system is typically limited to stick forms and improved stick forms, prefabricated forms, ganged forms, flying forms, slip or sliding forms, self-climbing forms, custom made forms, and special forms. The formwork materials are limited to lumber, aluminum, steel, (or a combination of each), and glass-fiber-reinforced plastic. The intended system will not include the domain of formwork for special structures (bridges, shells, folded plates, and long span roof structures). The reason for this exclusion is because each of these structures has different controlling criteria for formwork selection, and each problem, by itself, is worthy of a research study.

1.9. Organization of Report

This report is organized as follows: Chapter One introduces the problem and defines the research objectives and methodology. Chapter Two describes the life cycle of the typical formwork system in a flow model, a tree structure, and IDEF\textsubscript{0} graphic representation format. Chapter Three identifies all the formwork systems that are used in today's construction practices. Chapter Four explains the basic concepts of expert systems and describes expert system components and the different methods of knowledge representation. Chapter Five demonstrates the different techniques for knowledge acquisition along with the methods used in this research. Chapter Six
this research. Chapter Six addresses and identifies the major factors that affect the selection of formwork systems and combines them in a comparative analysis. Chapter Seven explains the procedure that was followed to develop the formwork selection system software. The capabilities and limitations of these systems are also provided. Chapter Eight explains the results of the parametric study. The relationships between building parameters (i.e. height, size, etc) and formwork systems is tabulated. Chapter Nine provides a conclusion and recommendations for future work and extension.
CHAPTER TWO
A CONCEPTUAL FORMWORK MODEL

The intent of this chapter is to develop a conceptual model which models the decision-making process of the different phases of the formwork life cycle. The IDEF0 modeling methodology is introduced as an appropriate tool for modeling formwork operations.

2.1. Modeling Definition/ Purpose

A model is a representation of the real life system or process by some mathematical or numerical expression which can be used as a substitute for the real thing when direct experimentation is too expensive or too dangerous to perform (24, 25). Models permit the user to change the input data parameters (factors) of the model and measure the model performance in order to predict what would happen in a real system.

2.2. Types of Models

Modeling techniques may be classified by their methods of representation, which range from full-scale reproduction of the real world system to purely mathematical formulae. In between, the model can exist in various degrees of reality. Many models are utilized by the Civil Engineering discipline in general and the
construction industry in particular. The classifications listed below illustrate some of the modeling techniques used by civil engineers, followed by a particular example for each (24).

2.2.1. Pure Physical Models

These are full-scale replicas of a physical object. These models permit expert to evaluate some aspect of the object. A particular example of this modeling technique is the architectural mock-up model. The preconstruction mock-up is a full-scale sample of architectural concrete, built at the job site by the contractor to assure the appearance of the exposed concrete (26).

2.2.2. Physical Geometric Models

These are geometrically scaled models retaining the physical characteristics of their full-scale version. A reduced-scale model of a beam, built to study the strength of the real scale beam, is a good example of this type of model (24).

2.2.3. Mathematical Models

These models are concerned with mathematical representation of the relationship between dependent variables and independent variables. Bidding models are good examples of mathematical models.
2.2.4. Simulation Models

These models are used to predict and/or optimize the performance of a system. For example, a loader-truck operation can be simulated to obtain the optimum balance between the number of trucks used to haul material and the number of loaders used to load those trucks to fully occupy the loaders.

2.2.5. Schematic Models

These are graphical representations of relationships between stages in complicated systems. CPM networks and organization charts are examples of schematic models. It should be noted that the proposed model used in this chapter (IDEF₀) is a schematic modeling technique.

2.3. The IDEF₀ Modeling Methodology

IDEF is a methodology developed by SofTech, Inc., based upon SofTech's Structured Analysis and Design Technique (SADT) (27). IDEF was developed to provide a disciplined approach to achieving an understanding of the user's needs prior to providing a software design solution. IDEF provides the user and system designer with a technique to structure the procedure of performing a specific task via diagrams.

Each IDEF model consists of a set of related diagrams that is organized in a hierarchical manner. Each diagram is either a
summary (parent) diagram or a detailing (child) diagram which is related to the parent diagram (Figure 2.1.).

Figure 2.1 begins by depicting the whole system as a simple unit (A-0) which is connected by a box with arrows representing interfaces to activities outside the system. A descriptive general name is written inside the box which reflects the overall process. Another general name is written above the external interface arrows, since they also represent a complete set of external factors.

The box which represents the system as a single module is then broken down into another reasonable number (3 to 6) of detailed boxes connected by interface arrows. These boxes represent major sub-divisions (submodules) of the single parent module. This decomposition reveals a complete set of sub-models whose boundaries are defined by interface arrows (diagram A0).

Any of the boxes in diagram A0 may then be further subdivided into A1, A2, . . . etc. Each of these subactivities (e.g. A3) may be divided again (e.g. A31, A32). Division is stopped when no further useful information appears to the user (17).

2.3.1. Types of IDEF0 Models

There are three types of IDEF models. These are:

1. IDEF0, an activity or process or function model, which is oriented toward the decomposition of activities. On an activity diagram within an activity model, the boxes
This diagram (A0) is the "parent" of this diagram (A3).

Figure 2.1  IDEFo  Model Structure (17)
correspond to activities, and the arrows correspond to data (Figure 2.2). These models are the focus of this chapter.

2. IDEF₁ is used to produce an information model which represents the structure of information needed to support the functions of the system.

3. IDEF₂ is used to develop a dynamic model which represents the time-varying behavior of functions, information and resources of the system.

2.3.2. Basic Steps in Creating IDEF₀ Diagrams for the Formwork Situation

The step-by-step procedure for creating the IDEF₀ model is summarized as follows:

1. Select the Purpose of the Diagram.

   The first step in creating any model is to define the model's purpose and orientation. The purpose of this model is to provide the contractor involved in formwork operations with a decision-making tool by gradual introduction of the basic activities involved in the formwork operation.
Figure 2.2 Sample IDEF0 Showing Relationship of Elements
2. Create the Context Diagram.

The model starts by creating a single box containing the name which encompasses the entire scope of the system being described. This single-box diagram bounds the context for the entire model and provides the basis for further decomposition. The "Provide Concrete Structure" activity represents the context diagram for the proposed model. An overview of all the activities included in the context diagram "Provide Concrete Structure" is shown in the activity tree in Figure 2.3.

3. Create Subsequent Diagrams.

The A (level 1) diagram is then decomposed into a manageable number of subactivities (3 to 6). The subactivities cover the same topic as the parent diagram but in more detail. The subactivities are further decomposed into more-detailed diagrams. For example, as shown in Figure 2.3, A1 (level 2) is decomposed into A11, A12, A13, and A14, (level 3). Decomposition was halted after all major elements in the cycle were identified.

2.4. An Integrated Concrete/Formwork Life Cycle

The process of providing formwork and concrete is highly integrated. Figure 2.4 shows the integration between the formwork and concrete life cycles. It should be noted that the terms used are the same as represented in Figure 2.3.
Figure 2.3 Decomposition of the Provide Concrete Structure Activity into Subactivities
Figure 2.4  Integrated Concrete Formwork Life Cycle
In Figure 2.4, the left circle represents the formwork life cycle, while the right circle includes the concrete construction life cycle. The two intersecting points represent the beginning and the end of the concrete construction life cycle. It should be noted that the Cure Concrete and the Strip Forms activities are interchangeable depending on the type of structural element. For example, columns and walls are cured after stripping the forms, while slabs and beams are cured before and after stripping.

The life cycle of formwork starts with the Choose Formwork activity, which represents the design life cycle of the forms. The physical activities in the formwork life cycle are represented by this step: (1) Fabricate Formwork; (2) Erect Formwork; and (3) Remove Formwork. The concrete construction life cycle starts after the Fabricate Formwork activity and ends before the Remove Formwork activity. The function of the formwork life cycle is to provide the structure with the specified shape and size, while the function of the concrete construction life cycle is to provide the structure with concrete of specified strength, durability, and surface texture.

In the last activity of the formwork life cycle, Repair/Reuse or Store, the formwork elements are either repaired and reused or stored and/or replaced. In the first case, Repair and Reuse, the formwork life cycle repeats itself, starting from the Erect Formwork activity (represented by dark line in Figure 2.4). In the second case, Stored and/or Replaced, formwork elements are either cleaned and stored for future reuse or replaced when they are no longer useful.
2.5. **Modeling the Concrete Structure**

The construction of concrete structures requires the use of formwork to contain the freshly mixed, plastic concrete. Using the function model of "Provide Concrete Structure," it is possible to view the overall function of formwork activities as an integrated part of the concrete structure activities.

The Provide Concrete Structure activity represents the entire construction process (Figure 2.5). In this activity, the resources are converted into a concrete structure. Another output produced by the activity is data for cost, time, safety, and quality, which provide the contractor with valuable historical data. The arrows entering the top of the box are the controlling data which include the building requirements. A detailed description of the resources and building requirements are provided in Appendix B.

2.6. **Provide Concrete Structure (A-0)**

A breakdown of all the activities involved in the Provide Concrete Structure activity is shown in the tree structure in Figure 2.3. The Provide Concrete Structure activity is divided into the four subactivities of Design Structure, Acquire Resources, Construct Structure, and Operate and Maintain Structure. A description of the activities and subactivities is listed below. It should be noted that in building the model, the emphasis is given to those activities that are related to the formwork operation (i.e., Choose Formwork, Provide Formwork, and Remove Formwork).
A1. Design Structure. Design, in general terms, is defined as the process by which systems, concepts, and ideas are developed, refined, and implemented into instructions (3). In the Design Structure activity, the designer must make a series of critical decisions that influence the success of the project. These include: Choosing a Structural System, Selecting a Material Handling System, Choosing a Formwork System, and Developing a Production Plan. These decisions are usually made in the office and not on the construction site.

A2. Acquire Resources. In this activity, all the resources needed to construct the structure are acquired and allocated. These include labor, materials, equipment, and tools. The intangible resources such as site conditions and the supporting organizations should also be reviewed (See Appendix B).

A3. Construct Structure. In this activity, the physical work that converts the resources into an existing structure is performed. This activity includes all the activities that are performed on the construction site.

A4. Operate and Maintain Structure. In this activity, the building components are tested, and major electrical and mechanical systems are checked. This activity also involves the warranty period during which the designer and the contractor can be asked to correct problems that were not immediately evident upon initial testing (2).
Selected boxes in Figure 2.3 are decomposed into subactivities. The criterion used for decomposition is to expand any box containing essential formwork activities. In the next sections (2.6.1 & 2.6.2.), activities A1 and A3 (level 2) are decomposed to show the typical design and physical formwork activities.

2.6.1. Design Structure (A1)

The Design Structure activity (level 2) is divided into the four level 3 subactivities shown in Figure 2.3. A detailed description of each follows prior to a direct focus on "Choose Formwork Systems" in section 2.6.3.

A11. Choose Structural Systems. This activity is coordinated by the Architectural and Structural Engineers. In this activity, alternatives for the main structural systems are evaluated and the best ones are selected. These include: (1) foundation system (shallow versus deep); (2) supporting elements (columns and/or walls); (3) floor system (one-way versus two-way slab); and (4) the lateral load resisting system (shear walls, moment resisting frames, and tube systems).

A12. Select Material Handling Systems. This activity includes the selection of the batching system, mixer, and transportation and handling systems. It also involves site layout, which includes assigning storage areas, positioning of the lifting devices (cranes), and preparing access roads.
A13. **Choose Formwork System.** This activity includes the process of selecting formwork systems for different structural elements. It also includes the process of selecting accessories, bracing, and a release agent for the selected formwork system.

A14. **Develop Production Logic.** The major activities included in this activity are:

- Prepare a construction plan which explains both vertical and horizontal construction sequences for formwork, rebar, and concrete placement.

- Prepare a construction schedule which includes the major milestones and the total duration of concrete placement as a part of the project. A summary and/or detailed CPM network is also prepared in this stage.

- Prepare detailed drawings for different structural elements, which include architectural, reinforcement, and formwork drawings.

- Prepare a construction cost estimating system and propose methods that should be followed to control the cost during construction.

2.6.2. **Construct Structure (A3)**

The Construct Structure activity (level 2) is divided into the three level 3 subactivities as shown in Figure 2.3. A detailed description of each follows prior to a direct focus on "Build Structure" in Section 2.6.4.
A31. Acquire Resources for Structure. The engineer's major activities included in this activity are (28):

- Providing resources, which include the material obtained from the quantity takeoff list, equipment, and tools.
- Receiving and inspecting resources, which includes checking and verifying the quality and the quantities of the acquired resources.
- Storing the resources and managing the inventory, which includes stockpiling and tracking material, equipment, labor, and tools.
- Repairing and maintaining resources, which includes the distribution of resources according to predetermined priorities.

A32. Build Structure. This activity includes the physical work of transforming the acquired resources into a tangible structure. It includes the organization and coordination of construction equipment, materials, money, technology, and methods, and the time required to complete the project on schedule, within the budget, and to the standards specified by the designer (2).

A33. Finish Structure. This activity includes the process of turning the completed structure into a useable facility. It includes providing the building with flooring, painting, false ceilings, and other finishing materials. This model does not include mechanical and electrical systems.
2.6.3. Choose Formwork System (A13)

The Choose Formwork activity (level 3), which is a subactivity of "Design Structure" (A1), is divided into four level 4 subactivities as shown in Figure 2.3. A detailed description of each follows:

A131. Obtain all Necessary Information. In this activity, all the necessary information should be collected so that intelligent decisions can be made at the beginning of the design process. Such data may include soil conditions, building codes, anticipated loading, available materials, area practice and technology, unit cost for material and labor, available crane capacity, and any other related information (See Building Requirements in Appendix B).

A132. Identify Changes. In this activity, system consistency and integrity is reviewed and the necessary changes are proposed. The output of this activity is in the form of change orders. It should be noted that the contractual approach has a major influence on this activity. Early selection of the contractor and/or construction management firm will facilitate the selection of the optimum system.

A133. Evaluate Alternatives. In this activity, the pros and cons of the different systems should be evaluated to avoid expensive start-up and detailed design time pursuing infeasible alternatives. Value engineering appears to be one scientific approach to use to assist in identifying the optimum choice.
A134. Design Formwork. After the final selection of a specific system is made, the different formwork elements are then designed according to the applicable codes and standards. The structural design of the formwork system is then reviewed with regard to cost, quality, and the proposed time to erect the selected system. Safety of erection and dismantling of the system should also be checked during this activity.

2.6.4. Build Structure (A32)

The Build Structure activity, which is a level 3 subactivity of "Construct Structure" (A3), is divided into three level 4 subactivities as shown in Figure 2.3. A detailed description of each follows:

A321. Provide Formwork. This activity includes the process of providing the total system of temporary supports for the freshly placed concrete, including sheathing, as well as all other supporting members, hardware, and bracing.

A 322. Provide Concrete. This activity includes the production of concrete, including batching, mixing, placing, consolidating, finishing, and curing of the concrete. In this activity, the concrete mix is converted into a strong and durable structural material of desired shape and size.
A323. Inspect/Repair Concrete. This activity includes the process of checking the quality of the hardened concrete and performing the necessary repairs for surface defects.

2.6.5. Provide Formwork (A321)

The Provide Formwork activity, which is a level 4 subactivity of "Build Structure" (A31), is divided into three level 5 subactivities as shown in Figure 2.3. A detailed description of each follows:

A3211. Fabricate Formwork. One of the aspects of this activity is the process of selecting the size and location of the form fabrication facility. It also includes: receiving materials, cutting and stockpiling the lumber by sizes, assembling the pieces into the desired shapes and sizes, and storing the forms near the lifting devices.

A3212. Erect Formwork. This activity includes the process of lifting, positioning, and aligning different formwork elements. Figure 2.6 illustrates the major activities involved in this activity in a logical flow chart format.
Figure 2.6. Logical Flow Chart for Erecting Forms
A3213. Remove Formwork. This activity includes the process of stripping different formwork elements, providing the appropriate shores and reshores, and then removing the forms for repair and future reuse or storage.

2.6.6. Provide Concrete (A322)

The Provide Concrete activity, which is a level 4 subactivity of "Build Structure" (A32), is divided into four level 5 subactivities as shown in Figure 2.3. A detailed description of each follows:

A3221. Place Inserts and Reinforcement. This activity includes the process of applying the form release agent, placing inserts for mechanical and electrical connections, openings for ducts and conduits, supporting bars for reinforcement, and the reinforcing steel for the structure.

A3222. Deliver Concrete. This activity includes the physical process of concrete production. It includes mixing, transporting, pumping, and placing concrete.

A3223. Consolidate Concrete. This activity includes striking the concrete to remove the humps and hollows, and consolidating the concrete with hand tools or mechanical vibrators to guarantee a dense structure.
A3224. Finish Concrete. This activity includes the process of treating the exposed concrete surfaces to produce the desired appearance, texture, or wearing qualities (27).

A3225. Cure Concrete. This activity includes the process of curing concrete with water, steam, or any other method to prevent the shrinkage and allow the concrete to gain sufficient early strength.

2.6.7. Remove Formwork (A3213)

The Remove Formwork activity, which is a level 5 subactivity of "Provide Formwork" (A321), is divided into four level 6 subactivities as shown in Figure 2.3. A detailed description of each follows:

A32131. Strip Forms. This activity includes the process of stripping the forms when the concrete is strong enough to eliminate immediate distress or deflection under loads.

A32132. Provide Shores/Reshores. This activity includes the process of providing temporary vertical support shores for the stripped structural elements which have not yet developed full design strength, and also providing temporary vertical support for the completed structure placed after the original shoring support has been removed (reshores).
A 32133. Remove Reshores. This activity includes the process of removing reshores after the supported slab or member has attained sufficient strength to support all loads transferred to it.

A 32134. Repair/Reuse or Store/Depreciate. This activity includes the process of cleaning, repairing, oiling, and stockpiling forms.

2.7. IDEF$_0$ Models to Support Expert System Development

Figure 2.3 shows six levels of detail for the Provide Concrete Structure activity which encompasses the entire scope of the model in general terms. Formwork activities are represented at different levels of detail. The Choose Formwork system (A13) activity is a part of the design phase (preconstruction activities). The Provide Formwork (A321) activities represent the physical work performed by site personnel (fabricate, erect, and remove).

The IDEF$_0$ model developed for the Choose Formwork (activity A13) will assist the expert system developer/user in identifying the logical decision sequences used by the human expert when choosing a formwork system. The IDEF$_0$ diagram shown in Figure 2.7 simulates the expert system performance. For example, activity A131, "Obtain all Necessary Information," is given by the expert system in the form of multiple choice questions. The expert system will evaluate all the alternatives (activity A133) by applying the appropriate rules and will provide the final design of the formwork system (activity A134).
Figure 2.7 IDEFO Model of "Choose Formwork System"
2.7.1. Choose Formwork System IDEFO Model

The purpose of this model is to select and sequence those activities suitable for the appropriate selection of each structural element. As noted in Figure 2.3, the context of this module is labeled A13. A level description is given in sections 2.5.1 and 2.5.3, of this chapter. As noted, the diagrams which define module A13 are represented in Figure 2.7.

2.7.2. Provide Formwork IDEFO Model

This model is intended to describe all the physical activities involved in the formwork life cycle. As noted in Figure 2.3, the context of this module is labeled A312. A level description is given in sections 2.5.4 and 2.5.5 of this chapter. The diagram which defines module A312 are represented in Figure 2.8.

2.7.3. Remove Formwork IDEFO Model

This model is concerned with the safety aspects of removing formwork. It represents the final stage of the formwork life cycle. As noted in Figure 2.3, the context of this module is labeled A3213. A level description is given in sections 2.5.5 and 2.5.7 of this chapter. The diagram which define module A3213 are represented in Figure 2.9.
2.8. Reading IDEF\textsubscript{0} Models and Their Diagrams

The IDEF\textsubscript{0} models are used to describe a system. The system is made up of boxes showing well-defined portions of the system. Figure 2.7 may be selected as an example of the IDEF\textsubscript{0} (activity model) for the activity Choose Formwork System, which is node A13 in Figure 2.5. It should be noted that nodes in the diagram may be referred to by their node numbers or by their titles.

Diagrams should be read from left to right. The information needed to select a formwork system is first obtained, and then the changes are identified. From the Evaluate Alternatives activity, a particular system is chosen and then designed to determine the safe formwork elements and hardware.

In each box, there are a number of arrows that enter the left side of the box and leave the box from the right side. These are inputs and outputs of each activity respectively. Inputs are converted by the activity into outputs (e.g. system consistency and integrity; the output of box 1 is converted to change orders by the activity (Identify Changes)).

A number of arrows also enter the top of the boxes, these are controlling factors (control data). Control data are not modified by the activity, but influence how the activity is performed. For example, in box 1, the contractual approach (i.e. traditional, turnkey, owner builder, and professional construction management), determines how early the contractor can obtain the necessary information to select the optimum formwork system.
2.9. **Summary**

The conceptual model for constructing a concrete structure has been described in some detail in this chapter. Emphasis has been placed on the formwork operations as an integrated part of the concrete structure. Formwork models have been designed using IDEF0 modeling methodology. The model described presents a decision support system for the transfer of information and data between the design and construction activities. The IDEF0 model for the "Choose Formwork System" provides the logical sequences of activities which are performed by the human expert to select the formwork system. The subactivities of node A13 "Choose Formwork System," as denoted by figures 2.7, 2.8, and 2.9, define the framework for and simulate the function of the expert system.
CHAPTER THREE

FACTORS AFFECTING THE SELECTION OF FORMWORK SYSTEMS FOR CONCRETE BUILDINGS

Chapter Two described the four subactivities that are required to Choose the Formwork System (Node A13 of Figure 2.3). These are: (1) Obtain all Necessary Information (A131); (2) Identify Changes (A132); (3) Evaluate Alternatives (A133); and (4) Design Formwork (A134). This chapter will focus on activities A131 (Obtain all Necessary Information). It will introduce the different forming systems available to the contractor, information that is essential to the contractor in making the decision.

This chapter begins with a brief presentation of the roles of the different parties involved in the selection of formwork systems. This is followed by a technical description of the formwork systems used for concrete buildings.

3.1. Introduction

This chapter describes the myriad forming systems available to concrete contractors and formwork subcontractors. Many concrete buildings may efficiently utilize either a few or many of these systems, depending on the requirements of the individual areas of the buildings.
The selection of the proper formwork system requires adequate information about available horizontal (Slabs), and vertical (Columns/Walls) forming systems. The information collected that describes the formwork systems should include the criteria used by contractors to select the system. These criteria are (4, 9):

1. The formwork system should be available and economically feasible for the contractor.
2. All major parties - owner, designer, and contractor - should be familiar with the selected forming systems, since certain systems, such as slip forms, require special economic evaluation, design configurations, and safety precautions.
3. The selected formwork system must be consistent with the architectural and structural requirements of the building. For example, if architectural concrete is required for the external columns, then slip form systems do not provide the appropriate forming solution.
4. The selected system must be compatible with the mechanical and electrical requirements of the building. For example, flying forms are not an economical solution when there are extensive penetrations through the slab (e.g. electrical and mechanical).
3.2. Parties Involved in Formwork Selection and Their Responsibilities

The proper selection of the formwork systems to be used in a cast-in-place concrete building is of concern to all involved parties. Some of the major responsibilities of these parties which need to be considered to achieve the proper and optimum selection of the formwork systems are discussed below (30, 31, 32).

3.2.1. Owner's Role

The owner's chief objectives are to minimize overall project cost and construction time and assure specified quality and safety of the finished product. Recognizing the fact that formwork is a high-cost item which controls the pace of construction, a knowledgeable owner should be involved or informed early in the project about the selected system and whether it satisfies his needs or not. Special mock-ups should be shown to the owner when special requirements such as architectural concrete are involved.

3.2.2. Designer's Role

Economical design for concrete isn't necessarily achieved by minimizing the dimensions of the structural elements. Some other factors have larger influences on building costs. For example, labor for formwork is a large cost item (See Figure 3.1), and thus a few
Figure 3.1 Standard Distribution of Costs for Cast-in-Place Concrete (33)
changes in column size or wall height to achieve uniformity and repetition can result in a substantial cost reduction in overall formwork cost. When designing a building, the designer should consider each of the following methods of reducing the cost of formwork (30, 31, 32):

1. Repetition

Repeating the same layout from floor to floor assures that the workers learn quickly, thus increasing the productivity (learning curve), and decreasing the labor cost. Also, the same forms can be effectively reused from floor to floor.

2. Standardization

Basing the design on readily available standard form sizes is less expensive than specifying custom-built forms for the project. For example, in designing a joist or waffle slab, the designer should consider the standard size pans available and base his design on these modules.

3. Consistency and Simplicity

The designer can save substantial construction cost by keeping the design simple and the elements consistent. Uniformity is achieved by maintaining a constant dimension for the different structural elements. Specific examples of consistency include:

a. maintaining constant breadth and depth for all beams.

b. maintaining constant column dimensions and spacing between columns.
c. maintaining constant spacing between beams and joists.

3.2.3. Contractor's Role

Most contractors carefully study the influence of formwork on project cost and progress. In selecting formwork, a contractor's primary list of concerns is to (5, 31):

1. Design formwork to achieve high quality with a minimum of possible cost and time. Safety is another major concern for the contractor; inadequate shoring and reshoring can result in failure or excessive deflection which requires chipping and grinding or demolition.

2. Use forming systems instead of job-built forms; this reduces labor costs (which represent 38% of the cost of cast-in-place concrete. Formwork systems can reduce the labor cost by 50% (See Figure 3.1).

3. Plan the formwork as an integrated part of the overall planning procedure so that the process of erecting and dismantling the forms can be accelerated.

3.3 Forming Systems

There are several ways to form any given concrete building. One of them will typically be the lowest cost method. Selecting the lowest cost method of forming requires searching through a maze of forming systems and their attributes. In the following sections, a
brief description of the forming systems currently used for different structural elements will be discussed.

3.3.1. Horizontal Forming Systems

There are seven horizontal forming systems that can be used to support each of the slab types described in Chapter Six. These are: (1) conventional wood systems (stick forms); (2) conventional metal systems (improved stick forms); (3) flying truss systems; (4) column-mounted shoring systems; (5) tunnel forming systems; (6) joist-slab forming systems; and (7) dome forming systems. It should be noted that joist-slab and dome forms are usually placed above the plywood sheathing. A description of each forming system follows.

3.3.1.1 Conventional Wood Systems

Conventional wood systems consist of wood shores supporting wood stringers and joists (runners), with the deck surface made of plywood (Figure 3.2). The deck may also be made of large panels tied or ganged together and supported by scaffold-type shoring (4, 34).

3.3.1.2 Conventional Metal Systems

Conventional aluminum systems may be either hand-set or panelized. Hand-set systems usually consist of wood or aluminum
Figure 3.2 Conventional Wood System (41)
shores supporting aluminum stringers and joists, with the deck surface made of plywood (Figure 3.3). The same type of deck forms can be made up of large panels tied or ganged together and supported by steel scaffold-type shoring. Aluminum panel models range in length from two to eight feet, and in width from two to 36 inches in two-inch increments (34, 35).

3.3.1.3 Flying Truss Systems

Flying truss forms usually consist of large sheathing panels supported by steel or aluminum trusses (beams), that rest on screw jacks which allow the forms to be adjusted to the right level (See Figure 3.4). For stripping, after the concrete has gained enough strength, the system can be lowered away from the slab by turning down the jacks. The truss mounted forms are then moved by crane from one casting position to the next (4, 30, 34).

3.3.1.4 Column-Mounted Shoring Systems

Typically, formwork under cast-in-place slabs has been supported by shores resting on the floor or ground below. Another way to cast the slab without using the shoring system is to use long span form panels supported by up-and-down adjustable brackets attached to the bearing walls or columns of the building itself. The system consists of plywood decking which can be assembled on the ground or in place, once the form has been flown and set on the
Figure 3.3  Conventional Metal System (4)
Representation of Flying Truss System

Representative Details for Casting a Concrete Slab and Beams Using Flying Truss System

Figure 3.4 Flying Truss System (30)
columns (See Figure 3.5). The plywood decking is supported by joists (headers), which are attached to the stringers (steel beams). For stripping, jacks are lowered until the framing beam of the deck rests on the rollers attached to the bracket. The entire form assembly is then rolled out and carried by crane to the next floor (36).

### 3.3.1.5 Tunnel Forming Systems

Tunnel forms are factory-made U-shaped or inverted L-shaped steel forms which permit casting of both the slab and supporting walls at the same time (See Figure 3.6 (a)). For stripping, after the concrete has gained enough strength, the tunnels are collapsed or telescoped and moved to the next pour (See Figure 3.6 (b)). Half tunnels are used for spanning wide rooms - full tunnels for spanning narrow rooms. Standard modular panels offer a wide range of flexibility in room size. WIDTHS from 13 ft. to 24 ft., heights from 7.5 ft. to 10 ft., and lengths up to 40 ft may be specified (37, 38).

### 3.3.1.6 Joist-Slab Forming Systems

A one-way joist slab is a monolithic combination of regularly spaced joists arranged in one direction and a thin slab cast in place to form an integral unit with the beams and columns (Figure 3.7 (a)). One-way joist slabs have frequently been formed with standard steel pans. Table 3.1 shows the dimensions of the standard form pans and
Figure 3.5  Representation of One of Several Systems Available for Column-Mounted Shoring System
(a) U or Inverted L shape
Steel Tunnel Forms (37)

(b) Stripping of Half Tunnel Form (38)

Figure 3.6 Tunnel Forming System
Figure 3.7 (a) Typical Wide-Module Joist Slab System (39)

Figure 3.7 (b) Dome Form for Waffle Slab
<table>
<thead>
<tr>
<th>STANDARD FORMS</th>
<th>Width</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>2'</td>
<td>2.0</td>
<td>8.10, 12</td>
</tr>
<tr>
<td>3'</td>
<td>3.0</td>
<td>10.15, 16, 20</td>
</tr>
<tr>
<td>4'</td>
<td>4.0</td>
<td>12.14, 18, 16, 24</td>
</tr>
<tr>
<td>5'</td>
<td>5.3</td>
<td>16, 20</td>
</tr>
<tr>
<td>6'</td>
<td>6.6</td>
<td>14, 16, 20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SPECIAL FILLER FORMS</th>
<th>Width</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.10, 12</td>
<td>8.10, 12, 14, 16, 20</td>
</tr>
<tr>
<td></td>
<td>10.15, 20</td>
<td>12.14, 16, 18, 20, 22, 24</td>
</tr>
</tbody>
</table>

All dimensions in inches
the special fillers for one way joist construction. It should be noted that any spacing between pans which exceeds 30 in. is referred to as a wide-modular or skip-joist system (4, 39).

3.3.1.7 Dome Forming Systems

Standard size domes are usually used for waffle slab construction. They are based on two, three, four, and five ft. modules. The two ft. size modules utilize 19 x 19 in. domes, with 5 in. ribs between them, and the 3-ft. size modules can be formed with 30 x 30 in. domes and 6 in. ribs. Figure 3.7 (b) shows the two standard modules that are used for waffle slab construction (4, 40).

3.3.1.8 Summary of Horizontal Formwork Systems

The preceding sections presented five different horizontal forming systems and two special ones, joist and waffle slab forming systems. Two of these systems, the conventional wood system and the conventional aluminum system, are classified as hand-set systems. The remaining systems are classified as crane-set systems. Joist-forms and dome forms can be handled by hand or attached to the surface deck of the flying form and "flown" to its place. Joist and waffle slabs are considered a special cases because they can be used and set above any of the forming systems explained in Sections 3.3.1.1. through 3.3.1.5.
3.3.2. Vertical Forming Systems

Vertical forming systems are those used to form the vertical supporting elements of the structure (i.e. columns, walls). The function of the vertical supporting systems is to transfer the floor loads to the foundations and to resist the lateral loads resulting from wind loads and earthquakes. Five types of vertical forming systems are available. These are conventional, gang, slip, jump, and self-raising forms.

3.3.2.1 Conventional Wall Forming Systems

This all-wood forming system consists of sheathing made of plywood or lumber, supported by vertical wood studs. Single or double horizontal wales are used to support the studs (Figure 3.8). Ties may be drilled through wales (single wale) or inserted between them (double-wale) to resist the horizontal pressure of plastic concrete. An inclined bracing system is used to prevent forms from moving (41).

3.3.2.2 Ganged Forming Systems

Gang forms are made of large panels joined together with special hardware and braced with strongbacks or special steel or aluminum frames. These large panels are usually built or assembled on the ground and raised into place by crane. In high wall
Figure 3.8 Conventional Wall System (41)
construction, the ganged panels are frequently raised by crane to the next pouring position, and supported by steel brackets fixed to the lift below. Figure 3.9 shows some of the standard ganged forms available for contractors (42).

3.3.2.3. Slip Forming Systems

Slip forming is usually used to cast walls, piers, towers, and structural cores. Slip forms consist of inner and outer forms, 3.5 to 6 feet high, using one-inch thick lumber. Forms may be fabricated from wood or steel, and supported by strong vertical yokes. These yokes are tied together at the top to give the form sides the rigidity needed. Locomotion is accomplished by jacks climbing on smooth steel rods or pipes anchored at the base of the structure and embedded in the concrete below the forms (foundations). These jacks may be hydraulic, electric, or pneumatic and operate at speeds up to 24 in/hr. Jacks usually have carrying capacities between three and 25 tons, and are spaced four ft. on centers (See Figure 3.10 (a)).

A working platform is attached to the inner form and slides up with it to provide a place from which workers can place concrete and fabricate steel reinforcement. Another working platform is suspended from the outer form to allow workers to finish the newly cast concrete (See Figure 3.10 (b)).
Figure 3.9  Standard Ganged Forms (42)
(a) Typical Schematic Cross Section of the Slipform (4)

(b) Typical Slipform With Deck & Finishing Scaffolding on Wales (4)

Figure 3.10 Slipform System (4)
Concrete is placed into the form at the top end as it is drawn upward. Thus, a continuous process is carried on, filling and moving the forms upward, often 24 hrs. a day, until the structure is complete.

3.3.2.4 Jump Form System

Jump forms are used where no floor is available on which to support the wall formwork, or the wall and column proceed ahead of the floor. Jump-forms consists of a framed panel attached to two or more strongbacks. They can be one floor high, supported on inserts set in the lift below. Two sets, each one floor high, that alternately jump past each other can also be used. Figure 3.11 shows a typical jump-form cycle, which consists of three basic operations: strip, fly, and reset (44).

3.3.2.5 Self Raising Forming Systems.

This system consists of upper form(s), and lower lifters (self-raisers). The lifters are attached to the wall already cast below the form. Figure 3.12 shows a schematic representation of the sequential steps involved in self-raising forms which can be explained as follows (45, 46, 47):

Step 1. The forms and lifters are placed against the wall, as they were after the last lift of concrete was placed.
Figure 3.11 A Typical Jumpform Cycle (44)

Strip:
A) Begin by removing all form ties and anchor positioning bolts.
B) Next, strip the gang by turning the pipe braces' adjusting screws.
C) With the inserts now accessible from the upper level platform, attach landing brackets for the next lift.
D) At the same time, while working from the lower platform, remove wind anchors and finish concrete patching.
E) Hook the crane up to the gang, workers leave the JumpForm.

Fly:
F) Lift the JumpForm, flying it to the next level.

Reset:
G) Where it automatically attaches to the landing brackets.
H) Workers then return to the JumpForm and immediately release the crane.
I) Wind anchors are attached at either the tie location or the landing bracket inserts.
J) Then, after cleaning andulling the gang from the upper platform of the opposite gang.
K) Plumb the gang using the adjustable pipe braces.
L) Crews can now set all steel and backouts, working from the upper level of the opposing form.
Figure 3.12  A Typical Self-Raising Form Cycle
Step 2. The lifters are unbolted from where they are attached and pulled away horizontally by stripping jacks.

Step 3. The lifters are lifted by hydraulic, pneumatic, or electric jacks to a new position immediately below the forms. It should be noted that the top pour has to gain enough strength to support the weight of the lifters.

Step 4. The lifters are pushed back against the wall by stripping jacks, and then reanchored to the wall just below the forms.

Step 5. The forms are unbolted, stripped, and dragged with the stripping jacks.

Step 6. The forms are lifted to the next casting position.

Step 7. The forms are brought into line, ties rods are installed, and the concrete is placed below the top of the form. It should be noted that the first two floors above the ground should be formed by a conventional forming systems before the self-raising form is used (46).

3.4. Summary

In setting criteria for the proper selection of the formwork system, this chapter has reviewed the myriad forming systems used for horizontal and vertical concrete work. Five different horizontal forming systems were introduced as possible candidates for slab forming. Joist and waffle slabs were considered special cases because they can be used with any of the five basic forming systems.
Five vertical forming systems were described. Three of these systems (conventional, slip, and self-raising) are crane independent (i.e. the crane is only used for material handling and placing concrete). The remaining two (gang and jump form) are crane-set systems, the crane serve the dual functions of erection and dismantling forms as well as delivering materials.
CHAPTER FOUR
EXPERT SYSTEMS

The actual judgement of whether or not a system is an expert system or a knowledge-based system is dependent on the source of knowledge. In knowledge-based systems, a great amount of compiled "textbook" knowledge is used. On the other hand, expert systems result from a true interaction between the knowledge engineer and the human expert (7).

The purpose of this chapter is to provide some insight into the construction of expert systems and their components, as well as the different methods of knowledge representation. The fundamental concepts and the key terms used with expert systems are also provided.

4.1 Definition of Expert Systems

Several researchers have defined the term "Expert Systems." Some of the popular definitions are:

1. "An intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution." (48)
2. "Expert systems are interactive computer programs incorporating judgment, experience, rules of thumb, intuition, and other expertise to provide knowledgeable advice about a variety of tasks." (49)

3. "A tool which has the capability to understand problem specific knowledge and use domain knowledge intelligently to suggest alternate paths of action." (50).

The above definitions contain three common features which clarify the concept of expert systems. The first is the fact that expert systems are interactive, intelligent computer programs. The word "intelligent" is used to describe the unique feature of expert systems which separates the control system from the database. It should be noted that in conventional programming languages such as FORTRAN and BASIC, the control system and the database are integrated parts of the program.

The second common feature of experts systems is that they use "inference procedure judgment." This phrase describes the knowledge that is contained in the expert system that is based on the judgement and rules of thumb which are characteristics of human decisions.

The third feature defines the expected performance of the expert system (goal); it provides knowledgeable advice, and suggests alternative paths of action. It thus provides performance similar to that of a human expert.
4.2 Components of Expert Systems

Figure 4.1 shows the basic architecture of an expert system program. The structure of the program consists of five basic components. These are a knowledge base, a working memory or database, an inference engine, a user interface, and a knowledge acquisition module (7, 50, 51). A brief description of each of these components follows.

4.2.1 Knowledge Base

The knowledge base contains general facts and heuristics about a specific domain. The facts are represented by declarative knowledge, heuristics take the form of procedural rules. For example, the knowledge for selecting the formwork system may include facts related to the physical characteristics of the site conditions such as site size, location, and accessibility. The rules that relate the selection of the formwork system to the site conditions are procedural rules, which are based on heuristics, experience, and rules of thumb.

It should be noted that rules contained in the knowledge base are static in nature. The knowledge-base includes rules on how to solve problems generally with no specific reference to a particular problem or situation.

1 This material has been drawn from (7, 61, 62)
Figure 4.1  Expert System Architecture (51)
4.2.2 Working Memory or Database

This component of expert systems contains the information about specific problems that are currently being solved (i.e. domain specific knowledge). The working memory is dynamic in the sense that information changes according to specific situations or each computer run (consultations).

4.2.3 Inference Engine

The inference engine is the part of the expert system that contains the control information. The inference engine performs two tasks. First, it adds new facts and rules to the database. Second, it determines in which order the rules are scanned and fired (i.e. evaluated). An efficient inference engine utilizes the knowledge base in an intelligent, accurate and appropriate manner. In some systems the inference engine works in a "forward" manner, using the facts in the memory to reach a conclusion. In other systems, the inference engine works in a "backward" manner, trying first one conclusion and then another, until it can find supporting facts for a particular conclusion (51). These techniques will be explained in more detail in Sections 4.3.1 and 4.3.2.

4.2.4 User Interface

The user interface provides a friendly medium for man/machine interaction. A user interface provides the acquired
knowledge in a way which reflects the problem solving strategies of
the system, which in turn reflects the knowledge acquired by the
expert. Some of the basic features of any sophisticated man/machine
interface include:

1. A facility that can help the user follow the lines of
reasoning performed by the system. This facility may
explain how the system reached a certain conclusion by
displaying the fired rules in a sequential manner.

2. A facility that allows the system to respond to questions
like "Why?" and "How?".

3. A facility that allows the system to present information
in an understandable format (i.e. English responses).

4.2.5 Knowledge Acquisition Module

The function of this component is to facilitate the process of
entering the knowledge into the knowledge base. In its simplest
form, this component acts as an editor or word processor for entering
the rules to a file (7). In a more sophisticated form, the knowledge
acquisition module can acquire relevant information directly from
the domain expert and encode it using suitable knowledge
representation techniques (i.e. automating the process of knowledge
acquisition). To date, few systems have provided such a module
(51).
4.3 Control Strategies

The portion of the inference engine that determines the order in which the rules are scanned, then fired, is called the control strategy. Many strategies for solving problems exist. Forward and backward chaining control strategies are the most popular and are frequently used in the development of today's expert systems.

4.3.1 Forward Chaining

In a forward chaining strategy, the inference engine starts with the facts and proceeds forward to find a solution that is supported by the facts. For example, in a rule based system, a rule becomes a candidate for execution whenever its conditional clauses are true. Forward chaining strategy is most useful in situations where there are many solutions and few input data or facts. Forward chaining strategies are often called data-driven or bottom-up searches.

4.3.2 Backward Chaining

In a backward chaining technique, an initial goal state is selected and the inference engine works backwards to find the facts that support that goal. As soon as it finds a valid goal, it moves to a subgoal for its conclusion and tests it. As an example, suppose the rule we are testing is:
Rule 1:

IF : The building is uniform
THEN : Use a flying truss system for horizontal forming

The system needs to know if the building is uniform. The inference engine would automatically check all rules to see if there is a rule that tells if the building is uniform. Suppose that it finds Rule 25:

Rule 25:

IF : Columns are of the same size and location from floor to floor
AND : Beams are of the same size and location from floor to floor
AND : The slab system is flat slab or flat plate
THEN : The building is uniform

The system will test Rule 25 before testing Rule 1. Rule 1 is now in the chain. If there are any rules that tell the system "the columns are of the same size and location" these rules will be tested before Rule 25, and so on, until there are no rules that can be tested. Then the chain will go back to the starting rule. It should be noted that the results are independent of the rule order.
4.4 Knowledge Representation

Humans possess knowledge in a variety of ways. In the previous section, a particular type of knowledge representation known as production rules were described. A survey of other alternative knowledge representation techniques, along with examples related to the domain of formwork, is provided in the next few subsections.

4.4.1 Semantic Networks

A semantic network is a graph structure composed of nodes and links. The nodes represent individual entities (objects) that can be seen or touched, or conceptual entities such as acts or events (52). The links represent relationships between nodes. Typical types of link relationships include:

Is-a: indicates an object is a member of larger class. For example, Flying forms is-a horizontal forming system.

has-a: indicates the object has a property of another node. For example, Flying forms has-a deep aluminum truss.

causd-by, machined-by, or carried-by:
indicates a causal relationships between two nodes. For example, Flying forms is carried-by tower crane.
Figure 4.2 represents the fact that the flying form is a member of larger class of horizontal forming system, and has a deep aluminum truss, and can fly. The same interpretation can be applied to the column-mounted shoring system.

4.4.2 Frames

A frame is a data structure that is used to describe one or more stereotyped situations arranged in slots or filler format. The slots represent factual knowledge such as Type, Use, Material, etc. The fillers are the associate descriptions of the slots (50). A frame is similar to a semantic network; the main difference is that the nodes in a semantic network represent simple concepts, whereas the nodes in a frame structure represent complex concepts. Figure 4.3 shows a frame structure which represents the general concept of a flying form.

4.4.3 Blackboard Representation

In blackboard representation, several independent knowledge bases are used to provide a mechanism for reasoning about problems (7). The knowledge bases may be from different knowledge sources, or levels, which permit the user to store the knowledge in a single
Figure 4.2 Semantic Net Representation Scheme
<table>
<thead>
<tr>
<th>Name of frame:</th>
<th>Horizontal Forming System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Flying Truss System</td>
</tr>
<tr>
<td>Use</td>
<td>To support concrete for slabs</td>
</tr>
<tr>
<td>Material</td>
<td>Plywood sheathing, aluminum truss</td>
</tr>
<tr>
<td>No of legs</td>
<td>2</td>
</tr>
<tr>
<td>Cost</td>
<td>10-15 $ /sq.ft./contact area</td>
</tr>
</tbody>
</table>

Figure 4.3  Frame Representation Scheme
working memory and still use the combined representation to solve problems. A blackboard model is illustrated in Figure 4.4 (7).

### 4.4.4 Predicate Calculus

This representation is a formal language for encoding knowledge and relationships of knowledge, and it is the base for the development of the "Prolog" programming language (52). In this representation scheme, the real world situation can be written in terms of logical clauses. For example, we can use notation such as:

- \( \exists x \) (form \( x \)) \( L \) name \( x \), flying_system

to represent a fact such as:
"There exists an \( x \) such that \( x \) is a form and the name of the form is flying_system.

We also can use formulae to further describe the object such as:
- \( \forall x \) (has_aluminum_truss\( x \)) \( --> \) is_flying_system \( x \)

to represent a fact such as:
"for all \( x \), if \( x \) has aluminum truss, then \( x \) is a flying system."

### 4.4.5 Rule Based Representation Scheme

Rule based systems are the most widely used representation schemes (7, 51, 52). In a rule based system, commonly referred to as a production system, the entire knowledge base is encoded in an IF-THEN rule format. There are two types of rules that are used to represent knowledge. These are:
Figure 4.4 Blackboard Representation Scheme (7)
1. Declarative rules

Declarative rules represent facts and assertions about the problem which relate two entities, called the LHS (Left-Hand Side), and the RHS (Right-Hand Side) of the rule. Declarative rules are used to represent static knowledge, which states that if the LHS is true (antecedent), then the RHS (consequent) is true. For example, the following declarative rule is used to describe the flying form system:

**IF** : The sheathing is made of plywood.
**AND** : The stringers are made of aluminum trusses.
**THEN** : The form is a flying truss system.

2. Procedural rules

In procedural rules, the LHS of the rule is called a situation or condition and the RHS is called an action. For example:

**IF** : The form is a flying truss system
**THEN** : Use tower crane for erection and dismantling.

The meaning of the procedural rules is that it would be appropriate to perform the action part of the rule whenever its condition part is true (50).
4.5. Summary

Expert systems are a special type of computer programs that differ from conventional computer programs. They use Symbols to process knowledge. Knowledge can be represented in a variety of ways. Five different methods of knowledge representation have been introduced in this chapter. Special emphasis was placed on the production rule representation technique.
CHAPTER FIVE
KNOWLEDGE ACQUISITION

This chapter describes the acquisition process that is utilized to build the knowledge base. It introduces the key methods of knowledge acquisition employed in current expert system development. These methods provide a broad perspective within which to work. Subsequent sections focus on the actual method of knowledge acquisition used in this research.

5.1. Introduction to the Problem of Knowledge Acquisition

Effective knowledge acquisition has been recognized as the chief limiting factor in the development of expert systems (54). This is due to the inability of the knowledge engineer to understand the expert's problem solving strategies and the nature of his expertise. This section provides a description of the different sources of knowledge along with the major features of each. Several characteristics which distinguish experts from non-experts or novices are also provided.

5.1.1. Sources of Knowledge

Knowledge typically consists of two types: public and private. Public knowledge is usually found in textbooks, journals, and other
written sources. Public knowledge does not change significantly over time and therefore can be considered static. Private knowledge is that possessed by humans and is not found in the published literature. It is usually acquired in the course of business through solving many similar problems in a given domain. This includes rules of thumb known as heuristics (52, 54).

5.1.2. Nature of Expertise

The expert is that individual who performs the task correctly with notable ease and efficiency. An expert has certain characteristics that distinguish him from other non-experts or novice individuals. Among these are (22, 23, 55):

1. An expert can adapt his problem-solving techniques to novel or unusual situations and apply his expertise efficiently.
2. An expert can often determine the limits of his scope of expertise.
3. An expert can explain and justify his problem-solving behavior.
4. An expert can employ plausible inference and reasoning from incomplete or uncertain data.
5. An expert can communicate with other experts at the same level of understanding and acquire new knowledge.
6. An expert can break the rules; experts have as many exceptions as the rules which they acquire. They also understand the intent of the rules.
5.2. **Knowledge Acquisition Techniques**

In the development of expert systems, the knowledge engineer plays a key role in acquiring and organizing the knowledge. The success of a project is influenced to a great extent by the ability of the knowledge engineer to perform these tasks. The following subsections provide a survey of some of the knowledge acquisition techniques that may be employed by the knowledge engineer, along with the merits and problems associated with each (20, 21, 22, 23, 56, 57, 58). They establish the foundation for section 5.3, where the actual data collection procedure used in this report is presented.

5.2.1. **Interviews**

An interview is the most widely used method of knowledge acquisition. An interview is conducted by identifying an expert and questioning him, or by getting a group of experts to talk to each other and recording their discussion. Interviews can be unstructured or preliminary (broadly focused), or structured (narrowly focused). In unstructured interviews (preliminary), the knowledge engineer might ask questions in general terms such as "When do you usually use the flying truss system?". In structured interviews, the knowledge engineer might ask more specific questions such as "What are the minimum dimensions of the flying form table needed to make it economically feasible?".

Unstructured interviews have the advantage of not forcing the questioner to limit the direction of the interview. As a result, less
obvious points emerge that can be very critical to the problem solution. These are very important in the early phase of knowledge acquisition. Structured interviews, on the other hand, achieve the results quickly when the knowledge engineer is confident of his understanding of the domain problem. They play a large role in the completion of the knowledge base.

The major problem with unstructured interviews is the lack of scope or end goal. It is also difficult for the knowledge engineer to expand the interview session in the right direction if he is not completely familiar with the problem domain.

The major problem with structured interviews is that the knowledge engineer may limit the identification of all the rules used to solve the problem. This can be overcome by introducing these later in the data collection process.

5.2.2. Protocol Analysis

Protocol analysis requires the knowledge engineer to observe an expert performing real world tasks. The expert is asked to provide procedural commentary while he carries out a task. The commentary is then recorded, transcribed, and analyzed in order to understand the problem solving strategies.

This procedure is particularly useful when the expert is not able to provide a reliable answer to the questions because of his inability to verbalize. Experts find it much easier to talk about specific problems rather than answer general questions or talk in abstract terms (21, 22). Protocol analysis also allows the knowledge
engineer to watch the expert when he uses specific references or information, thus enabling him to determine the factors that influence the expert's decision.

There are some problems associated with this technique. First, the knowledge engineer must be sufficiently acquainted with the domain in order to understand the expert's task. Second, not all experts are able to provide good running commentary and often omit steps that seem obvious to them. Laboratory studies have shown that producing a running commentary can affect the way a task is actually performed. Third, protocol analysis does not establish the limits of an expert's knowledge (21).

5.2.3 Machine Induction Technique

Induction is the procedure whereby rules or patterns are induced from a given set of examples provided by either the knowledge engineer or the human expert (56, 57). It is the converse of deduction, which generally involves deducing facts about specific problems from general rules.

In induction, the human expert provides a number of examples, called a training set, of different types of decisions from the problem domain. The expert also provides relevant factors, called attributes, which influence each decision. The induced rules can be obtained directly from a human expert through the use of the training set, or by the use of induction algorithms. This is a computer program in which the data (training set) can be fed. The
system then applies the inductive algorithm to discover the simplest set of rules that generate the desired results.

The advantage of machine induction over other knowledge acquisition techniques is that it automatically produces the rule base and eliminates the role of the knowledge engineer. Also, the expert finds it easier to refer to specific examples than to describe his problem solving process.

The major problem with machine induction is that in some domains it is not possible to supply a database of documented cases that covers the whole range of the problem domain. A second problem is that a poor set of attributes (factors) results in a poor set of rules. A third, more serious problem, is that it is difficult to determine the cut-off points from the training sets. For example, the training set given in Table 6.2 (Chapter Six) indicates no cut-off points for the minimum and maximum heights for the slip form operations.

5.3. Description of the Knowledge Acquisition Process for the Formwork Selection System

The techniques for efficiently extracting knowledge and creating the knowledge base for this research was described as six basic steps in section 1.7.2. These steps fall into three stages. These are:

1. Familiarization stage
2. Elicitation stage
3. Organization and presentation stage
Figure 5.1 shows these stages along with their purposes and methodologies. A detailed description of each stage follows.

5.3.1 Familiarization Stage

The purpose of this first stage is to explore the scope and complexity of the problem domain. This stage also identified whether the initial goals of this report were sufficiently narrow and self contained. Familiarization included a literature review and unstructured interviews.

5.3.1.1 Literature Review

In addition to the knowledge engineer's background in the problem domain, several published works provided an overview and orientation to the subject. Texts, magazine articles, technical papers and conference attendance provided the primary source of literature.

As noted in Chapter One, for the problem domain of concrete formwork, three texts provided a comprehensive description of the formwork systems used in concrete building. These are: Formwork for Concrete (4); Formwork (5); and Formwork for Concrete Structures (30). They contained little information describing the circumstances under which each system should be used, and omitted
Figure 5.1  The Knowledge Acquisition Process
a number of formwork systems such as self-raising, jump, column-mounted shoring, and tunnel.

Another source of public knowledge consisted of articles published in technical periodicals such as (1) *Concrete Construction*; (2) *Concrete International*; (3) *Engineering News Record*; and (4) *Construction Methods and Equipment*. The technical articles described case studies of successful application of specific forming techniques. Site conditions, cost savings, safety features, and the resulting quality of concrete were featured. Approximately thirty rules were developed by carefully studying these sample projects. The writer feels that these technical articles provided a substitution to induction technique described in section 5.2.3. These "real world" case studies provided a "training set" since relevant factors or "attributes" were frequently provided.

Very few articles were found about the relatively new forming systems. For example, only three articles were found that relate to self-raising forms, a relatively new system. Older systems such as slipforming, which can be traced back to beginning of this century, yielded fifteen articles.

The third source of published works was technical papers and reports. Recognizing the importance of the formwork domain, the American Concrete Institute sponsored a series of international conferences entitled "Forming Economical Concrete Buildings" (38, 46). The proceedings of these conferences contained both academic and practical papers. Only one paper was devoted to the selection of formwork systems. Most, however, presented little detail on the
topic. Careful review of these proceedings did however provide a valuable source of knowledge for this research.

This writer also was fortunate to attend the Fourth International Conference in this series, one which was totally devoted to the formwork industry (46). The speakers were representatives of formwork manufacturers and subcontractors. A group of experts attended the conference, and a useful discussion frequently occurred after each presentation. The outcome of this conference was eight hours of tape recorded discussions and presentations which were very helpful to this writer in the preparation of the knowledge base.

5.3.1.2 Unstructured Interviews

Three unstructured interviews were conducted with two major concrete contractors, and a structural designer in the Washington D.C. area. Also, each of the two contractors arranged three site visits in the area. The knowledge engineer conducted another set of unstructured interviews with the project manager of each site. In these interviews, the writer had a set of tentative questions, but the nature of the interviews led the writer to expand the interviews based upon the expert's own answers. The outcome of these interviews was a complete classification of the different formwork systems available to the contractor along with the main features which affect the selection of each. Between two and three answers were received for each question about the formwork system and influence factors. This indicated that the knowledge engineer was
familiar with the different formwork systems and the main factors affecting the selection of each. It should be noted that the questionnaire for the final structured interviews was completely different than the questionnaire prepared for the unstructured interviews.

As noted earlier, in this technique the knowledge engineer does not have an organized list of detailed questions to ask. Rather, he poses broadly focused questions. A fairly extensive set of rules was extracted for this writer's research using this technique. For example, the following is an excerpt from a dialogue which was recorded in the summer of 1988 with a formwork expert working for a major contractor in Washington D.C. area (73, 75).

Knowledge Engineer:

What type of formwork systems does your organization use?

Expert:

We are using 5/8" plywood sheathing supported by aluminum joists and stringers, which in turn are supported by steel shoring system.

Knowledge Engineer:

Why?

Expert:

In the Washington D.C. area, building heights are restricted to 10 to 13 floors high, because the local code prohibits any building higher than the top of the Capitol. Also, most of our buildings are small to medium size and are located in urban areas which lend themselves to this type of forming system.
Knowledge Engineer:
You said small to medium size buildings, what is your definition of small, medium, and large size buildings?

Expert:
Small size buildings have a 10,000 sq. ft. or less "foot print," medium size buildings are between 10,000 and 25,000 sq.ft, large buildings are more than 25,000 sq. ft.

From the above dialogue, the following points were extracted:

1. In response to the first question, the expert described the conventional aluminum system.

2. In response to the question "Why?" the expert cited some conditions that could be outlined in the form IF (condition) THEN (action):
   
   IF : Building size is small or medium
   AND : Building height is between 10 to 13 floors
   AND : Site condition is urban (restricted)
   THEN : Use conventional aluminum forming system.

3. The knowledge engineer used the expert's own answers to expand the discussion. For example, the expert said "our buildings are small," then the KE expanded the dialogue by asking "what is your definition of small size?".

4. The success of this technique is critically dependent on the time that the domain expert can devote to the interview, and the ability of the KE to expand the discussion in the proper direction.
Similar unstructured interviews were conducted concerning other horizontal formwork systems. These interviews provided the basis for establishing a comprehensive set of questions. These questions are listed in Appendix C - Section C.1.

5.3.2 Elicitation Stage "Structured Interviews"

The purposes of this stage are twofold: the first is to develop the search tree which enables the KE to efficiently build the knowledge base; the second is to extract the required knowledge in the form of rules which can be refined and later encoded in a computer system.

Many expert systems have been developed utilizing only information obtained from books and other published works. As a result, they have limited usefulness (16). The strength of expert systems is derived in part from their ability to encode and utilize the expert's knowledge into the system. In an undocumented field such as formwork selection, this private knowledge cannot be obtained from books. The knowledge engineer used structured interviews to capture the expert's approach to the problem, to elicit his knowledge of the rules used to solve the problem situation, and to determine the certainty factors attached to the rules.

The structured interviews used in this research are based on a combination of successful methodologies adapted from several references. These are outlined in the following steps (17, 56, 57, 58, 59).
The elicitation stage is directed at developing an organized procedure to structure the data acquisition before actually conducting an interview. Failure to carefully prepare for this stage will result in acquiring irrelevant knowledge. This step includes: (1) preparing the questionnaire (Section 5.3.2.1); (2) identifying the domain expert (Section 5.3.2.2); (3) establishing an interview kit (Section 5.3.2.3); (4) developing an organized set of questions (Section 5.3.2.4), and (5) preparing an interview record which can be quickly filled in during the interview session (Section 5.3.2.5). These steps will be explained in some detail in the following sections.

5.3.2.1. Prepare Questionnaire

Based on the unstructured interviews and literature search, a comprehensive set of questions was developed (See Appendix C - Section C.2) The questionnaire expands the unstructured interviews to obtain detailed information about specific aspects. For example, during unstructured interviews, the knowledge engineer asked the expert about the circumstances in which the flying truss system could be used. The expert answered "You should have a uniform modular building." Then, when preparing the questionnaire, the knowledge engineer developed a set of questions in an attempt to define what the expert meant by the word "modular." As a result, the questionnaire contained questions about beams, columns, walls, cantilever balconies, and openings and how the changes in the size and/or location of each element affected the expert's definition of "modular" buildings (See Question #1 in Appendix C- Section C.2).
5.3.2.2. Identify Domain Experts

The process of identifying the domain experts for this research included the following steps:

1. Identify Experts in Local, Recognized, Practicing, Formwork Companies.
   Senior vice presidents of three of the leading concrete companies in the Washington D.C. area were contacted. Washington is dominated by concrete construction, and at the time of the research was experiencing a building boom. This identification process was important to assure that senior management was involved and that it contributed to defining the problem and knowing how the eventual system would actually work. These company officers then identified the heads of their formwork departments as good sources of knowledge.

2. Identify Experts from Recommendation by Others.
   One of the characteristics of an expert, as outlined in Section 5.1.2, is that he can often determine the limitation and scope of his expertise. Consequently, formwork experts often refer the knowledge engineer to other persons when they are asked about questions outside their areas of expertise. As a result, the KE was introduced to five formwork experts working for major formwork manufacturers and subcontractors such as Ceco, Symons and Patent Scaffolding Co. The KE noticed
that these experts were friends and frequently communicated with each other asking for recommendations and advice.

3. Identify Experts from Different Levels in the Organization Hierarchy.
As mentioned above, interviews can be broadly focused or narrowly focused. Generally, broadly focused knowledge can be acquired by interviewing upper-level management, whereas narrowly focused knowledge can be obtained by interviewing lower level management. During an interview with the vice president of a major construction firm, this writer explained the research objectives and asked for an evaluation of the importance of the research topic. On the more narrowly focused level, a question such as "what is the size and composition of the work force required for erecting and dismantling this formwork system?" were asked of the same company's superintendent during a site visit.

4. Identify Other Experts
Other experts contacted by the knowledge engineer are listed in Appendix C - Section C.3. A structural designer was interviewed to determine the effect of the selection of the formwork system on the structure design. Ten rules concerning slip forms were acquired during the interview (51). For example, he stated "If the contractor
intends to use slip forms, we have to design the core walls straight and thick enough (more than 20 cy. yard/ft height) to justify the economy of the slip form."

5.3.2.3. Prepare Interview Kit

A standard interview kit was prepared and stored in an interview file. The interview kit included (17):

1. Interviewee name, address, and telephone number
2. Interview Date(s)
3. Interview duration
4. Interviewee title and position in his organization
5. Additional sources of knowledge identified during the interview including:
   - Titles and locations of documents
   - Other recommended interviewees
6. Interviewer's documents which were developed during the interview, included:
   - Interview notes and rough diagrams
   - Interviewee business card
   - Other related materials such as manufacturer catalogues, and any demonstration materials.

A complete interview kit is provided in Appendix C, Section C.3.
5.3.2.4. Prepare Interview Data Collection Forms

A key part of interviewing is to quickly record the information acquired from the expert. Interview data collection blank forms were prepared in a matrix format, where the horizontal rows represented the different forming systems, and the vertical columns represented the influence factors. Several blank columns and rows were provided to accommodate any new information the expert might provide (See Appendix A.1).

5.3.2.5. Conducting a Structured Interview

Twenty structured interview sessions were held over the course of this research. Twelve interviews were conducted in person. Eight follow up interviews were conducted by telephone. A sample interview is provided in Appendix C - Section C.4.

It was found that an average of two hours per interview session was quite sufficient. Some experts were available for several interviews. In follow-up interviews the KE summarized what was discussed in the previous meeting and presented his understanding of the current rules that he had derived from the document. The expert then agreed with or modified the approach and clarified the problem areas.

A tape recorder was used when the knowledge engineer attended the "World of Concrete 89." The writer felt that this approach affected the openness that was developed at the beginning
of the interview. As a result, this writer decided not to use this
technique again.

The writer found that experts were not interested in the actual
computer implementation, and so they were never shown the actual
knowledge source code. For example, when the knowledge engineer
showed the expert the subgoals established to reduce the number of
rules for the expert system development, the expert showed no
interest, and said "this is your job." Two experts did however show
interest in reviewing the search tree and as a result provided
valuable comments about it.

5.3.2.6. Interview Problems Encountered and Solutions

While interaction with an expert was the major source of
knowledge for this research, several problems were encountered
with this particular method of knowledge acquisition. Some of these
problems, together with the writer's solutions to overcome their
negative impacts, are discussed below.

1. Inaccessibility of Cost Data
Cost is a major factor in selecting a particular forming
system for buildings. Due to the competitive nature of
the construction industry, and the confidentiality of the
cost information, an accurate cost comparison could not
be obtained. It is interesting to note that for one of the
interviews, the writer was asked to sign a legal letter
which prohibited him from releasing any information
resulting from the interviews. The knowledge engineer asked the expert to provide an average or range of cost associated with each forming system. Some experts said that the factors stated in Figure 6.1 (Chapter 6) were directly correlated to the cost, and could be easily transferred to dollars. They felt that the final selection based on these factors reflects to a great extent the cost comparison of the formwork systems.

2. Interview Bias
To avoid bias, detect conflicts, and achieve completeness, it was important to coordinate a diversity of expertise with regard to each system. At least two interviews were conducted for approximately 70% of the formwork systems contained in the knowledge base. Due to the diversity of the forming systems included in the knowledge base, however, only a single source of knowledge was interviewed for the Self-Raising Form and the Jump Form systems. This writer was fortunate to interview the person who developed and introduced the Jump Form to the construction industry. This person provided very valuable information.

3. Lack of Written Response to Questionnaire
As mentioned above, area practice is an important factor when selecting the formwork system. Some systems are popular in some areas and virtually unknown in the
others. This writer originally proposed to acquire the inaccessible knowledge by sending out a questionnaire. This technique proved to be unsuccessful. Instead of eliminating this step (i.e., questionnaire), the writer decided to upgrade it and acquire knowledge by direct interviews. This was possible because, as noted earlier, the writer attended the Fourth International Conference of "Building Economical Concrete Buildings," held in New York City, December 1988 and the "World of Concrete 89," held in Atlanta, Georgia, in February 1989. At both conferences, the writer was able to interview nine experts from different organizations, attend seminars, record debates, and watch live and taped demonstrations. This opportunity enabled the writer to acquire the missing of information, detect conflicts, and collect a considerable amount of information in the form of formwork manufacturers' catalogues.

5.3.3. Organization and Representation Stage

The purpose of this stage is to structure the key concepts, rules and knowledge and transform them into a representative scheme suitable for the selected expert system "shell." This stage includes the following steps:
5.3.3.1. Record Interview Results

As mentioned above, blank forms of the matrix shown in Figures 6.4 and 6.5 (Chapter 6) were used to record the interviews. After several interviews had been conducted, these forms were cross checked to detect areas of conflict or agreement. If the expert's answers were compatible, the relevant cell was recorded and finalized. If the expert's answers were not compatible, the knowledge engineer conducted a follow up interview to resolve the conflict. Conflict resolution is explained in Section 5.3.3.4.

5.3.3.2. Conduct Feedback Interviews

The purpose of this step is to eliminate contradictions, assure completeness, and avoid repetition. This writer chose the matrix format for presenting the knowledge base. As the writer prepared this matrix, several gaps were spotted. Experts were then asked to fill in these gaps and to review other relevant information. For example, one expert stated that "In order to use the flying form systems (flying truss or column-mounted), all columns, beams, walls, should be of the same size and location from floor to floor," while another expert said that we can allow a difference in size and location between 10-20%. As a result, the knowledge engineer conducted a follow-up interview with the first expert and asked him about the 10-20% difference in columns size and location. He agreed with the second expert and the matter was resolved.
Another example occurred when the knowledge engineer asked both experts about their definition of small, medium, and large size buildings. The knowledge engineer received two different answers. One expert said that a small sized building is 70,000 sq. ft. or less, while the other expert defined a small building as 120,000 sq.ft. or less. A follow-up interview did not resolve the conflict. The knowledge engineer then asked a third expert, who specified 100,000 sq. ft. or less. In this case, the knowledge engineer decided to use the average of the three answers, which is approximately 100,000 sq. ft., and accordingly filled in that value in the corresponding cell in the knowledge base. A similar approach was followed with regard to the definition of medium and large sized buildings.

5.3.3.3. Organize the Knowledge Base

Once the knowledge acquired in stage two has been recorded, it then must be analyzed, categorized, and organized. This is accomplished by completing a tabular format which relates the different formwork systems to the controlling factors.

5.4. Summary

This chapter describes several techniques for knowledge acquisition used in developing expert systems. The knowledge acquisition process used in this research was presented in three basic stages: familiarization stage (which determined the scope and
complexity of the problem domain); elicitation stage (which explained how the interviews were prepared and conducted); and organization and representation stage (which describes how the acquired knowledge was organized and presented in a graphical and verbal format).
CHAPTER SIX
FACTORS AFFECTING THE SELECTION
OF A FORMWORK SYSTEM

This chapter provides a summary of the factors affecting the proper selection of the formwork system, and presents a tabular comparative analysis of usage and limitations of each formwork system. This tabular analysis represents the formwork knowledge base which the writer acquired. It should be viewed as one of the major accomplishment of this research study. A "real world" formwork selection problem is also provided to explain how these tables can be used to accurately select the optimum formwork system.

6.1. Introduction

Selecting the formwork system for cast-in-place reinforced concrete buildings is a critical decision affecting cost, safety, quality, and speed of construction. Many factors must be considered for the proper selection of the formwork system. Among these are:

1. Factors related to building architectural and structural design, which include slab type; lateral supporting system(s); and building shape and size (Section 6.2).
2. Factors related to project (job) specification, which include concrete appearance and speed of construction (Section 6.3).

3. Factors related to local conditions, which include area practice, weather conditions, and site characteristics (Section 6.4).

4. Factors related to the supporting organizations, which include available capital, hoisting equipment, home-office support, and availability of local or regional yard supporting facilities (Section 6.5).

An overview of all the factors affecting the selection of formwork systems is shown in Figure 6.1. The following subsections briefly define the terminology and explain how these factors affect the selection of the formwork system.

### 6.2. Building Design: Slab Type

The construction cost of slabs is often more than half the cost of structural framing systems, except in extremely tall buildings (9). Therefore, selection of the floor formwork system deserves considerable attention to minimize cost.

The selection of a formwork system should be made on the basis of the selected floor system that satisfies the structural loading conditions. Floor slabs in concrete buildings are classified into two basic types, based on the load distribution applied on the slab:

1. Two-way slab, in which the rectangularity ratio (slab
Figure 6.1 Factors Affecting the Selection of a Formwork System

- Building Design
  - Slab Type
    - Two-way flat plate
    - Two-way flat slab
    - Waffle slab
    - Two-way slab supported by beams
    - One-way slab beams, and grid
    - One-way slab supported by beams or bearing walls
    - One-way prestressed slab
  - Lateral Loads/Supporting System (Floor Height)
    - Shear walls
    - Framed-shear wall
    - Framed tube
    - Tube-in-tube
    - Irregular
    - Uniform
  - Building Shape
    - As-cast Surface finish
    - Exposed Concrete finish
    - Architectural Concrete finish
  - Concrete Finish
    - Floor Cycle
    - Rate of placement
    - Construction sequence
    - Labor quality
    - Labor cost
    - Hot Weather
    - Cold Weather
    - Suburban open site
  - Weather Conditions
  - Site Characteristics
    - Urban-restricted
    - Size
    - Initial cost (Make-Up)
    - Potential reuse
    - Stripping
    - Carrying capacity
    - Max/min. radii
    - Crane time involvement
    - Trouble-shooting Experience
    - Safety management
    - No yard facility
    - Local yard facility
    - Regional yard facility
  - Supporting Organization
    - Hosting Equipment
    - Home Office Support
    - Supporting Yard Facility
length/width) is between 1 and 2, and the slab load is transferred to the supporting beams in two directions. Two-way construction includes flat plate, flat slab, waffle slab, and two-way slabs supported by drop beams.

2. One-way slab, in which the rectangularity ratio (slab length/width) is more than 2, and the slab load is transferred to the supporting beams in one direction. One-way construction, usually includes solid slabs on beams or walls, one-way joist (ribbed) slabs supported on beams or bearing walls (9, 48).

6.2.1. Two-Way Flat Plate

A flat plate structural floor system consists of a concrete slab of constant thickness throughout, without beams or drop panels at the columns (See Figure 6.2(a)). Such slabs may be cantilevered at the exterior of the building to permit the use of exterior balconies. The supporting columns for flat plates are usually equally spaced to facilitate the design and construction of such slabs. This system is economical for spans of up to 23 ft. with mild reinforcing. Flat plates can be constructed in minimum time because they utilize the simplest possible formwork. Flat plates have been used successfully in multistory motel, hotel, hospital, and apartment buildings.
(a) Flat Plate

(b) Flat Slab

(c) Waffle Slab

(d) Two-Way Slab Supported by Beams

Figure 6.2 Two-Way Slab Systems (32)
6.2.2. Two-Way Flat Slab

A flat slab structural system consists of a constant thickness of concrete slab with drop panels at the columns (See Figure 6.2(b)). In earlier years, column capitals were used along with drop panels, but because of the higher form cost, column capitals are less favored in today's construction practice (40). Flat slabs are used to resist heavier loads and longer spans than flat plates. Generally, the system is most suitable for square or nearly square panels.

6.2.3. Waffle Slab

Waffle slab construction is shown in Figure 6.2 (c). It consists of rows of concrete joists at right angles to solid heads at the columns. Waffle slabs can be used for spans up to about 50 ft., and they are used to obtain an attractive ceiling.

6.2.4. Two-Way Slab Supported by Beams

This system consists of a solid slab designed to span in two directions to either concrete beams or walls (See Figure 6.2 (d)). The primary advantage of the system is the saving in reinforcing steel and slab section as a result of being able to take advantage of two-way action. Formwork for the two-way system is complicated and usually outweighs the cost advantages associated with the saving in reinforcing steel and slab thickness.
6.2.5. One-Way Slab, Beam, and Girder

This system consists of a solid slab, spanning to concrete beams which are uniformly spaced. The beams, in turn, are supported by girders at right angles to the beam, to carry loads into the columns (See Figure 6.3 (a)). This system generally affords the opportunity to span longer distances than two-way by designing deeper beams and girders.

6.2.6. One-Way Slab Supported by Beams or Bearing Walls

This system is a modification of the slab, beam, and girder system. It eliminates the secondary beams (See Figure 6.3 (b)). Reinforcing steel is relatively simple, and existence of openings is generally not a critical concern.

6.2.7. One-Way Joist (Ribbed) Slab

One-way joist slabs are a monolithic combination of uniformly spaced beams or joists and a thin cast-in-place slab to form an integral unit. When the joists are parallel, it is referred to as one-way joist construction (See Figure 6.3 (c)). Joists are very attractive to architectural layout and support mechanical systems.
(a) One-Way Slab, Beam, and Girder

(b) One-Way Slab, Supported by Beams or Walls

(c) One-Way Joist Slab

Figure 6.3 One-Way Slab System (9)
6.3. Building Design: Lateral Load Supporting Systems

Buildings are classified as being tall when their height is between two and three times as great as their breadth (49). For example, a building with a minimum dimension of 50 ft. in plan, and a height of 100 ft. or more is considered a high-rise building.

One of the major characteristics of high-rise building design is the need to resist the lateral forces due to winds and earthquakes. As a result special structural elements must be provided to resist lateral forces and prevent or minimize the building sway. In the following sections, a brief description of lateral load resisting systems, along with their corresponding height limitations are presented (9, 49, 50).

6.3.1. Type I Structure (Rigid Frame System)

Rigid frame systems consist of rectangles of vertical columns and horizontal beams connected together in the same plane (See Figure 6.4). It should be noted that a bearing wall is a special case of the rigid frame system.

6.3.2 Type II Structure (Shear Walls)

Figure 6.5 shows shear wall formation which is a thin slender beam cantilevered vertically to resist lateral forces. It can take the
Figure 6.4 Type I Structure - Rigid Frame Systems (49)
Figure 6.5 Type II Structure - Shear Walls (49)
form of a rectangle or box-shaped core, which can be used to gather vertical transportation and energy distribution systems (e.g., stairs, elevators, toilets, mechanical shafts). Figure 6.5 illustrates some possible shear wall systems (49).

6.3.3. Type III Structure (Framed-Shear Wall Systems)

This system consists of a combination of frames which utilize beams and columns with the shear wall designed to resist lateral loads (See Figure 6.6).

6.3.4. Type IV Structure (Framed Tube)

This tube is a structural system in which the perimeter of the building, consisting of vertical, closely-spaced supports, connected by beams or bracing members, acts as a giant vertical internally stiffened tube (See Figure 6.7).

6.3.5. Type V Structure (Tube-in-Tube Systems)

This system is a combination of the framed-shear wall (type III structure) which acts as an interior tube, and the framed tube (type IV structure), which acts as an exterior tube. The floor structure ties the interior and exterior tubes together to allow them to act as an unit to resist lateral loads (See Figure 6.8).

Table 6.1 indicates the optimum height of each lateral support
Figure 6.6 Type III Structure - Framed Shear Wall (49)
Figure 6.7 Type IV Structure - Framed Tube (49)
Figure 6.8 Type V Structure - Tube-in-Tube (49)
<table>
<thead>
<tr>
<th>Type of Structure</th>
<th>Description of Structure</th>
<th>Optimum Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Total Frame Building</td>
<td>Up to 20 stories</td>
</tr>
<tr>
<td>II</td>
<td>Shear-Wall Building</td>
<td>Up to 35 stories</td>
</tr>
<tr>
<td>III</td>
<td>Framed Shear Wall Building</td>
<td>Up to 50 stories</td>
</tr>
<tr>
<td>IV</td>
<td>Framed Tube</td>
<td>Up to 55 stories</td>
</tr>
<tr>
<td>V</td>
<td>Tube-in-Tube</td>
<td>Up to 65 stories</td>
</tr>
</tbody>
</table>
system (49, 50). It should be noted that Table 6.1 serves as a rough guide for determining the suitable lateral supporting system for each building height. Judgment, experience, and the personal preference of the designer are all important factors in choosing the proper lateral support system.

6.4. Building Design: Building Shape

Special buildings such as industrial buildings and power plants usually have extensive electrical and mechanical requirements which do not lend themselves to any "formwork system." As a result, they should be constructed using the traditional forming method (i.e., stick forms).

Some of the factors that enable the contractor to decide whether to use a formwork system or a traditional forming method are:

1. Variation of column and wall location.
2. Variation of beam depth and location.
3. Variation of story height.
4. Existence of blockouts and openings for windows and doors.
5. Extensive HVAC requirements.

A building's structural layout is either uniform "modular" or irregular. Uniform "modular" design is characterized by regular spacing between columns and walls, equal story heights, and regular spacing of cantilevers and openings. Irregular design is
characterized by irregular positions of the different structural elements and broken lines or irregular curves in architectural plans.

6.5. Job Specifications

Contract documents always include information about the quality of the finished concrete and the time needed to finish the project. A brief description about how this information can affect the selection of the formwork system is provided below.

6.5.1. Concrete Finish

Surface quality and appearance are always referred to as the concrete finish. Concrete surfaces can be classified as rough finish "as-cast surface", smooth exposed, or covered (with a special cladding material or painted), and textured (with an architectural surface texture and treatment). Concrete finish is not a major factor for most horizontal concrete work (floors), because floors are almost always covered underneath with a false ceiling or paint. The only exception is for joist and waffle slabs which require a smooth concrete finish.

As-cast concrete finish typically shows some irregularity on the surfaces and may contain some concrete surface defects. An as-cast concrete finish is usually found in concrete buildings where appearance is not important, such as warehouses.

Exposed concrete finish is characterized by a smooth regular concrete surfaces, and regular positions of form ties. Exposed concrete surfaces are typically found in columns, and bearing walls.
Architectural concrete is favored in vertical concrete elements (columns and walls). As a result, concrete finish must be considered as one of the major factors in the selection of a formwork system. Architectural concrete requires a careful selection of a formwork system which includes stiffer form liners, tighter joints, smoother finishes, and more care in implementing chamfers and rustifications.

6.5.2. Speed of Construction

The most important advantage of using a formwork system is the speed of construction. The speed of construction affects cost because it determines the time when the building will be available for use and also reduces the financial charges. The major factors that determine the speed of construction follow.

1. Floor Cycle

In recent years, casting two floors per week in high-rise buildings has been achieved, especially in metropolitan areas (48, 50). This fast floor cycle can only be achieved by using sophisticated forming techniques such as flying forms and self-raising forms which are capable of forming one story every two days.

2. Rate of Placement

The speed at which concrete is placed in vertical formwork has the largest influence on the horizontal pressure that is imposed on the formwork. The lateral pressure is increased by increasing the rate of placement, up to a limit equal to the full fluid pressure.
Higher rates of placement influence the size, material, and tie pattern of the selected system.

3. Construction Sequence.

Construction sequence may be another factor. Tall buildings typically have an inside core to resist lateral loads. One alternative is to completely construct the inside core in order to create a "closed" area for the other trades to start. This alternative has proven to be faster than constructing and finishing floor by floor. This can be accomplished by using slipforms or self-raising forms.

6.6. Local Conditions

The nature of the job, including local conditions, is one of the primary factors in formwork selection. Some of the factors that should be considered are explained below.

6.6.1. Area Practice

In areas where the labor force is expensive and unskilled, the use of formwork "systems" can substantially reduce the cost. In areas where the labor force is inexpensive and skilled, a conventional formwork system is a economical alternative even if the building features lend itself to a formwork "system." As a result, some areas use preassembled formwork "systems" because of the lack of inexpensive skilled labor force.
Area practice has an important impact on the selected formwork system. This influence is evident in slipform operations which are highly labor intensive and usually subject to premium pay. Table 6.2 shows some excellent examples of slipform techniques in the United States. The data in Table 6.2 indicates that slipforms are most prevalent in the Northeast, Southeast, and Hawaii (9, 43, 51-59). It is interesting to note that the average height for slipform is approximately 400 ft., which is the optimum height for a shear wall lateral supporting system (See Table 6.2).

6.6.2. Weather Conditions

Vertical forming systems are sensitive to weather conditions. Typically, in vertical forming systems, the newly placed concrete is supported by the wall already cast below it. The lower wall section must gain sufficient strength to support the fresh concrete above. The rate of strength gain for the lower wall is influenced by the ambient temperature, moisture content, and the freezing and thawing cycles.

Another factor that affects the economy of the selected system is the effect of stopping forming and concreting because of extreme weather conditions. For example, in slipform, the work is usually continuous, 24 hours around the clock, with a minimum crew requirement, of 50 to 75 laborers for a medium size shear wall. If the slipform stops because of the weather conditions, the contractor has to pay the workers a show-up time, plus the cost of inactive
<table>
<thead>
<tr>
<th>Building</th>
<th>City</th>
<th>Height</th>
<th>Rate of Placing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erie County Saving Bank</td>
<td>Buffalo, NY</td>
<td>360 ft.</td>
<td>9 in./hr</td>
</tr>
<tr>
<td>USF &amp; G Building</td>
<td>Baltimore, MD</td>
<td>556 ft.</td>
<td>Not recorded</td>
</tr>
<tr>
<td>Hilton Hotel</td>
<td>Petersburg, FL</td>
<td>150 ft.</td>
<td>12 in./hr</td>
</tr>
<tr>
<td>Penn Mutual Building</td>
<td>Philadelphia, PA</td>
<td>360 ft.</td>
<td>Not recorded</td>
</tr>
<tr>
<td>Kerr-McGee Building</td>
<td>Oklahoma City, OK</td>
<td>310 ft.</td>
<td>Not recorded</td>
</tr>
<tr>
<td>Sheraton-Waikiki Hotel</td>
<td>Waikiki-Hawaii</td>
<td>329 ft.</td>
<td>18 in./hr</td>
</tr>
<tr>
<td>Bay View Terrace</td>
<td>Milwaukee,</td>
<td>225 ft.</td>
<td>8 in/hr</td>
</tr>
<tr>
<td>IBM Building</td>
<td>Philadelphia, PA</td>
<td>240 ft.</td>
<td>9 in/hr</td>
</tr>
<tr>
<td>Apartment Building</td>
<td>Milwaukee</td>
<td>250 ft.</td>
<td>8 in./hr</td>
</tr>
<tr>
<td>Lincoln-Rochester Trust</td>
<td>Rochester, NY</td>
<td>406 ft.</td>
<td>Not recorded</td>
</tr>
<tr>
<td>US Fidelity Guaranty Bldg.</td>
<td>Baltimore, MD</td>
<td>535 ft.</td>
<td>Not recorded</td>
</tr>
<tr>
<td>Knights of Columbus</td>
<td>New Haven, Conn.</td>
<td>320 ft.</td>
<td>Not recorded</td>
</tr>
<tr>
<td>Two Liberty Place</td>
<td>Philadelphia, PA</td>
<td>755 ft.</td>
<td>Not recorded</td>
</tr>
<tr>
<td>IBM Building</td>
<td>Atlanta, GA</td>
<td>725 ft.</td>
<td>Not recorded</td>
</tr>
<tr>
<td>West Burry Condominium</td>
<td>Honolulu, Hawaii</td>
<td>400 ft.</td>
<td>Not recorded</td>
</tr>
<tr>
<td>Energy Centre</td>
<td>Denver, Col</td>
<td>735 ft.</td>
<td>Not recorded</td>
</tr>
</tbody>
</table>

* Sources (9, 43, 65, 66, 67, 68, 69, 70, 71, 72)
cranes and their operators (43). As a result, if severe weather conditions are expected, some formwork systems such as slip forms should be avoided.

6.6.3. Site Characteristics

The building site itself may influence the selection of a suitable forming system, because of site limitations and accessibility for construction operations. The feasibility of using ganged or flying forms, for instance, is influenced by site characteristics, which include (16):

1. Accessibility to the site.
2. Availability of a make-up area.
3. Surrounding area restrictions such as property lines, adjacent buildings, power lines, and busy streets. In open and unrestricted suburban sites, all forming systems are visible and some other considerations should be evaluated to determine the most efficient and cost effective system. In downtown restricted sites, the only possible system may be ganged units that can be transferred from floor to floor.

6.7. Supporting Organization

Most of the ganged forming systems (i.e. flying form, jump form, and slipform), require high initial investment and intensive crane involvement. The major resource requirements that should be
carefully evaluated when deciding upon a forming system are discussed below.

6.7.1. Available Capital (Cost)

The cost of concrete formwork is influenced by three factors (50):

1. Initial cost or make-up cost, which include cost of transportation, materials, assembly, and erection.

2. Potential reuse, which decreases the final total cost per square foot of contact area. The data in Table 6.3 indicates that the maximum economy can be achieved by maximizing the number of reuses.

3. Stripping cost, which also includes the cost of cleaning and repair. This item tends to remain constant for each reuse up to a certain point, at which the total cost of repairing and cleaning start rising rapidly.

In deciding to use a specific formwork system, the initial cost should be evaluated versus the available capital allocated for formwork cost. Some systems tend to have a high initial cost, but through repetitive reuse, they become economical. For example, slipforms have a high initial cost, but the average potential reuse (usually over 100) reduces the final cost per sq. ft. per contact area of this alternative. In the case of rented formwork systems, the period of time in which the formwork is in use has a great effect on the cost of formwork.
Table 6.3 Effect of Reuse on Concrete Formwork Cost Based on One Use Equal to 1.00 (50)

<table>
<thead>
<tr>
<th>Number of Uses</th>
<th>Cost per sq. ft./ct&lt;sup&gt;1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wood Form</td>
</tr>
<tr>
<td>One</td>
<td>1.00</td>
</tr>
<tr>
<td>Two</td>
<td>0.62</td>
</tr>
<tr>
<td>Three</td>
<td>0.50</td>
</tr>
<tr>
<td>Four</td>
<td>0.44</td>
</tr>
<tr>
<td>Five</td>
<td>0.4</td>
</tr>
<tr>
<td>Six</td>
<td>0.37</td>
</tr>
<tr>
<td>Seven</td>
<td>0.36</td>
</tr>
<tr>
<td>Eight</td>
<td>0.35</td>
</tr>
<tr>
<td>Nine</td>
<td>0.33</td>
</tr>
<tr>
<td>Ten</td>
<td>0.32</td>
</tr>
</tbody>
</table>

1. Cost per square feet per contact area
2. Fiber reinforced plastic
6.7.2. Hoisting Equipment (Cranes)

Some formwork systems require special handling techniques including good crane service. The flying truss system is a good example of crane influence on the selected system. The size of the flying modules may be limited by the crane carrying capacity and its maximum and minimum lift radii.

Another important factor that influences the selection of the formwork system is the available crane time. In a case study (47: pp.1-7), the limited crane time available for formwork erection to meet the project completion date was the major factor that led the formwork designer to choose the self-raising form alternative (which requires no crane time).

6.7.3. Home-Office Support

When deciding to use a special forming technique, the contractor has to evaluate his own in-house expertise, which includes trouble-shooting experience and safety management. For example, in vertical forming systems such as slipform and self-raising forms, the in-house experts have to deal with special problems such as leaking hydraulic equipment, leveling of the hoist jacks, keeping the forms plumb within specified tolerance, and placing inserts and openings under the fast rate of placement (51).

Safety management is another area of in-house expertise that should be available to support a specific forming technique. For example, the availability of fire protection expertise is necessary in
slipforming to prevent a fire several hundred feet in the air resulting from the inflammable oil used in the hydraulic jacks. The availability of such expertise may be a factor which determines if a special forming technique is or is not used.

6.7.4 Supporting Yard Facility

The feasibility of using ganged or prefabricated forms for floors or walls is largely influenced by the availability of a local or central (regional) yard facility. When a local or central yard facility is available, the standard formwork elements can be manufactured and assembled under efficient working conditions. However, the cost of transporting form sections to the site may influence the economy of the selected system.


Tables 6.4 and 6.5 shows the effect of the above-mentioned influence factors on the selected formwork systems for both horizontal and vertical concrete work respectively. The information provided by both tables (from 34-38, 42-46, 51-70) represents the formwork selection knowledge base.

These tables were established in accordance with the search tree provided in Figure 6.1 and should be read along with the search tree. The comparative analysis provided by Tables 6.4 and 6.5 followed the same format of the factor tree shown in Figure 6.1. The branches on Figure 6.1 are the deciding factors which directly
<table>
<thead>
<tr>
<th>Building Design</th>
<th>Formwork System</th>
<th>Conventional Wood System</th>
<th>Conventional Metal System</th>
<th>Flying Truss System</th>
<th>Column-Mounted Shoring System</th>
<th>Tunnel Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab Type</td>
<td>Slab Type</td>
<td>- All slab systems</td>
<td>- Most suited for two-way slab supported by beams or one-way slab, beam, girder</td>
<td>- Two-way: flat plate and flat slab</td>
<td>- One-way: slab supported by beams or walls and joist slab (standard or skip-joist)</td>
<td>- One-way slab supported by walls</td>
</tr>
<tr>
<td>Compatibility with lateral load supporting system</td>
<td>- Compatible with all lateral load supporting systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Bearing wall</td>
</tr>
<tr>
<td>Vertical Uniformity / Irregularity</td>
<td>- System can handle variations in beam size and location</td>
<td>- System can handle variations in cantilever shape, size, and location</td>
<td>- Beams should be of the same size and location or within 20% difference from floor to floor</td>
<td>- Cantilever should be of the same size and location or within 20% difference from floor to floor</td>
<td>- Beams should be of the same size and location, cantilever balconies should be of the same size and location</td>
<td></td>
</tr>
<tr>
<td>High Stories (Higher than 14')</td>
<td>- Not suitable for high stories</td>
<td>- More suitable for high stories (light alum. wt.)</td>
<td>- Limited by truss depth (up to 20')</td>
<td>Height Independent system</td>
<td>- Limited height system (up to 10')</td>
<td></td>
</tr>
<tr>
<td>Openings</td>
<td>- System can handle variation in opening size and location</td>
<td></td>
<td>- Can handle limited variation (20%) in opening size and location</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slopes &amp; Cambers</td>
<td>- Slopes and cambers can be accommodated at additional cost</td>
<td>- System must be designed to accommodate slopes and cambers</td>
<td></td>
<td>- Slopes and camber must be identical from floor to floor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HVAC</td>
<td>- Can accommodate extensive HVAC</td>
<td>- Can not accommodate extensive HVAC</td>
<td></td>
<td>- HVAC should be minimal and identical from floor to floor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimension Limitations</td>
<td>- Used for small building size (less than 100,000 sq. ft.)</td>
<td>- Used for medium building size (between 100,000 and 200,000 sq. ft.)</td>
<td></td>
<td>- Used for large size buildings (more than 200,000 sq. ft.)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Table 6.4 "continued" Factors Affecting the Selection of Horizontal Forming Systems (page 2 of 4)**

<table>
<thead>
<tr>
<th>Influence Factor</th>
<th>Formwork System</th>
<th>Conventional Wood System</th>
<th>Conventional Metal System</th>
<th>Flying Truss System</th>
<th>Column-Mounted Shoring System</th>
<th>Tunnel Form</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete Finish</td>
<td>- Generally, not a major factor for horizontal concrete work</td>
<td>- System produces &quot;as-cast&quot; concrete finish</td>
<td>- Generally, not a major factor for horizontal concrete work</td>
<td>- System produces &quot;exposed&quot; concrete Finish</td>
<td></td>
<td>- Best concrete finish, few or no joints</td>
</tr>
<tr>
<td>Floor Cycle</td>
<td>- Typically floor every 5 working days</td>
<td>- Faster cycle can be accommodated at additional cost (increasing number of stories to be shored and reshored)</td>
<td>- Floor every 3-4 days</td>
<td>- Floor every 1-2 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate of Placement</td>
<td>- Generally, not a major factor in horizontal concrete work, average rate between 25-30 cy/hr.</td>
<td>- Pouring columns, then beams and slabs</td>
<td>- Slab on grade is not necessarily to be in place, but cost can be reduced if slab on grade is in place</td>
<td>- Pouring columns, then beams and slabs</td>
<td>- Slab on grade should be in place for the form to be used in first floor</td>
<td>- Pouring slabs and walls together - 3 * starter wall is necessarily</td>
</tr>
<tr>
<td>Construction</td>
<td>- Pouring columns, then beams and slabs</td>
<td>- Slab on grade is not necessarily to be in place, but cost can be reduced if slab on grade is in place</td>
<td>- Pouring columns, then beams and slabs</td>
<td>- Slab on grade should be in place for the form to be used in first floor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed of</td>
<td>- Work best in areas of high quality, low cost labor force</td>
<td>- Work best in areas of high quality, high cost labor force</td>
<td>- Generally, work in areas of high cost, low quality labor force</td>
<td>- Generally, work in areas of high quality, high cost labor force</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>- Generally not a factor in horizontal concrete work</td>
<td>- Require minimum storage and make-up area</td>
<td>- Small make-up area is required if system is panelized</td>
<td>- Site must have adequate storage and make-up area</td>
<td>- System is preassembled - Minimum storage area is required.</td>
<td></td>
</tr>
<tr>
<td>Site Characteristics</td>
<td>- Require minimum storage and make-up area</td>
<td>- Small make-up area is required if system is panelized</td>
<td>- Site must have adequate storage and make-up area</td>
<td>- System is preassembled - Minimum storage area is required.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Access to Site</td>
<td>- Generally, not a factor for hand-set systems</td>
<td>- Job must be accessible for large form units - May not be a factor if forms are assembled on site</td>
<td>- Job must be accessible for large preassembled steel forms</td>
<td>- Job must be accessible for large preassembled steel forms</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6.4 "continued"  Factors Affecting the Selection of Horizontal Forming Systems (page 3 of 4)

<table>
<thead>
<tr>
<th>Influence Factor</th>
<th>Formwork System</th>
<th>Conventional Wood System</th>
<th>Conventional Metal System</th>
<th>Flying Truss System</th>
<th>Column-Mounted Shoring System</th>
<th>Tunnel Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial &quot;make-up&quot; Cost</td>
<td>- Average cost range from $1 to $3 per sq.ft. of contact area</td>
<td>- Average cost range from $10 to $15 per sq. ft. of contact area</td>
<td>- Minimum of 20 reuses</td>
<td>- Minimum of 15-20 reuses should be available</td>
<td>- Minimum of 50 reuses should be available</td>
<td>- Average cost ranges from $20 to $50 per sq. ft. of contact area</td>
</tr>
<tr>
<td>Potential Reuse</td>
<td>- Up to 15 reuses</td>
<td>- Up to 20 reuses</td>
<td>- Minimum of 12-15 reuses should be available</td>
<td>- Minimum of 15-20 reuses should be available</td>
<td>- Minimum of 50 reuses should be available</td>
<td>- Average cost ranges from $20 to $50 per sq. ft. of contact area</td>
</tr>
<tr>
<td>Stripping Cost</td>
<td>- High stripping cost (approximately 1/3 of the makeup cost)</td>
<td>- Low stripping cost (approximately 1/2 of the hand set systems)</td>
<td>- Low stripping cost</td>
<td>- Low stripping cost</td>
<td>- Low stripping cost</td>
<td>- Low stripping cost</td>
</tr>
<tr>
<td>Average Labor Productivity</td>
<td>- 12 sq. ft. per contact area</td>
<td>- 18 sq. ft. per contact area</td>
<td>- 36 sq. ft. per contact area</td>
<td>- 45 sq. ft. per contact area</td>
<td>- 50 sq. ft. per contact area</td>
<td>- 50 sq. ft. per contact area</td>
</tr>
<tr>
<td>Availability of Crane and Crane Time</td>
<td>- Can be hand-set - Less expensive if crane is available</td>
<td>- Can be hand-set - Crane is necessary if made into panels</td>
<td>- Adequate hoisting equipment must be available</td>
<td>- Adequate hoisting equipment must be available</td>
<td>- Adequate hoisting equipment must be available</td>
<td>- Adequate hoisting equipment must be available</td>
</tr>
<tr>
<td>Adjacent Building Traffic, and Other Obstructions</td>
<td>- Generally, not a factor</td>
<td>- Generally, not a factor</td>
<td>- A major factor, there must be open space at least 1.5 the length of the large panel from the face of the building</td>
<td>- A major factor, there must be open space at least 1.5 the length of the large panel from the face of the building</td>
<td>- A major factor, there must be open space at least 1.5 the length of the large panel from the face of the building</td>
<td>- A major factor, there must be open space at least 1.5 the length of the large panel from the face of the building</td>
</tr>
<tr>
<td>Adequacy of Crane Carrying Capacity</td>
<td>- Generally, not a factor</td>
<td>- Generally, not a factor</td>
<td>- Crane should have adequate carrying capacity at maximum and minimum radii.</td>
<td>- Crane should have adequate carrying capacity at maximum and minimum radii.</td>
<td>- Crane should have adequate carrying capacity at maximum and minimum radii.</td>
<td>- Crane should have adequate carrying capacity at maximum and minimum radii.</td>
</tr>
<tr>
<td>Influence Factor</td>
<td>Formwork System</td>
<td>Conventional Wood System</td>
<td>Conventional Metal System</td>
<td>Flying Truss System</td>
<td>Column-Mounted Shoring System</td>
<td>Tunnel Form</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-----------------</td>
<td>-----------------------------------</td>
<td>-----------------------------------</td>
<td>---------------------</td>
<td>-------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Safety Management</td>
<td></td>
<td>- Normal safety precautions are required</td>
<td>- Special safety in dealing with crane operation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supervision &quot;Trouble Shooting Experience&quot;</td>
<td></td>
<td>- Minimum engineering supervision</td>
<td>- Requires skilled crew, requires moderate engineering supervision</td>
<td>- Required high engineering supervision</td>
<td>- Requires high degree of engineering supervision</td>
<td></td>
</tr>
<tr>
<td>Supporting Yard Facility</td>
<td></td>
<td>- Min. yard is required</td>
<td>- Requires local yard if made into panels</td>
<td>- Required enough supporting local or regional yard facility</td>
<td>- System should be available in close by area</td>
<td>- No yard is required</td>
</tr>
</tbody>
</table>
### Table 6.5 Factors Affecting Selection of Vertical Formwork Systems

<table>
<thead>
<tr>
<th>Formwork Systems</th>
<th>Lateral Support System</th>
<th>Building Height</th>
<th>Column/Wall Size and Location</th>
<th>Openings/Inserts</th>
<th>Concrete Finish</th>
<th>Construction Sequence</th>
<th>Cycle Time</th>
<th>Speed of Construction</th>
<th>Laminated Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ganged Forms (Load Gathering System)</td>
<td>Most suited for frames and retaining walls</td>
<td>Up to 120 ft.</td>
<td>System can handle variation of column/wall size and location</td>
<td>Variation in opening's size and location can be accommodated at additional cost</td>
<td>&quot;As Cast&quot; concrete finish</td>
<td>Slabs and walls are placed concurrently</td>
<td>1 Floor every 2-3 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jump Form</td>
<td>Shear walls</td>
<td>Up to 350 ft.</td>
<td>System can handle variation of column/wall size and location</td>
<td>Openings/inserts of different size and location</td>
<td>Smooth concrete finish</td>
<td>System produces rough concrete finish</td>
<td>1 Floor every 2-3 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slip Form</td>
<td>Shear walls</td>
<td>Average 400 ft.</td>
<td>Walls should be minimum 20 ft.</td>
<td>Should be minimum 10 ft.</td>
<td>Smooth concrete finish</td>
<td>Walls are ahead of the floor</td>
<td>1 Floor every 2-3 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-Raising Form</td>
<td>Shear walls, Tube systems, Tube-in-tube, No max.</td>
<td>At least 300 ft.</td>
<td>System can handle moderate variation in column size and location</td>
<td>System can handle moderate variation in column size and location</td>
<td>Smooth concrete finish</td>
<td>Other method is used for the first 1-2 stories</td>
<td>1 Floor every 2-3 days</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Building Shape**: Laminated Support
- **Laminated Support**: Laminated Design
- **Job Specification**: Building Design
- **Speed of Construction**: 1 Floor every 2-3 days
### Table 6.5 "continued" Factors Affecting Selection of Vertical Formwork Systems (page 2 of 3)

<table>
<thead>
<tr>
<th>Influence Factor</th>
<th>Formwork Systems</th>
<th>Conventional Column/Wall form</th>
<th>Ganged Forms &quot;Load Gathering System</th>
<th>Jump Form</th>
<th>Slip Form</th>
<th>Self-Raising Form</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>Stripping</td>
<td>- Hand strip</td>
<td>- Crane is used to strip the system</td>
<td>- Forms are equipped with mechanism for stripping</td>
<td>- Forms are stripped at the end of the project</td>
<td>- Forms are equipped with mechanism for stripping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- High stripping cost</td>
<td>- High stripping cost</td>
<td>- Min stripping cost</td>
<td>- Min stripping cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reuse</td>
<td>- Less than 10</td>
<td>- Between 40 and 50</td>
<td>- Between 15 and 30</td>
<td>- Between 50 and 100 (i.e between 200 ft and 400 ft high)</td>
<td>- At least 30 reuses should be available vertically</td>
</tr>
<tr>
<td></td>
<td>Location of Adjacent Building and Obstruction</td>
<td>- Generally not a factor</td>
<td>- A major factor, system must have a free space to be moved from floor to floor</td>
<td>- Minimum free space should be available for crane movement</td>
<td>- Not a major factor system can be used in downtown restricted areas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crane Time</td>
<td>- Not a factor, system can be hand set</td>
<td>- Crane dependent system, sufficient crane time is a must</td>
<td>- System substantially reduce crane time</td>
<td>- Crane is used only for materials delivery and concrete placing</td>
<td>- Crane independent system</td>
</tr>
<tr>
<td></td>
<td>Operating System</td>
<td>- Hand set system, crane increases system efficiency and reduces cost</td>
<td>- Crane set system - Crane serves two functions: lifting and supporting the forms</td>
<td>- Crane is used only to lift the forms. - Crane is not used for forms dismantling</td>
<td>- Locomotion is provided by electric, pneumatic, or hydraulic jacks climbing on smooth steel rods</td>
<td>- System is lifted by hydraulic, electric, or pneumatic lifters.</td>
</tr>
<tr>
<td></td>
<td>Safety</td>
<td>- No special safety features are required</td>
<td>- Special care for handling the large ganged units by crane</td>
<td>- Safety features - Safe guarded platform - No one needs to be on the form during crane handling</td>
<td>- For hydraulic systems, special safety precautions must be taken to prevent fire several hundred feet above the ground</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yard Facility, Supplier or Make-up Area</td>
<td>- Not a major factor, but system is more efficient, if a local yard facility is available</td>
<td>- A major factor, system must have an adequate make-up area or close by supplier</td>
<td>System is rented or purchased</td>
<td>- Continuous materials delivery is a must. Un-interrupted concrete placement must be assured.</td>
<td>- System is pre-assembled, make-up area is not a factor. Local supplier must be available</td>
</tr>
</tbody>
</table>
### Table 6.5 "continued" Factors Affecting Selection of Vertical Formwork Systems (page 3 of 3)

<table>
<thead>
<tr>
<th>Influence Factor</th>
<th>Formwork System</th>
<th>Conventional Column/Wall form</th>
<th>Ganged Forms &quot;Load Gathering System&quot;</th>
<th>Jump Form</th>
<th>Slip Form</th>
<th>Self-Raising Form</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Area Practice</strong></td>
<td>- More efficient in areas of high quality, low cost labor force</td>
<td>- Work best in high cost, low quality labor force</td>
<td>- System is easy to learn and adapt - Learning curve is quite short</td>
<td>- System can be learned in 2-3 weeks</td>
<td>- System requires high quality supervision</td>
<td></td>
</tr>
<tr>
<td><strong>Weather</strong></td>
<td>- Generally not a major factor</td>
<td>- A major factor, walls should have sufficient strength before stripping which is largely influenced by weather condition - High winds limit the crane movement</td>
<td>- Hot or cold weather affect the concrete rate of setting which slow the rate of rise</td>
<td>- In cold weather, forms should be protected and concrete should be heated</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Local Conditions</strong></td>
<td><strong>Site Characteristics</strong></td>
<td><strong>Access to site</strong></td>
<td>- Generally not a factor for loose forms</td>
<td>- Can be a major factor if the system is pre-assembled in a local yard facility</td>
<td>- Site must be accessible, forms can be up to 16 ft. high and 44 ft. wide</td>
<td>- System must have a limited access for material delivery</td>
</tr>
<tr>
<td></td>
<td><strong>Site size</strong></td>
<td>- Not a factor</td>
<td>- Can be a major factor if the forms have to be built in site</td>
<td>- Not a major factor, forms are pre-assembled and unloaded directly</td>
<td>- Not a major factor, system can be used in restricted small sites</td>
<td></td>
</tr>
</tbody>
</table>
affect the selection of a particular system. Each group of similar branches which are represented by a root branch in Figure 6.1, are written vertically in Tables 6.4 and 6.5.

The factor tree shown in Figure 6.1 indicates the general factors affecting the selection of both horizontal and vertical formwork systems. However, some of these factors, such as rate of placement and weather conditions, have a strong influence on the selection of the vertical formwork system and virtually no effect on the selection of the horizontal formwork systems. As a result, these factors are either omitted from the comparison of horizontal formwork systems or written as "Generally not a major factor."

Tunnel forms are used to form the horizontal slab and its corresponding supporting walls. As a result, this technique can be considered as both a horizontal and a vertical forming system. The writer chose to include this system with the other horizontal systems to avoid repetition and because the primary use of this system is to accelerate the forming of horizontal slabs.

These tables represent the end result of the knowledge acquisition phase and as such are the knowledge base that is used directly to either create the subgoals or to develop the rules for the expert system. For example, in developing the expert system for the horizontal formwork system, there were two subgoals called adequate crane service and inadequate crane service. These subgoals represent the synthesis of availability of crane and crane time involvement, existence of adjacent buildings and other obstructions, and adequacy of crane carrying capacity. These three factors are shown in Table 6.4 under the title "Hoisting Equipment."
Chapter Seven provides an example of how to use these tables to develop rules.

6.8.1. Choosing the Proper Formwork System Using the Comparison Tables.

Tables 6.4 and 6.5 can be used to directly help the formwork designer/selector choose the appropriate formwork system even if he does not use the expert system that is developed as a part of this research. These tables show the relationship between the factors affecting the selection of formwork systems and the different forming systems available for horizontal and vertical concrete work. The user must first list all the known major components of his project and then compare them to the characteristics listed in the table under each forming system. The best formwork system can then be identified when the project features agree with most of the characteristics of particular system.

The following example shows how Table 6.4 can be used to identify the best formwork system for horizontal concrete work. A similar approach can be used in conjunction with Table 6.5 to choose a formwork system for vertical concrete work.

6.8.2 Example Project

A 14-story concrete building, located at 1001 Pennsylvania Avenue, Washington D.C. Building size is approximately 22,500 square feet per floor. Floor slabs are 8" flat slab with drop panels at
every column. Column sizes and locations vary due to the existence of a three story high entrance, free from columns. Story heights vary from 14.5" for the first three floors to 10.5" for the remaining eleven stories. There are no cantilevered balconies, and the slab on grade will not be in place before forming operations start. The building is located in a highly restricted downtown area.

Existing buildings and traffic limit the movement of equipment on all sides of the building. The area has a highly qualified labor force and high hourly labor costs.

6.8.3. Use the Table 6.4

The fact that a tunnel form is used for only one-way slabs supported by a wall makes this system (tunnel form) an inappropriate choice. It should therefore be eliminated. Also, the potential number of reuses (fourteen) can not justify the use of tunnel forms which require at least fifty reuses. Flying truss and column mounted shoring systems are also eliminated because of the restricted site characteristics in downtown Washington D.C., on Pennsylvania Avenue. Crane movement is limited even though adequate crane service is available. Also, the irregular column spacing strongly suggests the elimination of these systems. As a result the choice is narrowed to either conventional wood or aluminum systems. A review of Table 6.4 reveals that a conventional aluminum system is a more appropriate selection than a conventional wood system for the following reasons:
1. The building size is 315,000 sq ft. which is more appropriate for the aluminum system (look at building shape "dimension limitations")

2. The story height in the first three floors is 14.5' (look at height stories)

3. The area is characterized by high quality and expensive labor force (look at area practice).

It should be noted that the conventional wood system can be used, but the conventional aluminum system is more appropriate.

6.9. Summary

The factors affecting the selection of formwork systems have been discussed, along with a specific example which explains the influence of each factor on the selected system. This chapter has concluded with a tabular comparative analysis indicating the effect of each factor on each forming system and an example showing how to use the tables in selecting a formwork system. This tabular analysis represents the knowledge base about formwork which the writer acquired. It should be viewed as one of the major accomplishment of this research study.
CHAPTER SEVEN
EXPERT SYSTEM DEVELOPMENT FOR
THE SELECTION OF FORMWORK SYSTEMS

After the organization and representation stages described in Chapter Five were completed, the acquired knowledge was transformed into a knowledge base in Chapter Six.

This chapter describes how the acquired knowledge is transformed into rules accepted by the selected shell (EXSYS Professional). The ease with which knowledge is represented and processed is largely dependent on the selected tool. SLABFORM and WALLFORM are the names chosen for the selection of the floor and wall forming systems respectively. The structure and implementation of these systems are provided along with the main features of EXSYS Professional. SLABFORM and WALLFORM capabilities and limitations are described last.

7.1. Languages and Tools for Building Expert Systems

A number of languages and tools are currently available for building expert systems. These tools can be categorized into three groups (19).
7.1.1. General Purpose Programming Language (GPPL)

Expert systems may be implemented from scratch using high-level general purpose programming languages. LISP (list processing) and PROLOG (programming in logic) are the most widely used programming languages for expert system development (19). General purpose programming languages provide maximum flexibility, but it is difficult to develop a rapid prototype when using them.

7.1.2. General Purpose Representation Languages (GPRL)

General purpose representation languages are programming languages developed specifically for knowledge engineering. They are much less flexible than GPPL to the extent that they are best classified by environment. KEE and OPS5 are examples of general purpose representation languages.

7.1.3. Domain Independent Expert System Framework

A domain independent expert system framework provides the expert system builder with an inference engine from which the application can be built by adding domain specific knowledge. Expert system shells fall under this category. An expert system shell is a fully developed expert system which has had its knowledge base removed. It contains a variety of user friendly modules to assist with the input of the knowledge base.
7.2. Shell Selection/Function

7.2.1. Selection of an Appropriate Tool for the System Development

Figure 7.1 shows the relation between the ease of expert systems development and the flexibility of the developed system. The level of flexibility is represented on the horizontal axis and ranges from inflexible (limited choice in input and output) to very flexible (unlimited choice in input and output). The ease of development and usage is represented by the vertical axis and ranges from easy to develop and use (need general computer knowledge) to difficult to develop and use (need good programming skills). The use of expert systems shells are only appropriate for the corner of the graph representing usages for specific circumstances. Shells are used when the ease of use and rapid development is highly desired and the flexibility is a lower priority.

The primary users of the proposed expert system for the selection of formwork systems are general contractors and formwork subcontractors, where little or no knowledge of programming languages is expected. As a result, the selection of an expert system shell is appropriate for the system development.
Figure 7.1  Appropriate Use of Expert System Shells
7.2.2. Choice of EXSYS Professional for Systems Development

EXSYS Professional, an expert system shell produced by EXSYS Inc., was chosen for representation of the formwork selection knowledge. As noted in Chapter One, five major considerations were important to the writer. First was the "user friendliness" of the system - because the intended users of the system have little or no experience in programming. Second was the flexibility of the system - the ability to modify and expand the system. Third was the availability of the system to the contractor on a single floppy disk which can run on a high density drive IBM machines or compatibles. Fourth was the capacity and ability to handle a large database. EXSYS Professional is a robust shell and is capable of handling up to 3000 rules. Fifth was the availability of the shell. EXSYS is available for application at the Civil Engineering Department and this writer is familiar with the system.

7.2.3. Overview of EXSYS Professional

Figure 7.2 shows the basic structure of EXSYS Professional and its relation with the domain expert, knowledge engineer, and the end user. The cycle starts with the interaction between the domain expert and the knowledge engineer, who also acts as the system developer. The knowledge engineer extracts the expert's knowledge and utilizes it to build the knowledge base. EXSYS Professional has a
Figure 7.2 Basic Structure of EXSYS Professional and its Relation with the User, Knowledge Engineer, and Domain Expert
built-in inference engine. The control mechanism of the inference engine uses the input data and facts, and attempts to search through the knowledge base to reach a conclusion. The user inputs information by answering multiple choice questions. The user may raise why and how questions, the explanation facility can answer the user's inquiry. The explanation facility also provides the user with a numeric rating of the selected systems, and some recommendations which should be followed in particular situations.

The thick lines in Figure 7.2 represent the feedback process. The user either accepts the result and stops, changes the input data and reruns, or completely rejects the result. The later case requires the system developer to restructure the system in order to give satisfactory conditions.

7.3. Representing Formwork Knowledge

As information relevant to the problem was initially acquired, much thought was given to the method of presenting this knowledge. The following procedure was developed by the writer to represent the acquired knowledge in a simple, organized, effective format. It is also well suited for the selected shell. Some of this knowledge has been covered in depth under Chapter Five - "Knowledge Acquisition." It is included here as the bridge to the development of the expert system.
7.3.1. **Develop the Search Tree**

This step started with the creation of a list of all the relevant factors which affect the selection of formwork systems. By conducting interviews and reviewing literature, a complete list of all the relevant factors was established (See Figure 6.1). The final list included 40 different factors. The writer then classified these isolated factors into a group of similar features. These factors were then represented in a hierarchical tree format. Several versions of this tree were prepared and reviewed by two experts and the research principal investigator.

7.3.2. **Prepare the Tabular Knowledge Base**

The influence factors along with all the possible solutions for horizontal and vertical forming systems were arranged in a tabular format where the columns represent all the possible solutions (i.e. the different types of forming systems), and the rows show the effect of the influence factors on each forming system (See Tables 6.4, and 6.5). The tabular knowledge representation format proved to be very effective in facilitating the task of the knowledge engineer. The following advantages were noted during the preparation of these tables:

1. This format facilitates the recording of data received in an interview. Several blank sheets were prepared before an interview, and the knowledge engineer filled in the cells directly during the interview.
2. During the preparation of the final comparative analysis, vacant cell could easily be detected. As a result, follow up interviews were short, narrowly focused, and could even be conducted by telephone.

3. Vertical and horizontal repetition of cells could be easily observed and recorded. The detection of this repetition was helpful in defining the subgoals, as will be explained in next section.

7.4. Building the Prototype

7.4.1. Extract Rules/Subgoals from Tabular Knowledge Base

Figure 7.3 shows how the rules were extracted from the tabular knowledge base (Table 6.4 & 6.5). These tables were also used to create subgoals. For example, in developing the expert system for the horizontal formwork system, there was a subgoal called "adequacy of hoisting equipment." This subgoal is a synthesis of availability of crane and crane time involvement, existence of adjacent buildings and other obstructions, and adequacy of crane carrying capacity. Figure 7.4 shows how the tabular knowledge was used to create this subgoal.
Figure 7.3. Example of Extracting Rule from the Tabular Knowledge Base

* Capital letters represent data about a specific formwork system, while small letters represent the controlling factors which are shared by all the systems.
<table>
<thead>
<tr>
<th>Influence Factor</th>
<th>Conventional Wood System</th>
<th>Conventional Metal System</th>
<th>Flying Truss System</th>
<th>Column-Mounted Shoring System</th>
<th>Tunnel Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability of Crane and crane time involvement</td>
<td>- Can be hand-set</td>
<td>- Can be hand-set</td>
<td>Crane is necessary if made into panels</td>
<td>- Adequate hoisting equipment must be available</td>
<td></td>
</tr>
<tr>
<td>Adjacent building traffic, and other obstruction</td>
<td>Generally, not a factor</td>
<td>- Generally, not a factor</td>
<td>- May be a factor if system panelized</td>
<td>A major factor, there must be open space at least 1.5 the length of the large panel from the face of the building</td>
<td></td>
</tr>
<tr>
<td>Adequacy of Crane carrying capacity</td>
<td>Generally, not a factor</td>
<td></td>
<td></td>
<td></td>
<td>Crane should have adequate carrying capacity at maximum and minimum radii</td>
</tr>
</tbody>
</table>

Subgoal "Adequacy of Hoisting Equipment"

IF: Crane is available with enough crane time involvement
AND: Adjacent buildings, traffic, and other obstruction are nonexistent
AND: Available crane has a sufficient carrying capacity at different radii

THEN: Hoisting equipment is adequate
ELSE: Hoisting equipment is inadequate

Figure 7.4 The Use of Tabular Knowledge Base to Develop Expert System Subgoals
7.4.2. Transform Rules into Format Compatible with EXSYS

Knowledge was loaded directly into EXSYS in the form of IF-THEN rules. The rules are developed by creating a series of qualifiers. A qualifier has two parts - the first is an incomplete sentence ending with a verb, and the second is associate values representing all the possible relevant situations to the qualifier. For example, Figure 7.5 presents three qualifiers that are used to develop the rule shown in Figure 7.6.

The IF part of the rule consists of one or more of the qualifier's values, and the THEN part consists of another qualifier value or variable or choices (possible solution to the rule).

7.4.3. Develop The Prototype System

As noted in Chapter One, the prototype system is a complete expert system but on a smaller scale (i.e., smaller number of rules). The purpose of developing a prototype is to assure that the system is valid and capable of producing valid results. Accordingly twenty three rules were entered into EXSYS to represent a prototype for the selection of horizontal formwork systems. The twenty-three rules represent the major deciding factors which affect the selection of horizontal formwork systems. These factors were building design (uniform, irregular), hoisting equipment (adequate, inadequate), site characteristics (restricted, unrestricted). These deciding factors were represented and entered in the system in abstract terms. For
Qualifier # 13

Hoisting equipment is
1. not available or primitive
2. available with limited carrying capacity at different radii
3. available with sufficient carrying capacity at different radii

Qualifier # 14

Adjacent buildings, power lines, and other obstructions are
1. nonexistant, or exist and do not limit the movement of the crane
2. existant and can be temporarily eliminated
3. existant and limit the movement of the crane

Qualifier # 15

Adequate crane(s) time is
1. available for materials handling, concrete delivery, and formwork erection and dismantling
2. available only for materials handling and concrete delivery

Figure 7.5 Sample Qualifiers for Adequacy of Hoisting Equipment Subgoal
Rule # 15

IF     : Hoisting equipment is available with sufficient
carrying capacity at different radii.

AND    : Adjacent buildings, power lines, and other obstructions
do not exist, or exist and do not limit the movement of
the crane, or exist and can be temporarily eliminated.

AND    : Adequate crane(s) time is available for materials
handling, concrete delivery, and formwork erection
and dismantling.

THEN   : Crane service is adequate

ELSE   : Crane service is inadequate

Figure 7.6 Sample Rule Developed Using
Qualifier # 13, 14, and 17
example, in the prototype system, building design was classified as uniform and irregular in abstract terms without any details about what is meant by "uniform" or "irregular." In the completely developed system, building uniformity is a synthesis of three subgoals: horizontal uniformity, vertical uniformity, and miscellaneous uniformity. Each subgoal in turn is a synthesis of items. For example, a horizontally uniform building is achieved by satisfying three conditions: regular slab type, identical beam size and location, and regular reoccurrence of cantilevered balconies.

7.4.4. Test the Prototype System

The prototype system developed for the selection of horizontal formwork system was then tested on hypothetical projects. The output of the prototype system was designed to give results in abstract terms. For example, horizontal formwork system was divided into two main categories: hand-set systems (conventional wood and metal systems), and crane-set systems (flying truss, column-mounted shoring systems, and tunnel forms). The expert system was tested and provided valid results.

7.5. Development of the Complete Expert System

As mentioned above, the prototype system was designed to process rules and produce output in abstract terms. The process of developing the complete expert system consisted of three steps:
The first step was to incrementally increase the number of rules to cover the full scope of each subgoal. For example, when developing the prototype, site characteristics were classified as either restricted or unrestricted. In the complete system, a number of rules were entered to completely define restricted or unrestricted site characteristics. These included existence of adjacent buildings, close-by traffic and power lines, site accessibility, and availability of storage and make-up area. This process was repeated to add the rules that define design uniformity or irregularity, and adequacy of hoisting equipment.

The second step was to add the rules that distinguish each formwork system. It should be noted that the above mentioned rules were added to the system to enable the system to determine whether the selected formwork system is hand-set or crane-set. The next step added the rules which characterized each formwork system. For example, the following rule was added to distinguish between the selection of the flying truss formwork systems and the column mounted shoring system:

IF : Story height is higher than 20 ft.
AND : The story height varies on the same floor
THEN : Column-mounted shoring system (confidence)=9/10
AND : Flying truss systems (confidence)=1/10

The third step was to add the "stationary rules." After the implemented expert system chose a specific formwork system, it also provided the user with some advice. For example:
IF : The selected system is flying truss system
AND : The clear distance between columns in the facade is more than 30 ft.
THEN : Divide the flying truss panels into two each of width
       = (clear distance between column - 3 ft.) / 2.

It should be noted that the above rule is stationary and belongs only in the flying truss formwork system. Other "stationary" rules were added concerning the rest of the formwork systems.

7.6. Development of the Formwork Selection System

Section 7.5 describes the general procedure that was followed to bridge from the prototype system to the complete system. The next sections describe the actual design "structure" of the two systems developed for the selection of formwork systems.

WALLFORM and SLABFORM are the names chosen for the expert systems developed for the vertical and horizontal formwork systems respectively. The vertical formwork expert system is separated from the horizontal formwork expert system because the information required to select each system is not the same, and they both have different functions. This allows the user to enter information relevant to the selection of either the vertical formwork system or the horizontal formwork system. The compatibility between each vertical and horizontal system was considered when building the expert system.
7.6.1. Development of WALLFORM (Decision Tree Approach)

The decision tree approach was adopted to develop a solution for the selection of vertical forming systems. A careful review of Table 6.5 reveals that there are four major factors that directly influence the selection. These are:

a. Building height
b. Type of the lateral and vertical support system.
c. Site characteristics
d. Adequacy of crane service

These factors are arranged in four different levels which represent the depth of the tree. Figure 7.7 shows the decision tree for the selection of the vertical forming system. The first level is the building height, which is divided into three height ranges (low, medium, and high). Each height category is further expanded to its possible corresponding lateral support system. It should be noted that each lateral support system is suitable for specific ranges of height. For example, frames are used only for building up to 20 stories high, while tube-in-tube systems are suitable for buildings higher than 50 stories.

After the first two levels have been established, the tree is further expanded to Levels 3 and 4 until the goal state can be reached. Rules can be extracted directly from the tree by tracing each branch to the goal state. For example, the following rule is developed by tracing the thick line in Figure 7.7.
Figure 7.7 Decision Tree for WALLFORM
Rule # 16

IF : The building is a medium rise building (between 20-50 stories)
AND : The lateral support system is shear wall
AND : Site characteristics are restricted "downtown"
AND : The crane service is adequate or inadequate
THEN : Slip form (probability = 9/10)

Decision trees have been created and published for many expert system developments. The advantage of such trees is that they are easily and directly converted to expert system rules, and are easily visualized and understood.

This approach, however, has some drawbacks. One of its major problems is that it is suited for a shallow tree. If the trees have many branches this approach results in more rules than are needed.

7.6.2. Development of SLABFORM (Subgoals Approach)

As the number of branches in the decision tree increases, it becomes difficult to read and maintain. One approach to increasing the efficiency and readability of the tree is to create subgoals. Subgoals are simply a way of specifying parts of the decision tree which have similar features. Subgoals provide a very convenient way to specify a branch point in one condition rather than many.

Figures 7.8 and 7.9 provide a visual and written presentation of the subgoals. Figure 7.8 shows that the horizontal forming system
can be classified into hand set systems, such as conventional wood systems and conventional aluminum systems; and crane set, such as flying truss systems, column-mounted shoring systems, and tunnel forms. The figure 7.8 shows that three conditions (subgoals) are necessary and must be met for the selection of the crane set system. These are: modular building design, adequacy of the crane service, and open site characteristics. For the building to be modular, three other subgoals should be satisfied. These are: horizontal uniformity, vertical uniformity, and miscellaneous uniformity (See Figure 7.8).

7.7. System Features Inherited from EXSYS

The following sections explain some of the main features which are inherited from EXSYS and characterize the implemented systems: SLABFORM and WALLFORM. It should be noted that the following features are not the only features offered by the shell, they are the ones selected by the writer.

7.7.1. Control Strategy/Chaining Mechanism

SLABFORM and WALLFORM utilize backward chaining mechanisms to arrive at a conclusion. They assume a goal state and reason backward to known data or facts which support or discount the assumed goal.
Figure 7.8 Subgoals Development for the Horizontal Forming System
RULE # 1. Horizontal Uniformity

IF : Slab type for the whole building or the part of the building under investigation is flat plate OR flat slab OR one-way slab supported by beams OR one-way slab supported by walls

AND : Beams are of the same size and location on each floor OR within 20% difference in size and/or location on each floor OR nonexistent "embedded or flat plate"

AND : Cantilevers and overhangs are regularly recurring from floor to floor or nonexistent

THEN : Horizontal slab system is uniform

ELSE : Horizontal slab system is irregular

RULE # 6. Vertical uniformity

IF : Columns are of the same size and location on each floor OR within 20% difference in size and/or location on each floor OR nonexistent "slab supported by walls."

AND : Walls are of the same size and location on each floor OR within 20% difference in size and/or location on each floor OR nonexistent "slabs supported by column only"

THEN : Vertical supporting system is uniform

ELSE : Vertical supporting system is irregular

Figure 7.9 Sample Rules for Modular Building Design
EXSYS Professional has the capability to utilize both forward and backward chaining. However, the problem addressed in this research is a design problem, which is characterized by a limited number of goal states or solutions. This warrants the use of backward chaining.

7.7.2. Explanation Facility

SLABFORM and WALLFORM explanation facilities are designed to respond to two types of sceneries:

1. During the consultation, if the user wonders why the program needs to know the information it is requesting. This is done by typing WHY, the program will respond by displaying the rule(s) for which it is trying to determine validity. The rules contain a textual note which clarifies their purpose and the terminology associated with each rule. It also contains a reference telling the user where the information for the rule was obtained.

2. At the end of the consultation session, if the user desires an explanation of a certain conclusion output. This is done by typing the line number of the choice or statement. The system will respond by displaying all of the rules used to determine the value of that choice or statement (line of reasoning).
7.7.3. Choices (Possible Solutions to the Problem)

Choices are all the possible solutions to the problem among which the expert system will decide. SLABFORM and WALLFORM contain 12 possible solutions (formwork systems), seven for the horizontal forming system, and five for the vertical forming systems. The goal of an expert system is achieved by selection of the most likely choice based on the data input, or by a list of all possible choices arranged in order of likelihood.

At the end of each run, the system will display the selected types of formwork followed by "probability=" or "confidence=" and a number. The number indicates the confidence that the choice is correct.

7.7.4. Confidence Factors

EXSYS Professional supports five systems of probability or confidence factors.

1. 0 or 1. This system is a yes or no system with no confidence factor. This system is good when the developer can write rules that are definitely yes or no.

2. 0 to 10. This system is the most generally useful. It is used to develop both SLABFORM and WALLFORM. In this system, 0 indicates definitely NO, and 10 indicates definitely YES. Values between 1 and 9 are degrees of certainty between the extremes. In this mode, the final confidence factors are simply the averages of the fired
rules which contain choices in their consequents. An assignment of values 0 or 10 to a choice by any rule, however, excludes all other confidence factors from consideration.

3. -100 to 100. This system has values over the range of -100 to +100. In this mode, confidence factors can be averaged or they can be combined as dependent or independent probabilities. This system can be used when two significant figures are required (usually only if there is valid statistical data available).

4. Increment, Decrement. This system allows points to be added or subtracted from the choice. A rule can be added or subtracted up to 100 points from the total for a choice.

5. Custom formulas. These allow complex formulas to be used in combining confidence factors.

SLABFORM and WALLFORM utilize the 0 to 10 mode (see explanation below) and contain confidence factors for each of the rules whose consequents are goal stated (formwork systems). The confidence factors assigned to the goal depend upon the importance of the IF part of the rules. Most of the confidence factors attached to the rules represent the expert's own evaluation. However, some lower values of confidence factors were assigned by the writer. For example, conventional wood systems can be used for virtually every situation, even when they are not really appropriate. As a result, lower confidence factors are assigned to conventional forming
systems in every rule which contain choices in their consequents. It is interesting to note that City Spire, a seventy-five-story building in New York City, completed in 1987, was built using conventional forming system in a two-days-per-floor cycle (69).

There are several reasons for choosing a 0 to 10 mode for confidence factors. These are:

1. Often a human expert's intuitive knowledge of the likelihood of a particular situation is only known up to one significant figure.
2. By having 11 possible values (0-10), there are enough divisions to choose from.
3. No valid statistical data were available to justify using more sophisticated techniques.
4. The 0 to 10 system is easy to use and understand to the user.

7.7.5. Default Rules for Incomplete Knowledge

Default rules allow a system to be utilized when information is missing or unavailable. It is provided to mimic the expert's assumptions in his problem solving strategy when he encounters a missing data situation.

Whenever user input to a question is unknown, the system defaults to the worst case value of the requested input. For example, to determine the number of floors that should be connected (reshored), the system asks the user for the ratio between dead load to the live load (D.L/L.L). When the user answers "unknown," the
system defaults to the worst situation, which gives the maximum number of reshored floors for a particular floor cycle. At the end of the consultation, the user is reminded of the unknown information and its effect on the outcome.

It should be noted that the assignment of the worst possible values was observed as one of the expert's behaviors in dealing with unknown knowledge.

7.7.6. Addition/Deletion of Knowledge

In a pure production system, rule ordering is not important. Therefore, addition and deletion of rules is quite simple. The only concern is the effect of the changes (addition or deletion) on the structure of the subgoals.

7.8. System Capabilities/Limitations

1. SLABFORM and WALLFORM are rule based expert systems, designed to assist formwork designers/planners to select the optimum formwork system. SLABFORM selects the horizontal (floor) formwork system, shoring and reshoring system, advises the user in a unique situation, and recommends some formwork manufacturers to contact. WALLFORM selects the vertical formwork system, tie type and pattern, and recommends some formwork manufacturer's products.
2 The primary users of these systems are general contractors and formwork subcontractors. The system assumes that the user has some knowledge about formwork. The user would be at the early phase in the development of the project, with some information available about building shape, site conditions, and resources.

3. In multi-purpose high-rise buildings, each set of floors has certain functions and features which may result in the use of different formwork systems for each section. In this situation, the user is advised to run the system more than one time to determine the optimum system for each part of the building.

4. The two systems were developed as a result of intensive interviews and a literature search. However, some information was extracted from a single source of expertise, which may tend to be biased.

7.9. Summary

This chapter provides an explanation of the expert system development starting from preparing the knowledge base to the development of the complete expert system. SLABFORM and WALLFORM were developed to assist the contractor in selecting the optimum formwork system. These systems are rule-based systems built using EXSYS Professional, an expert system shell. Both systems utilize backward chaining mechanisms to arrive at a conclusion. The
systems provide the user with a list of candidate systems followed by a number which represents the most appropriate system for usage.
CHAPTER EIGHT

SYSTEM VALIDATION AND PARAMETRIC ANALYSIS

The preceding chapters provided a sound background of the basic principles of expert systems, the different formwork systems, the factors affecting the selection of a particular system, and the development of SLABFORM and WALLFORM systems. In this chapter, both systems are tested via "real word" test cases located in different areas around the country. Complete guidelines about how to use the systems are also provided. The chapter ends with a parametric study indicating the effect of changing the different parameters on the final selection provided by the system.

8.1. Method of Testing

The purpose of this step is to validate the implemented expert system via "real word" test cases and refine the system if necessary. It should be noted that the system at this stage is the complete system and no drastic changes are expected because the system had been tested several times during development, but in the absence of a human expert. Testing of the system proceeded as follows:

1. The knowledge engineer contacted the head of the formwork department of a general contractor in Washington D.C. area and asked him to provide the information for test cases of his choice. It should be
noted that this expert was one of the sources of knowledge and is familiar with this research effort.

2. The expert provided two test cases featuring diversity in building design, site characteristics, and location. The first test case involved the selection of the horizontal and vertical formwork system (Test Case #1). The second test case (Test Case #2) involved the selection of horizontal formwork. The features of the second building are completely different from those on the first building.

3. The above test cases are for buildings of medium height (i.e. lower than 25 story). In order to test the WALLFORM system for high rise building, the writer chose an interesting test case (Test Case #3) described in an article devoted entirely to the selection of vertical formwork systems (47).

4. All test cases were run using SLABFORM and WALLFORM, results were printed and shown to the human expert who provided some comments which were then considered by the system developer.

8.2. System Validation/Testing

The fact that the construction of an expert system is an iterative process led to an early development of a prototype system. A working system "prototype" was developed early in the process to provide a starting point for more adjustments. This prototype system was then refined and expanded to produce decisions
acceptable to the expert. The prototype system was then tested on a series of sample problems. Running the prototype system on these sample problems led to the detection of some inconsistencies in the knowledge base. These problems were corrected and more rules were added.

Once this writer was satisfied that the expert system was fully developed and performing with consistency and reliability, it was applied to some test cases. Each test case will be described below:

8.3. Test Case # 1

A 14-story concrete building, located at 1001 Pennsylvania Avenue, Washington D. C. Building size is approximately 22,500 square feet per floor. Floor slabs are 8" flat slab with drop panels at every column. Column sizes and locations vary due to the existence of a three story high entrance, free from columns. Story heights vary from 14.5' for the first three floors to 10.5' for the remaining eleven stories. There are no cantilevered balconies, and the slab on grade will not be in place before forming operations start. The building is located in a highly restricted downtown area.

Existing buildings and traffic limit the movement of equipment on all sides of the building. The area is characterized by a highly qualified labor force at a high hourly cost.
8.3.1. Tutorial Run with Test Case # 1

A detailed description of the tutorial run is provided for test case # 1. For other test cases, only the user input along with the final systems selection is displayed. The description of the tutorial run refers regularly to the screens displayed by the system in a sequential manner. These screens are included as Appendix D.

8.3.1.1. System Requirements>Loading

The system works on an IBM personal computer or compatible with a minimum of 640 K of RAM. A hard disk or high density disk is necessary. If the system will be used for educational purposes within the Construction Engineering and Management program at the Pennsylvania State University, the system can be loaded on the hard disk. If the system will be used for other purposes, the user has to have a high density drive. A monochrome or multicolored screen can be used.

8.3.1.2. Description of Analysis Using the Expert System Software

If the user has EXSYS professional loaded on his hard disk, the system is installed under a subdirectory called EXSYSP. The user should type Cd/EXSYSP in respond to C: > EXSYSP >., and screen 1 will be displayed
If the system is used on a high density drive, SLABFORM and WALLFORM are loaded on a high density floppy disk and are self booting, so that the user needs no other disks. In response to prompt A, the user should type the word EXSYSP SLABFORM with one space between them. After hitting the RETURN key, screen 1 will be displayed.

Pressing any key will cause screen 2 to be displayed. In this screen, the system asks the user if he wishes an instruction on running the program. A first-time user of SLABFORM should type "YES" to the first question.

In screen 3, the system asks the user if he wishes to have the rules displayed as they are used. One should always answer no or hit RETURN, unless one is doing an in-depth study of the system or if it is being used for educational purposes. It should be noted that answering yes will substantially increase the time needed for the run and will cause unnecessary information to be displayed on the screen.

Screen 4 includes the title of the system and the author's name. Screen 5 provides an explanatory text which explains what the knowledge base will do and how to run the system.

Once the initial screens have been displayed, the program will start to execute the rules in the expert system knowledge base. This requires some input data from the user. There are two standard types of questions to which users must answer by selecting a multiple choice response or provide a numerical value.

SLABFORM asks the user questions by displaying a statement and ending in a verb, followed by a numeric list of possible
completions for the sentence. The user answers the questions by typing the number or numbers of the values correct to his situation, and then pressing the RETURN key. If more than one number is desired, the user should separate the numbers with a comma. If the user inputs any number outside the range of the list, the computer will re-ask the question.

The menu at the bottom of screen #6 appears with every question. Typing QUIT allows the user to save all of his data to this point, turn off the system, and return to it later. Typing < H > (Help), provides the user with further guidance. If the user wonders why a question is being asked, he can type WHY, and the system will display the rule(s) it is trying to fire. The system also displays the status of the rule by color. The conditions in the rule are color coded so the user can tell which conditions in the IF part are true, false, or unknown. The yellow is used to indicate "true" conditions, red for "false," and blue for "status unknown." If all of the IF conditions in a rule are displayed in yellow "true condition," the rule is true and the "then" part will also be yellow.

As displayed in screen 6, the proper response for the test case is 2 - flat slab with or without drop panel. Thus 2 and RETURN were typed. Screens 7 to 18 were generated using the data from the case study.

An example of how the system can deal with uncertain data is illustrated in screen 17. The system asks the user about the ratio between live load and dead load during construction. If the user is uncertain and types 8 (unknown), the system will assume the worst
situation in which the ratio is 0.5, which gives the maximum number of stories to be reshored.

The program will continue asking questions until it has considered all the rules relevant to the possible solutions and will then display its result. Just prior to the display of the results, the program displays information interpreting the meaning of the values assigned to the choices "screen."

Screens 19, 20, and 21 are the result of the analysis and should be carefully read. Screen 19 displays the system's final selection and useful design information.

Lines 1, 2 of screen 19 give the rating scored by each system. This rating is a final value obtained by combining the values from all the rules used that had that choice in their THEN part. It should be noted that only the numerator will be displayed (e.g. 8 not, 8/10).

Lines 3 to 10 provide a text statement with no associated numeric value displayed. These statements are intended to be messages for the user, and they do not have any associate confidence factors. Copies of all screens mentioned above are provided in Appendix D.

8.3.1.3. System Performance and Expert Evaluation for Test Case # 1

The system selected a Conventional Metal System and a Conventional Wood System as strong candidates for this building. The actual selection of the human expert was the Conventional Metal
System. The human expert attributed his selection of Conventional aluminum system to the following reasons (75):

1. Crane set systems (flying truss system, column-mounted shoring system, and tunnel form) were eliminated because of the highly restricted site conditions in downtown Washington D.C. and the irregular column location in the project.

2. A conventional wood system and a conventional aluminum system are both good candidates for this project. But the choice was a conventional aluminum system because of the large size of the building, high story height in some places, and the available good crane service which make it possible to penalize the system in some areas.

This writer's chosen system agrees with the selection of the human expert, and the justification of his selection is represented by rules contained within the system.

WALLFORM was used to select the appropriate formwork system for columns and walls for test case #1. Steps similar to the ones mentioned above were followed to run WALLFORM. The selection provided by the system was the conventional wall form. The selection of the expert system agreed with the one provided by the human expert. The human expert attributed his selection to the small number of reuses which was reflected in the building height. The expert's justification was represented by rule #9 contained within the system.
8.4. Test Case # 2

8.4.1. Project Description.

Grand Bay Hotel is a reinforced concrete building located in Miami, Florida. The slab is a 7" flat plate spanning over six columns in the short direction. Building size is approximately 16,500 square feet per floor. Column sizes and locations are identical from floor to floor. There are trapezoidal cantilever balconies at the same location on all the floors. Story heights are constant over all the building (8 feet clear high). Slab on grade will be in place before forming operations start.

Adequate crane service is available. Existing buildings do not limit crane movement on any side. Local labor force is inexpensive and unskilled.

8.4.2. System Performance Via Expert Evaluation

The actual selection of the human expert was the flying truss system. The expert contributed his selection to: (1) modular building design; (2) unrestricted site condition; (3) and availability of adequate crane service. He also stressed the fact that most of the labor force in Miami area are unskilled and its very important to increase the engineering supervision and avoid any system which requires a highly skilled labor force (i.e. Conventional Wood System).

SLABFORM was used to test the above described case study. SLABFORM scored 9/10 for both the flying truss system and the
column-mounted shoring system. When the knowledge engineer asked the expert about his evaluation of the expert system performance he stated that the column-mounted shoring system can be used in this case and it is feasible alternative, but the reason for their preference of flying truss system over the column-mounted is based on an economic evaluation of the local material prices.

In cases where the expert system selects two or more formwork systems with equal or approximately equal confidence (three points or less), the user can choose the system with which he is familiar or which is available in his yard facility or through local suppliers.

In cases where the expert system selects two or more formwork systems with considerable differences in the confidence factor associated with the selection (three points or more), the user should chose the system with the higher confidence. The selection of the formwork system with the lower confidence will cause either higher cost or slower progress.

In cases where the expert system eliminates one or more formwork system(s), the user should avoid using these systems.

8.5. Test Case # 3

8.5.1. Project Description

Tabor Center, is a 1.3 million square feet (20,000 square feet per floor), multi-use facility in the center of downtown Denver. It consists of twin office towers of 32 and 40 stories. The tower
structure is composed of three elements: the exterior wall, the central core, and the interior deck area that ties the two together (tube-in-tube). The core is structural steel with a concrete diaphragm or infill walls up to floor 12 to resist part of the lateral loading. The deck area is also structural steel with a metal deck and concrete fill. The exterior wall consists of closely spaced columns (tube system). A study showed that the crane time is not adequate for hoisting formwork and it will only be used for material handling and concrete placing. Architectural concrete is required for the exterior walls.

8.5.2. System Performance Via Expert Evaluation

WALLFORM was used to select the formwork system for the exterior "wall." The expert system selection was a self-raising form and scored 9/10. Using the explanation facility provided by the system, several rules were found to be responsible for this selection. These are:

1. The self raising form is suitable for buildings higher than 25 stories.
2. It can accommodate architectural concrete requirements.
3. The self raising form is a crane independent system.
4. The self raising form can accommodate restricted site conditions.

This case study was extracted from an article entitled "Building Production and Quality into Architectural Concrete" (47). The whole
article was devoted to the problem of selecting the formwork system. The author is an expert in selecting formwork systems, and he is the author of two articles entirely devoted to the selection of formwork systems (29, 86). The author attributed his selection to the same reasons stated above. In his article, he explained that renting or buying another crane was impossible because of the site conditions in "Downtown Denver." It was also economically infeasible.

8.6. Parametric Analysis

Typically, a parametric analysis is conducted by changing one or more of the influencing parameters (factors), and studying the effect of this change on the final result. The task of performing this analysis using the implemented expert systems was not easy because of the large number of influence factors. As a result, the four major factors which have the most impact on the vertical forming systems, were chosen to study the effect of a change of each on the selected formwork system. These factors are: lateral support system, crane service, site conditions, and concrete surface.

WALLFORM was run several times and for each run, one of these factors was changed to its extremes and the final selection of the system was recorded. As mentioned above, the system ranks its selection using a numeric score. The highest score recorded is called "strong candidate," other recorded scores are called "can be used."

The results are tabulated in the matrix format shown in Figure 8.1. The selected influence factors are arranged vertically and
Figure 8.1 Parametric Analysis for the Vertical Forming System
horizontally. Expert system selections are indicated in the matrix's cells. In this figure, the "strong candidates" are arranged in the left lower part of the matrix. The other candidates ("can be used"), are arranged in the upper right side of the matrix.

Test case # 3 was used to explain how to use the table. As mentioned above, the lateral support system is tube-in-tube, site conditions are restricted, crane service is inadequate, and architectural concrete is required. The reader should locate the appropriate lateral support system at the top of the table and go down to match the other factors. For the example provided, the selection is a self raising form or a slipform. This is appropriate given the inadequate crane service, and restricted site conditions. Slipforms were excluded because of the requirement for architectural concrete.

8.7 Expert's Evaluation of System

To assure the validity and credibility of the implemented expert system, the tabular knowledge base was sent to Ms. M. K. Hurd, the author of the well recognized book concerning formwork - Formwork for Concrete (4). Ms. Hurd reacted favorably to the tabular knowledge base. It should be noted that Ms. Hurd was not a major source of knowledge for this research, and thus her views were considered unbiased.

The second attempt at validation was provided by Mr. J. M. Covarrubias of The George Hyman Construction Co.. Mr. Covarrubias used the system to select a formwork system for one of his current
projects. The system provided him with the answer he was expecting. Mr. Covarrubias then changed some parameters and reran the system. It again provided him his expected answer. It should be noted that Mr. Covarrubias was one of the major sources of knowledge for horizontal formwork system and he also reviewed the tabular knowledge base and the decision tree.

8.8. Summary

This chapter presented a "screen by screen" tutorial run for a selected test case. Three test cases were used to validate the performance of the system. The first test case aimed at the evaluation of the horizontal and vertical formwork selection system. The second only focused on the selection of horizontal formwork system. The third test case was provided to test the system for a high rise building situation. The selection of the expert system agreed with the selection of human experts. This chapter concluded with a parametric analysis to study the effects of four key different parameters on the selected vertical formwork system.
CHAPTER NINE
SUMMARY AND CONCLUSIONS

9.1 Problem Domain/Appropriateness as a Knowledge Based Expert System

The selection of a formwork system has been identified as one of the major problems which the construction planner/designer encounters. Furthermore, the current practices of rapid placement of concrete have forced the planner/designer to search for new or modified systems that can facilitate the construction process.

In most reinforced concrete buildings, the contractor evaluates different formwork systems and selects one that will give the most efficient construction sequence. The evaluation and selection of a formwork system is typically made by a senior member of the contractor's organization. The decision is heavily based on that individual's experience, intuition and judgment. As a result, the problem is well suited to a solution by expert systems.

This research is aimed at assisting construction planners with the evaluation of potentially suitable formwork systems and the eventual selection of the optimum system. This is accomplished by the development of microcomputer based computer software using an expert system shell.
9.2 Summary and Issues of System Development

Two issues related to system development have been studied in-depth as part of this research: (1) the process of knowledge acquisition, and (2) the collection, organization, and transformation of the acquired knowledge to the selected shell.

Knowledge was acquired for the selection of a formwork system both from published literature and via direct interaction with several experts. Books and other published literature often fall short of providing adequate information to build the knowledge base. As a result, interaction with an expert is invaluable, there is no substitute.

Twelve different forming systems were found to be used in today's construction practices. Seven of these systems were classified as horizontal forming systems, information about these were used to build "SLABFORM." The other five were classified as vertical forming systems, information about these was utilized to build "WALLFORM." SLABFORM selects the horizontal forming system, while WALLFORM selects the vertical forming systems for a building. WALLFORM may be used more than once on a building e.g., to select the column forming system, the wall forming system and the core forming system.

Formwork systems, as defined in Chapter One, are the total system of support for freshly placed concrete, including sheathing as well as other supporting elements, such as hardware and bracing. The selection of the number of floors that should be shored and reshored is provided by "SLABFORM" for different cycle times.
(number of floors/weeks). Selection of tie types and loading capacity is provided by "WALLFORM."

2.3 Current Status of the System

The systems as described in Chapters 5 and 6, are implemented in EXSYS Professional, an expert system shell, to assist the contractor in better selection of his formwork system. The systems take input from the contractor concerning building size and features, site characteristics, crane services, job specification and schedule, and the resources offered by the supporting organizations. It then selects appropriate formwork systems and ranks their suitability for the job. The systems also recommend shoring and reshoring schemes.

SLABFORM and WALLFORM are production systems utilizing backward chaining to reach a conclusion. They have the ability to explain their reasoning during and after the consultation session. Confidence factors have been utilized to provide the user with a degree of certainty for the final selection. The system also provides the user with recommendations in regard to the selection of other formwork components. The system can be modified by adding more rules or deleting existing ones.

2.4. Contributions to Knowledge

This research effort has led to the following contributions to knowledge in the area of formwork and expert systems:
1. The study introduces a life cycle oriented model which shows the interaction of the subactivities required to provide formwork systems with each other, and with the concrete structure's own life cycle.

2. It is the first survey to study and classify the formwork systems that are available to the contractors in the United States.

3. The study introduces several formwork systems that are used by contractors but never published in literature. As a result, this research is considered the first publication of jump forms, and the column-mounted shoring system.

4. The factors affecting the selection of the formwork system were introduced in a decision tree and a tabular representation. The knowledge base is the result of twenty unstructured and structured interviews. It should be noted that, to date, this knowledge base is the only formal one of its kind in the United States.

5. This research effectively utilized several knowledge acquisition techniques. It also reinforces the importance of unstructured interviews, and how the knowledge engineer can expand the unstructured interviews in the right direction, and thus extract rules from the unstructured interviews.

6. This study has developed an expert system and proven that the use of an expert system shell can facilitate the task of the knowledge engineer and give him the time to concentrate on the knowledge acquisition process.
7. The examples used in the test cases prove that a contractor can use the system effectively to select formwork systems, and to train staff on selection procedures.

8. Finally, this study has provided a parametric chart defining the parameters within which formwork systems can be effectively used.

9.5 Areas for Future Research

During the course of this research effort, several areas for potential research were identified. Some of these areas represent an extension to this research, the others are related to the formwork domain.

9.5.1. Extension to the Current Research

The development of an expert system is a dynamic process (19). As a result, the current version of SLABFORM and WALLFORM forms the foundation for a fully developed expert system. More work needs to be done to increase the utility and credibility of the current version. Such work includes:

1. The validation of the knowledge base through more extensive expert interaction. Such interaction would expand and modify the current knowledge base and eliminate any bias. The writer suggests that SLABFORM and WALLFORM be distributed to a number of
contractors and their observations and suggestions for future improvements be recorded.

2. The improvement of the certainty factors by conducting more interviews. The current systems do not utilize the full potential and power of the expert system shell.

3. Initially, it was hoped that the system would be able to provide a cost comparison between the different systems, but this goal could not be accomplished for the reasons discussed in Chapter Five. The writer proposes to expand this work to include cost data for a particular contractor under appropriate legal provisions.

4. Another area for potential research is a result of the extensive amount of brochures and formwork data collected during this research and the capability of the EXSYS Professional to interact with dBase III Plus, a database software package. The data manipulation capabilities of dBase III Plus, and the heuristic rules that can be built using EXSYS, offer more valuable tools for the contractor to automate the whole formwork cycle described in Chapter Two.

9.5.2 Necessary Related Research

As mentioned above, twelve forming systems are currently used in construction practice. This writer noticed serious gaps in the current documents which guided the contractor, such as ACI 318-86, and ACI 347-78. Among these are:
1. No guidelines or specifications are given by any of these documents with regard to design, materials properties, and erection and dismantling procedures for most systems. It was also noted that there was no attempt made to standardize the names of these systems. The current literature uses many different names for the same forming systems. For example, self-raising forms are sometimes referred to as climbing forms, while the name "climbing form" is used to describe the jump form.

2. No safety precautions or guidelines are provided by the basic safety documents, such as OSHA and ANSI, with regard to most of these systems such as tunnel forms for buildings, jump forms, and self-raising forms. This writer noticed that the Canadian Specifications cover most of these gaps.

3. All the formwork reference books repeatedly cover the traditional systems or the relatively old systems fairly well, while there is brief or no description of the relatively new systems. For example, tunnel forms and self-raising forms are never mentioned by any of the basic reference books of formwork. New books or updated versions of the existing ones are urgently needed to cover these gaps.

The writer feels that this research laid the seeds for his own research direction for years to come.
9.5.3 Other Areas for Future Research

Construction planning has frequently been identified as one of the major factors in the success of any construction project. Formwork selection is one of several important decisions that has to be made during the planning phase of a project. Little work has been carried out to provide the construction planner with a computer tool that can facilitate his work. The writer proposes the following areas for future research which ultimately integrate the construction planning process.

1. Selection of earth moving equipment is heavily based on personnel experience in the earth moving methods and equipment, and thus it is a potential candidate for expert system development.

2. Selection of the number, type, and position of tower or mobile crane combines mathematical algorithm with rules of thumb.

3. Selection of materials handling equipment, which includes the selection of concrete delivery method (crane delivery or pumping).

9.6 Conclusion

This research has attempt to capture the expert's knowledge in selecting the optimum formwork system for concrete buildings. The acquired knowledge has been organized in a tabular format (Tables 6.4 and 6.5) to show the relationship between the factors affecting
the selection of formwork systems and each formwork system. These tables were then used to create rules and subgoals in a form suitable for the selected shell. SLABFORM and WALLFORM are the expert systems developed for the selection of horizontal and vertical formwork systems respectively. These systems were developed using an expert system shell (EXSYS Professional) and were validated via three test cases and expert review. Finally the results of a parametric study, using the expert system are presented.
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    Proceeding of the Second International Conference "Forming
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    Roofs.* Concrete International, January 1986.

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APPENDIX A.1

GENERAL INSTRUCTION FOR QUESTIONNAIRE

1. Only buildings made of Reinforced Concrete, Prestressed Concrete, Prefabricated Concrete, and combinations of all should be considered in your response.

2. Buildings having straight lines shapes, broken lines, and curved shapes should be considered in your response.

3. Special structures such as Domes, Folded Plates, Tanks, Bridges . . . etc. should be excluded from your response.

4. If there are portions of this questionnaire that required knowledge outside your area of personal expertise. Please refrain from responding and write "OAE" (Outside Area of Expertise).

5. Please provide the following data to help us identify your personal area(s) of activity and expertise. All replies will be kept confidential

Name ............................................................

Organization ................................................

Title ...........................................................

Area(s) of expertise: (Check as many as appropriate)

( ) General Contractor ( ) Manufacturer

( ) Sub-Contractor ( ) Designer

( ) Construction Management
Please return this questionnaire in the enclosed stamped envelop prior to January, 1989 to:

Awad S. Hanna
212 Sackett Building
Pennsylvania State University
Civil Engineering Department
University Park, PA 16802
QUESTION 1

A. In choosing a formwork system, describe in sequential manner the main activities that lead you to a particular formwork system.
B. For each selected activity, what is the necessary information for you to perform each activity and what are the sources of these information.
C. What are the outputs of each selected activity, and how it will influence the following activity.
D. What are the factors that affect each step (activity).
QUESTION 2

In the table given below, check ( ) those characteristics included by your organization in selecting formwork systems. In addition, indicate your assessment of the importance for each of the characteristics listed using scale 1 to 10, in which 1 indicates "not important", and 10 indicates "very important". Add any characteristics that you think should be included.

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>IMPORTANCE INDEX</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DESCRIPTION</strong></td>
<td>Conventional wood</td>
</tr>
<tr>
<td>Building</td>
<td></td>
</tr>
<tr>
<td>High rise</td>
<td></td>
</tr>
<tr>
<td>Low rise</td>
<td></td>
</tr>
<tr>
<td>Large size</td>
<td></td>
</tr>
<tr>
<td>Small size</td>
<td></td>
</tr>
<tr>
<td>Uniform</td>
<td></td>
</tr>
<tr>
<td>Irregular</td>
<td></td>
</tr>
<tr>
<td>Slab</td>
<td></td>
</tr>
<tr>
<td>Flat slab</td>
<td></td>
</tr>
<tr>
<td>Flat slab w/ drop-panel</td>
<td></td>
</tr>
<tr>
<td>Solid slab on beams or walls</td>
<td></td>
</tr>
<tr>
<td>Waffle slab</td>
<td></td>
</tr>
<tr>
<td>Frame</td>
<td></td>
</tr>
<tr>
<td>Shear walls</td>
<td></td>
</tr>
<tr>
<td>Frame/ shear wall</td>
<td></td>
</tr>
<tr>
<td>Tube-in-tube</td>
<td></td>
</tr>
<tr>
<td>Bundle tube</td>
<td></td>
</tr>
<tr>
<td>Framed tube w/ interior walls</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX A.2

A LIST OF COMPANIES INCLUDED IN THE QUESTIONNAIRE

1. Marketing Director,
   Smith Elwin G., Div.,
   Cyclops Corp.,
   100 Walls St., Pittsburgh, PA 15202

2. Marketing Director,
   Universal Form Clamp Co.,
   461 N. Leavitt St.,
   Chicago, IL 60612

3. Marketing Director,
   Sonoco Products Co., Industrial Products Div.,
   P.O. Box 160
   Hartsville, SC 29550

4. Simplex Forms System Co.,
   2859 N. Natoma Ave.,
   Chicago IL, 60634
   Richmond Screw Anchor Co., Inc.,
   7214 Burns Street,
   Fort Worth, TX 76118

5. Rexnord Inc.,
   P.O. Box 2022,
   W. Milwaukee, WI 53201

6. Plastic Corp. of Chicago
   5 Greenwood Ave.,
   Romeoville Lockport, IL 60441

7. National Metal Fabricators
   2395 Greenleaf Ave.,
   ELK Grove Village, IL 60007

8. Metrodeck Inc., Goldsmith Metal Lath Co., Div, The
   4501 Chickering Ave.,
   Cincinnati, OH 45232
9. Metal Forms Corp.,
   3334 N. Booth St.,
   Milwaukee, WI 53212

10. McCracken Concrete Pipe Machinery Co.,
    P.O. Box 1708
    Sioux City, IA 51102

11. Mansonite Corp., Industrial Div.,
    29 N Wacker Dr.,
    Chicago IL 60606

12. Lyn-Weld Co., Inc.,
    Fellows Ave.,
    Wilkes-Barre, PA 18702

13. Lunn Industries, Inc., Straight Path, Dept ECD,
    Wyandanch, L.I., NY 11798

14. Louisiana- Pacific Corp.,
    111 S.W. 5 th av.,
    Portland, OR 97204

15. Leigh Industries Inc.,
    PO Drawer 627,
    Ashtabula, OH 44004

16. Kirk & Blum Mfg., Co.,
    3141 Forrer St.,
    Cincinnati, OH 45209

17. Heltzel Co.,
    1750 Thomas Rd.,
    Warren OH 44481

18. Gitco Inc.,
    P.O. Box 1296,
    Media, PA 19063

19. Gateway Building Products Div.,
    Gateway Construction Company Inc.,
    3233 W. Grand av., Chicago, IL 60651
20. Fabricated Metals Corp.,
6300 Kenjoy Dr., P.O. Box 14006,
Louisville KY 40214

21. Ellis Manufacturing Co., Inc.,
4803 N. Cooper Rd.,
Oklahoma City, OK 73118

22. Elgood Mayo Corp.,
1817- U.S. Colonial Village Ln,
Lancaster, PA 17601

23. Economy Forms Corp.,
P.O. Box D, East 14 th St., Station.,
Des Moines, IA 50316

24. Dee Concrete Associates Co.,
P.O. Box 10086, Chicago, IL 60610

25. Dayton Superior Corp.,
721 Richmond St.,
Miamisburg, OH 45342

26. Custom Form Associates,
P.O. Box 316 Neodesha, KS 66757

27. Crescent Paper Tube Co., Inc.,
Florence, KY 41042

28. Clevepak Corporation,
925 West Chester Ave.,
White Plains, NY 10604

29. Burke Co.,
2655 Campus Dr., P.O. Box 5818,
San Mateo, CA 94402

30. Bird & Son Inc., Tube & Core Div.,
91 Glenn St., Lawrence, MA 01843
31. Baker- Roos Division, Baker & Company  
   Hugh J., P.O. Box 892 CM, 
   Indianapolis, IN 46206

32. BMF Metal Forms, Jaquith Industries, Inc., 
   E. Brighton Ave., P.O. Box 780, Syracuse, NY 13205

33. Alpha-One Mfg., Co., Ltd. 
   P.O. Box 3009, 
   Farmingdale, NY 11735

34. Allenform Inc., 
   1130 West Fullerton, 
   Addison, IL 60101

35. Aetna Plywood & Veneer Co., 
   1731 Elston Ave., 
   Chicago IL 60622

36. Aero Tech Laboratories Inc., (ATL), 
   Spear Rd. Industrial Park, 
   Ramsey, NJ 07446

37. Able Mfg Co., 
   21000 N. Washington Highway, 
   Glen Allen, VA 23060
### APPENDIX A.3 The Experimental Design Matrix of Experts that were Directly Interviewed

| Level in Firm | Location | Washington D.C.  
"Restricted Height Area" | DENVER, CO  
"Moderate Height Area" | Pittsburgh  
"Moderate Height Area" | Proposed Time for Interview |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of Firm</strong></td>
<td>OMNI Construction General Contractor</td>
<td>Cagley &amp; Associates Design/Consultant</td>
<td>PATENT SCAFFOLDING CO.</td>
<td>CECO Industrial Formwork Subcontractor</td>
<td></td>
</tr>
<tr>
<td><strong>Level 1 Name</strong></td>
<td>R. Caudery Senior Vice Pres.</td>
<td>J. Cagley President</td>
<td>ROGER S. JOHNSON</td>
<td>W.R. Anthony Mkt. Director</td>
<td>1 hour</td>
</tr>
<tr>
<td><strong>Level 2 Name</strong></td>
<td>D. Ladd Form Designer</td>
<td>J. Sullivan Structural Engineer</td>
<td>TONY GALLIS</td>
<td>W.T. Scott Form Designer</td>
<td>2 hours</td>
</tr>
<tr>
<td><strong>Level 3 Name</strong></td>
<td>K. Dugan Project Manager</td>
<td></td>
<td></td>
<td>Unknown at this point</td>
<td>3 hours</td>
</tr>
</tbody>
</table>
APPENDIX B

1. BUILDING REQUIREMENTS

1.1. Contract Documents

- Loads: Loads for which the structure is designed, which include, dead loads, live loads, and allowance for partitions, mechanical condition or special conditions.
- Tolerance: Tolerance for plumb, level, thickness and location - as applied to structural members and the structure as a whole.
- Camber: Amount of camber, where required for slab soffits and other structural members.
- Time- Amount of time available to perform the project.
- Quantity take-off.

1.2. Engineering Drawings

1.2.1. Architectural Drawings

- Components, dimension, shape, and basic geometry.
- Architectural concrete, location and details.
- Surface quality, limits of acceptability.
- Chambers, where required or prohibited on beam soffits, column corners.
- Control Joints, expansion and contraction joints location and details.
- Inserts, waterstops, built in frame for openings.
1.2.2. Reinforcement Drawings

- Amount, diameter, and grade of reinforcement.
- Construction Joints:
  * Vertical construction joints where two sections of long wall meet.
  * Horizontal construction joints when high walls are placed into two or more lifts
- Openings, reinforcement details and dimensions.

2. RESOURCES

2.1. Labor

- Labor availability
- Union versus non-union
- Area construction practice
- Labor productivity

2.2. Materials

- Materials for forms
  - Timber - lumber - plywood
  - Metal - steel - aluminum
  - Glass-fiber-reinforced plastic
- Plastic (form liners)
- Rubber (rubber liners)
- Materials for accessories
- Ties (steel rods versus wires)
- Plastic, PVC, asbestos at the end of wall ties

2.3. Time
- Contract time
- Milestones (partial operation)
- Proposed construction speed

2.4. Cost
- Labor wages
- Equipment rental
- Material local prices

2.5. Equipments
- Lifting (cranes)
  - Availability of cranes.
  - Carrying capacity at different radii.
  - Maximum and minimum working radii.
- Batching
  - Directly into skip (hooper)
  - Central batching plant
- Mixer
  - Wheel mounted unit
  - Trailer mounted unit
  - Stationary unit
  - Truck mounted concrete mixer
- Transporting and handling
  - Wheel barrows
- Buggies
- Powered buggies
- Chutes
- Conveyers
- Pump
- Buckets
- Trucks

2.6. Site Conditions
- Site description
- Vegetation, trees, terrain, depth of topsoil, existing structures, groundwater table, access and existing utilities.
- Utilities Serving Site
- Electricity, gas, water, sanitary sewer, railroad siding, and highway.
- Climatological Data
- Maximum and minimum temperature, precipitation.

2.7. Supporting Organizations
- Local, State, and federal codes.
- Inspection and permits.
- Surveying and testing laboratories.

2.8. Formwork Available
- Loose pieces
- Stick forms
- Improved stick forms
- Formwork systems
  - Ganged forms
  - Giant forms
  - Slip forms
  - Self raising forms
APPENDIX C.1
UNSTRUCTURED INTERVIEWS

1. Describe the life cycle of a concrete construction building?
2. What types of building does your company build?
   * Building shape (rectangular, irregular, . . etc.)
3. What is the most important decision concerning formwork?
4. What is the kind of decision that requires the most expertise?
5. What is the company's major concern with regard to formwork?
   * Cost * Safety * Quality * Schedule (time) * Others (such as possible reuse)
6. Who selects the formwork system?
   - Vice president
   - Area manager
   - Construction manager
7. What is the typical formwork system that your organization uses?
8. Why is this system used?
9. What is the influence of each of the following items on the selected system?
   - Site characteristics.
   - Building shape
   - Crane service.

Note: These questions are tentative; the unstructured interviews depended largely on the ability of the knowledge engineer to expand the interview in the right direction.
APPENDIX C.2

- QUESTIONS FOR FORM DESIGNER/SELECTOR

- What are the criteria (factors) that control the selection of the formwork system?
- Do you usually ask for a change order from either the owner or the architectural engineer in order to use forms that you own?
- What type of formwork systems does your company usually use for column, wall, slabs, foundations, and beams?
- What is the preferable formwork material in each case? Why?
- Do you usually rent, purchase, manufacture (custom-make) your own formwork?
- Does the company have its own fabrication yard?
- What items, if any, need to be manufactured on site?
- What area do you feel needs more research in formwork?
- What is the cost percentage of formwork with respect to the cost of the reinforced concrete building frame? What are the other component materials - (e.g. concrete, labor, rebar)?
- If available, can you give me a percentage breakdown for the cost of labor, material, equipment, and transport for formwork?
- What do you see as the key areas of cost reduction?
  * Maximum reuse
  * Economical form construction
  * Efficient setting and stripping
  * Other
- What is the most dangerous formwork system? Why?
- How does the owner pay for the cost of formwork?
  a) Separate items
  b) Included in the unit price paid for the reinforced concrete?
- By whom is the formwork usually designed?
- By whom and for what features is formwork inspected?
- What approvals will be required for formwork drawings?

**QUESTIONS FOR DESIGN FIRM**

- Describe the life cycle of formwork.
- What are the major codes that govern your design?
  * ACI 318-86
  * ACI 347-78
  * Others
- Is there any local code that you have to follow?
- What is the role of the A/E firm?
- What are the major factors that influence formwork design, other than the load? (i.e. crane size . . etc.)
- Are there any special tables or charts you use?
- Are you using special computer programs for your design?
  If yes,
- What do the programs do?
  * Are you using commercially available software?
  * What is the computer system platform (main-frame; PCs)?
  * What is the input/output of such a system?
- What are the most common formwork systems you design?
- What methods are you using in your design?
Traditional (sheathing-joist-stringers, and bracing)?

* Special method (please specify)

- What are the loads you consider in your design?
- Specifically, what are the horizontal loads you consider when you design the formwork?
- What checks do you usually make when you design a formwork element?
- From your experience, what are the major causes of failure in formwork? Are they design-related?
- Describe any coordination between you and the A/E firm?
- Who reviews your design and approves it?
- Is the designer involved in the decision concerning the selection of the formwork system?
- How often do you ask for building design change by the A/E firm in order to achieve more economical design?
- Do you usually check/inspect your own formwork design?
- What are the factors that affect the selection of formwork accessories?
- What items of formwork accessories should be designed?
- Are you involved in the decision of stripping the formwork?
- What are the major factors that should be considered when stripping the formwork?
- What are the design criteria for the bracing, if any?
- In designing the formwork, which element heavily rely on experience?
- What do you feel is the most needed area for research in formwork?
QUESTIONS FOR SITE VISIT

- Describe the life cycle of formwork on site.
- Describe the floor cycle.
- How does it change as you go up from the foundations?
- What formwork design do you get from the office?
- How do you implement this? What changes do you make?
- Who orders the formwork?
- How long does the first floor normally take?
- How are columns formed?
- Describe the systems you use vs. safety, cost, etc.
- How are slabs formed?
- How are walls formed?
- How are beams formed?
- How are any other components formed?
- How do you coordinate with rebar, concrete placement?
- What type of data do you collect?
APPENDIX C.3

LIST OF INTERVIEWEES

NAME : DANIEL LADD
ADDRESS : 7500 Old GeorgeTown Road, Bethesda, MD 20814
TELEPHONE : (301) 657-7428
POSITION : Chief Engineer, Concrete Division
DATE : 6-10-1988, 1-12-1988 & Telephone Interviews & Correspondence
DURATION : Two hours each

NAME : ROGER S. JOHNSON
ADDRESS : 7500 Dahlia Street, P. O. BOX 2411, Denver, CO. 80201
TELEPHONE : (303) 288-2722
POSITION : Field Product Manager, Forming Products
DATE : 1-12-1989
DURATION : Two hours each

NAME : TONY GALLIS
ADDRESS : 7500 Dahlia Street, P. O. BOX 2411, Denver, CO. 80201
TELEPHONE : (201) 461-8700
DATE : 2-18-1989 & Telephone Interviews
DURATION : Two hours

NAME : JAMES R. CAGLEY
COMPANY : Cagley & Associates
ADDRESS : 6141 Executive Boulevard Rockville, Maryland 20852
TELEPHONE : (301) 881-9050
POSITION : Structural Engineer
DATE : 6-10-1988
DURATION : Two Hours
NAME: JOSEPH PUSTIS
ADDRESS: 4824 Rugby Avenue, Bethesda, Maryland 20814
TELEPHONE: (301) 657-8000
POSITION: Project Estimator
DATE: 6-10-1988 & 1-12-1989
DURATION: Two hours each

NAME: KARL HEINZ JOSCHKO
COMPANY: PERI FORMWORK SYSTEM, INC.
ADDRESS: 3101 Washington Blvd. Baltimore, MD 21230
TELEPHONE: (301) 646-5010
POSITION: Product Manager
DATE: 2-19-1989
DURATION: Two hours

NAME: JAQUE S. SCHWARZ
COMPANY: Arrding Forms, Inc.,
ADDRESS: 8034 Deering Avenue, Canoga Park, California 91304
TELEPHONE: (818) 883-4990
POSITION: Managing Director, Senior Vice-President
DATE: 1-4-1989
DURATION: 20 minutes

NAME: WALTER J. TUCKER
COMPANY: J.A. Jones Construction Co.
ADDRESS: 311 South Wacker Drive, Chicago, Illinois 60606
TELEPHONE: (312) 939-4152
POSITION: Field Manager
DATE: 12-8-1988
DURATION: One hour
NAME : MIKE CARLSON
COMPANY : Western Forms International, Inc.
ADDRESS : 6200 Equitable Rd. Kansas City, Missouri 64120
TELEPHONE : (816) 241-0478 Or 1- 800-821-3870
DATE : 12-7-1988
DURATION : Half an hour

NAME : MARY K. HURD
COMPANY : Concrete Construction Publications, Inc.,
ADDRESS : 33742 Lyncroft Road. Farmington hills, MI 48331
TELEPHONE : (313) 473- 1322
POSTION : Engineering Editor
DATE : 12-6-1988
DURATION : One hour

NAME : JUAN M. COVARRUBIAS
COMPANY : The George Hyman Construction Co.,
ADDRESS : 7500 Old Georgetown Road. Bethesda, Maryland 20814-6196
TELEPHONE : (301) 986-8191
DATE : 1-12-1989 & 1-22-1989
DURATION : Two hours each

NAME : BILL FULTON
COMPANY : Symons Corp.
ADDRESS : 1155 Church Hills Dr., New Braunfels, TX, 78130
POSTION : Field Manager
DATE : 12-7-1988
DURATION : Half an hour
<table>
<thead>
<tr>
<th>NAME</th>
<th>LAURENCE E. SVAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPANY</td>
<td>Ceco Corp.</td>
</tr>
<tr>
<td>ADDRESS</td>
<td>One Tower lane, Oakbrook Terrace IL, 60181</td>
</tr>
<tr>
<td>DATE</td>
<td>12-8-1988 &amp; Telephone Interviews</td>
</tr>
<tr>
<td>DURATION</td>
<td>One Hour</td>
</tr>
</tbody>
</table>
APPENDIX C.4
EXAMPLE - SPECIFIC INTERVIEW SESSION

1. General

The knowledge engineer starts the interview by explaining the objectives and the scope of the interview. The limitations of the interviews are as follows.

1. This interview considers only buildings made of reinforced concrete.
2. Any type of building shape should be considered in your response (i.e. straight lines, broken lines, and curved).
3. Special structures such as Domes, Folded Plates, Shells, etc., should be excluded from your responses.
4. If there are portions of this interview that require knowledge outside your area of expertise, please give me the name and telephone number of the person who you believe to be an expert in those areas.

2. Sample Interview With an Expert

KE: Literature review reveals five types of lateral supporting systems for buildings. These are: (1) Rigid Frames; (2) Shear Walls; (3) Framed Shear Walls; (4) Framed Tubes; and (5) Tube-in-Tube. Which of these systems is most suitable for jump form?
E. Any vertical supporting system between five and 20 stories is suitable for jump forms. Because the tube systems are used for buildings higher than 30 stories, jump forms are suitable for any shape of shear wall.

KE. Can't be used for any shape of shear walls (i.e. straight lines, broken lines, and curved lines)?

E. Jump forms can be assembled to pour concrete walls of any plan, shape, or size. It also can be easily adjusted during construction to accommodate changes in wall thickness.

KE. What are the dimension limitations of this system?

E. Jump forms cover a wide range of lift heights from 8 ft. to 16 ft. and from 8 ft. to 44 ft. wide.

KE. Buildings typically have high floor heights in the first few floors. Do you think the system can be used in floors higher than 16 ft.?

E. Yes, you can achieve this on several lifts.

KE. What type of slab system is most appropriate for the jump form?
E. Any type of reasonably uniform slab and beam system could be used. With the addition of block outs or removable form panels, provision can be made for concrete beams of any depth to be connected.

KE. What are the typical construction sequences associated with jump forms?

E. The system works best when the walls are poured ahead of the floor. However, the system allows the floor and the engaged core walls to be poured in one operation. The system also allows a core and slab to be broken into convenient pours to provide work continuity for the trades involved, and to spread the crane operations over the floor cycle time.

KE. If the job specifications require architectural concrete for walls, can we use the jump form in this situation?

E. Yes, the system can be used to produce architectural concrete. This can be achieved by attaching form liners to produce a wide range of architectural finishes or texture. However, without using form liners, the system produces high quality concrete (i.e., exposed concrete).

KE. With regard to the speed of construction, what is the typical cycle time which the system can achieve?
E. This is different from site to site, but on average 2 to 3 days per floor is a typical cycle.

KE. If high rate of placing is required, can the system sustain high rate of placing?

E. The system should be designed for high rate of placing. Ties spacing and cross section should be designed by following the same principals of the conventional wall systems.
APPENDIX D
SAMPLE SCREEN OF TUTORIAL RUN

EXSYS
PROFESSIONAL

RUNTIME

(C) COPYRIGHT 1983, 84, 85 EXSYS, Inc.,
Ver. 1.1.1

Press any key to start

Screen 1
Do you wish instruction on running the program?  (Y/N)

Screen 2
Do you wish to have the rules displayed as they are used? (Y/N) (Default=N)
Selection of formwork system for reinforced concrete buildings

by: Awad S. Hanna

Press any key to start:

Screen 4
SLABFORM is a rule-based expert system, designed to assist the designer/planner in selecting the optimum formwork system. The system selects a horizontal forming system, the supporting shoring and reshoring systems, and provides advice on a variety of issues. The system requires the user to answer questions in a multiple choice format. The questions cover a variety of items including: building shape, specifications, construction loads, site characteristics, and available resources. To gain the largest benefit, run SLABFORM before you prepare the project estimate. The system could be used for the whole building or for the part of the building which has repetitive features. When the analysis is complete, SLABFORM will provide a list of formwork systems with numerical ratings reflecting suitability of the system. The system also provides the user with guidelines for the proper shoring and reshoring system.

Press any key to start

Screen 5
Slab type for the whole building or the part under investigation is

1. flat plate
2. flat slab with or without drop panel
3. one-way slab supported by beams
4. one-way slab, beam, girder
5. two-way slab supported by beams
6. one-way joist slab
7. waffle slab

Enter the number(s) of the value(s) WHY to display rule being used
QUIT to save data <H> for Help

Screen 6
Beams are:
1. of the same size and location on each floor
2. within a 20% difference in size and/or location on each floor
3. of various sizes and locations on each floor
4. nonexistent "embedded or flat plate"

Enter the number(s) of the value(s) WHY to display rule being used
QUIT to save data <H> for Help

Screen 7
Cantilevers and overhands are

1. of the same size and location on each floor
2. varied in shape and dimension on each floor
3. nonexistent

Enter the number(s) of the value(s) WHY to display rule being used
QUIT to save data <H> for Help

Screen 8
Columns are

1. of the same size and location on each floor
2. within a 20% difference in size and/or location on each floor
3. of various sizes and locations on each floor
4. nonexistent "slab supported by walls"

Enter the number(s) of the value(s) WHY to display rule being used
QUIT to save data  <H> for Help

Screen 9
Walls are:
1. of the same size and location on each floor
2. within a 20% difference in size and/or location on each floor
3. of various sizes and locations on each floor
4. nonexistent "slab supported by walls"

Enter the number(s) of the value(s) WHY to display rule being used
QUIT to save data <H> for Help

Screen 10
Total building size is

1  small - "less than 100,000 sq.ft"
2  medium - "between 100,000 and 200,000 sq ft."
3  large - "more than 200,000 sq. ft."

Enter the number(s) of the value(s)  WHY to display rule being used
QUIT to save data  <H> for Help

Screen 11
Local Labor forces are

1. skilled, low hourly rate
2. skilled, high hourly rate
3. unskilled, low hourly rate
4. unskilled, high hourly rate

Enter the number(s) of the value(s) WHY to display rule being used
QUIT to save data  <H> for Help

Screen 12
Available engineering supervision is

1. minimum
2. moderate
3. adequate

Enter the number(s) of the value(s) WHY to display rule being used
QUIT to save data <H> for Help

Screen 13
Number of potential reuse of formwork is

1. less than 12
2. between 12 and 15
3. between 15 and 20
4. between 20 and 30
5. more than 150

Screen 14
Story height is

1. less than 10 ft.
2. between 10 and 16 ft.
3. higher than 16 ft.

1, 2

Enter the number(s) of the value(s) WHY to display rule being used
QUIT to save data <H> for Help

Screen 15
HVAC requirements are
1 minimal
2 extensive

Enter the number(s) of the value(s) WHY to display rule being used
QUIT to save data  <H> for Help

Screen 16
Ratio of live loads to dead loads is

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>0.75</td>
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<tr>
<td>3</td>
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<tr>
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<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>1.75</td>
</tr>
<tr>
<td>7</td>
<td>2.0</td>
</tr>
<tr>
<td>8</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Enter the number(s) of the value(s) WHY to display rule being used
QUIT to save data <H> for Help
Type of cement used is

1 Type I cement
2 Type III cement

Enter the number(s) of the value(s) WHY to display rule being used
QUIT to save data  <H> for Help

Screen 18
Values based on 0 - 10 system

<table>
<thead>
<tr>
<th></th>
<th>Conventional wood system</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Conventional metal system</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>The total number of levels below floor being cast is THREE levels of reshores plus one level of form</td>
<td></td>
</tr>
</tbody>
</table>

All choices <A> only if value >1  <G> Print <P> Change and rerun <c>
Rules used <line #> Quit/Save <Q> Help <H> Done <D>:

Screen 19
VITA

Awad Soliman Hanna was born on April 5, 1952, in Cairo, Egypt. He received a Bachelor of Science Degree in Civil Engineering from the Faculty of Engineering at Cairo University. In January 1986, he earned a Master's Degree in Civil Engineering at The Pennsylvania State University.

From 1986 to 1989, Mr. Hanna was a Ph.D. candidate in the Department of Civil Engineering at The Pennsylvania State University.

Mr. Hanna has been a lecturer at The Faculty of Engineering, Shoubra, Zagazig University, Banha Branch. His research interests are in the areas of Expert Systems, Concrete Construction, Construction Engineering and Management, and Statistical Quality Control.
Abstract
Title of Thesis: An Interactive Knowledge Based Formwork Selection System For Buildings
Author's Name: Awad Soliman Hanna
Ph.D.; August 1989
The Pennsylvania State University
Victor Sanvido, Thesis Adviser

The selection/design of a formwork system for a project is influenced by the building design, site constraints, the contractor's experience with different systems, and their availability. Typically the selection of a formwork system is made by a senior member of the contractor's organization. The decision is heavily based on that individual's experience. This experience may limit the selection of a system to one that is not the optimum. This thesis presents a tool to assist the formwork selector/designer in making that decision. This tool was developed by systematically capturing the expertise of people involved in all phases of the life of the formwork, from design through erection and concrete placement to its removal. The end result of this research is (1) a conceptual model which models the decision-making process of the expert; (2) a formwork selection knowledge base; (3) a rule-based computer tool that can help the designer in selecting the optimum formwork system; (4) a parametric guideline for formwork selection.