THE CONCEPT AND FEASIBILITY OF AUTOMATED ELECTRICAL PLAT DESIGN VIA AN INTELLIGENT DECISION SUPPORT SYSTEM APPROACH

by

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Abstract

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The design of underground electrical supply for residential development is presently carried out manually, resulting often in an overdesigned, costly, and nonstandardized solution. Up to now no comprehensive computerized tool exists that encompasses design of the secondary, primary, and street lighting systems which are components of the overall residential electrical supply. As an ill-structured and open-ended problem, this design is hard to automate with conventional methods such as operational research or CAD. An additional complexity in automating electrical plat design is imposed by the need to process spatial data such as circuit maps and construction plans. After a comprehensive knowledge acquisition, the author has proposed an Artificial Intelligence (AI) methodology, namely Intelligent Decision Support Systems (IDSS) to automate electrical plat design (AEPD). To accommodate diverse software environments, data models, and problem solving paradigms, the author has proposed a conceptually new problem solving architecture. This architecture, called the Blackboard Based IDSS, consists of different knowledge sources, including the human designer, concentrated around a global database. The knowledge sources are implemented in a Geographic Information System (GIS), procedural programs, and an expert system shell. In a such hybrid environment, the GIS principal task is to structure and formalize a "real world" representation required by other AEPD knowledge sources. To evaluate the feasibility of the proposed concept, the author has developed an AEPD prototype that functionally covers the secondary part of the electrical plat design. The results obtained by testing the AEPD prototype on an actual plat, and comparison with the results of the manual design, prove the feasibility of the proposed AEPD concept. An additional outcome of this dissertation is the successful demonstration of the application of novel technologies: GIS, and AI. These are used for structuring the required data and for capturing the designer problem solving technique, respectively. The synergy of these two agents, one "being able to see" and another "being able to think" provides the distribution system designers with a viable tool to support their decision making.

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Last but not least, the author would like to convey his gratitude to his wife and colleague Helena for her moral and professional support. Without that this work could not be possible. In fact she and Mr. Luis Gaggero, both Puget Power Graduate Fellows, did all the coding in GIS.

Dedicated to my parents and my children

Chapter 1

INTRODUCTION

1.1 Automated Electrical Plat Design

Webster's dictionary defines plat as: "a plan, map or chart of a piece of land with actual or proposed features, usually a piece of land divided into building lots." Within the context of this dissertation, the **plat** represents physical layouts of the residential area to be developed including dimensions, layout of streets, layout of utility lines and other pertinent information. In modern electric utilities, the pertinent information is electronically stored using Automated Mapping and Facilities Management (AM/FM) in the form of a Geographic Information System (GIS) that forms a part of the corporate database .

The design of the underground electric distribution supply system for the new residential development is an everyday task for electric utility engineers. Such a design is presently carried out manually with varying cost estimates, thus making the design options unreliable and undependable. The development of a tool for the computerized (automated) design of the residential underground electric supply system, called Automated Electrical Plat Design (AEPD), is highly desired by the electric utility companies. The AEPD tool, based on the plat information stored in the GIS database, will ultimately make the distribution design not only standardized and economical, but will also speed up and streamline the design process. Furthermore, additional benefits such as material management, inventory control, preventive maintenance and system performance can be accomplished systematically and cost-effectively [1].

1.2 Present Day Practice in Automated Distribution Design

Since the early days of computers, there have been attempts to computerize some activities in the process of distribution system design. Some progress has been accomplished in automating routine tasks such as substation wiring diagrams [2]. Furthermore, computerized methods are established for well-defined engineering problems like fault analysis, power flow calculations, voltage drop and flicker determination, which are used for proper sizing of the distribution facilities and devices.

There is yet another class of problems in distribution systems design that is not easy to define, formulate, or structure in order to solve by conventional computerized methods. These complex problems are characterized by the absence of one or both of the following features:

1) predetermined decision path from the initial state to the goal, constituting an ill-structured problem.
2) well-defined criteria for whether an obtained solution is acceptable or not, leading to an open-ended problem.

For these problems conventional overall computerized tools still do not exist, although some segments of the distribution system facilities design problem can be solved with conventional methods. Recent developments in Artificial Intelligence (AI), particularly in knowledge engineering, can be used to broaden the scope of the distribution facilities design problems that can be solved by computerized methods.

The design of the distribution system facilities relies on heuristic strategies and rules of thumb based on the extensive experience gained from previous problems. In the classical "manual" approach, a distribution system is usually overdesigned by a factor of two (or more) for reliability and security reasons. This approach, though intrinsically robust, is basically insensitive to inaccuracy and inconsistency of data, and problem ill-structuredness. This approach is now considered by many as a waste of capacity that can be used in lieu of investing in system expansion. The availability of computerized tools allows the system to be designed more economically and to operate much closer to its limits. Automated distribution design can contribute significantly to the design of efficient, low-cost power systems [3].

The design process can be viewed as a search through the problem space of alternative designs defined by imposed constraints. The number of possible design solutions that satisfy a given set of spatial, technical, and economical constraints, which define "the search space" [4,5,6,7], is quite large for the average plat size. Multiple goals, as well as interdependence and fuzziness of the goals and constraints, make the design problem hard to formulate. Furthermore, some control variables, such as "customer satisfaction," although important, cannot be quantified and included simply into the model. To apply conventional optimization routines from Operational Research (OR) theory [8-16], a well-defined objective function has to be derived. Due to the ill-structured and open-ended nature of the problem, it is not possible to derive an objective function without sacrificing salient decision factors. All these facts make conventional procedural optimization methods inappropriate. However, optimization routines can still be used to solve some segments within the design process. The lack of an optimizing algorithm for the overall design indicates that the Artificial Intelligence

(AI) approach might be worthwhile to explore. Although in such cases AI techniques do not guarantee an optimal solution, a "satisficing" (a word coined by H. Simon [17]) solution can always be obtained.

1.3 Data Issues in Automated Electrical Plat Design

The problem encountered in computerized planning and design methods is that data required

- may not be available,
- may be excessively expensive to gather,
- may be of suspect accuracy, or
- may be hard to model.

In order to come up with an "optimal" automated design, an accurate and reliable database must be available. Load data, which are of particular importance for the design, are notably hard to gather. The estimation of load data involves much uncertainty and usually comes up with several possible alternatives. Conventional expert system techniques, based on the production rules paradigm, are not ideally suited to handle the uncertainties and open-ended problems associated with multiple alternatives. Therefore, the problem solving methodology for this class of problems must allow the user to easily change and explore the outcome of various alternatives.

In the residential underground distribution system design, an additional requirement is imposed by the specific type of data used. Geographically referenced data which represent circuit maps and records, construction maps and other spatial information, need to be automatically stored and retrieved for planning purposes. Modern electric utilities are already using Automated Mapping and Facilities

Management (AM/FM) system within a Geographic Information System (GIS) as a part of the corporate database. Significant amounts of information are stored in the form of a GIS type database [18]. This type of database is very efficient in representing circuit maps and records, construction maps, and other types of spatial information. In addition to providing data consistency and increasing productivity, a GIS based AM/FM system enables automated modeling for a host of engineering applications used in distribution system planning and design. The geographic information system forms a repository from which relevant information is drawn for design purposes. For that reason, the computerized tool aimed at automating electrical plat design (AEPD) must have provisions for operation within the GIS environment.

1.4 Dissertation Objectives

Distribution system planning as a whole, and particularly design of the secondary distribution system facilities, is one of the power engineering domains that did not benefit as much from recent developments in computer technology and computational techniques as other domains in power systems. The two primary reasons are an absence of an appropriate technology to automate geographically referenced data required in distribution planning, and the absence of an appropriate computational technique to accommodate such a complex problem.

The major goal of this dissertation is to define a concept of an automated electrical plat design and to prove its feasibility.

To reach this goal the following objectives are set:

- to acquire knowledge on the manual electrical plat design process and structure it
- to identify appropriate planning and designing techniques needed for this problem
- to develop the required problem solving architecture for the automated electric plat design
- to develop an AEPD prototype that covers a secondary system design
- to identify potential benefits which can accrue from automating this everyday task for electric utility engineers

The additional goal of this dissertation is to demonstrate how new technologies, namely Geographic Information System (GIS) and Artificial Intelligence (AI), used for structuring required data and capturing the designer's problem solving technique, can help automating the process of distribution system design. The synergy of these two agents, one "being able to see" and another "being able to think," can provide designers with a viable tool to support their decision making process in the area of electrical plat design.

The concepts and ideas established in this dissertation are generic and can be applied to a host of ill-structured, open-ended problems that require spatial reasoning. It is the author's wish to propose a new standard for automating these problems. Many such problems exist in the distribution system planning and design areas, among which the Automated Electrical Plat Design is the first that will benefit from applying the concepts and ideas developed in this dissertation.

1.5 Dissertation Organization

The dissertation is organized into ten chapters.

Chapter 2 contains a description and findings of the knowledge acquisition procedure of the electrical plat design problem. In addition to presenting acquired facts and rules, special emphasis is given to knowledge structuring and identifying the designers' approach to problem solving.

In Chapter 3, a review of existing methodologies employed in the distribution planning and design area is given. The comparison of the conventional approaches, namely Operational Research and Computer Aided Engineering versus Artificial Intelligence approach is presented. Upon completion of the review, the need for a new hybrid approach capable of accommodating the complex AEPD problem solving procedure is identified.

Chapter 4 gives an overview of the GIS as a software environment in which resides a major portion of the AEPD. A GIS is used to accommodate geographic data modeling and to enable the spatial processing required for AEPD.

Chapter 5 is devoted to the design of the new hybrid problem solving architecture called Blackboard Based Intelligent Decision Support System (IDSS), developed to automate the electrical plat design. The proposed tool is designed to support rather than merely automate the design process through the prescribed computational approach. The structure of the proposed tool and the role of each knowledge source used in the design process including the human partner is presented. At the end of this chapter the structure of the AEPD prototype developed to prove the feasibility of the proposed problem solving architecture is outlined.

Chapter 6 deals with the Plat Preprocessor. To identify attributes that are required for automating electrical plat design, the LISP based Secondary Runs Designer knowledge source prototype is initially developed (Appendix C). Based on that development, required GIS coverages are identified in this chapter. Batch processing needed to automatically extract basic spatial relationship, and the processing required to create new objects, are also given. Chapter 6 concludes with a feature attribute tables created by the Plat Preprocessor that are posted to the blackboard.

In Chapter 7 description of the Transformer Placer knowledge source implemented in the GIS environment is given. The procedure of lots clustering and transformer and handhole placement is described, and cluster data structuring is outlined.

Chapter 8 discusses the rule based Secondary Runs Designer knowledge source. In the AEPD prototype this Knowledge Source is implemented in an expert system shell. The "object oriented real world structuring," required for AI processing is presented. The inference control mechanism of the expert system shell and database-expert system bridge are also addressed.

Chapter 9 presents the results of the AEPD prototype feasibility evaluation. The results of the GIS preprocessing required to extract basic spatial attributes among the objects, and to create new objects are given. In addition, the results of Transformer Placer Knowledge Source implemented in GIS environment are presented as well. The result of the expert system secondary routing on the "plat described by the GIS," is shown. Chapter 9 concludes with comparison of the secondary systems obtained manually vis-a-vis three different automated designs. The results of computational time requirements and capital costs for all of them are presented for the economic evaluation of the AEPD concept .

Finally Chapter 10 contains summary, conclusions and directions for future research. Since this is a pioneering effort, this dissertation necessarily identifies some questions and topics to be addressed in the future.

The Glossary, List of References and three Appendices provide supporting material for the dissertation.

Chapter 2

KNOWLEDGE ACQUISITION FOR THE AUTOMATED ELECTRICAL PLAT DESIGN

2.1 Knowledge Acquisition Process

In order to gain more insight into the design process of the residential underground distribution electric supply system, a comprehensive knowledge acquisition program was undertaken. The knowledge acquisition process lasted six months and included twenty-eight experts from the local utility. Eighteen of them were designers from service centers, actively involved in the process of plat design, while the remaining were engineers and managers responsible for creating corporate policy concerning plat design. Through interviewing, observing experts at their work, and recording verbal protocols, a critical amount of domain-specific knowledge was acquired. The purpose of the knowledge acquisition process was not only to capture facts and rules employed by the designers, but also to identify the designers' problem solving methodology when dealing with such a complex, open-ended, ill-structured problem.

The results of the knowledge acquisition process which collected applicable standards, electric utility company practices, codes, as well as facts, rules and problem-solving procedures are given in full detail in [19]. Most of the significant rules acquired are presented in Appendix A. In the following subsections, a select set of acquired knowledge needed for problem understanding is presented.

2.2 Design Procedure

The process of the plat design can be divided into three independent parts. These parts are:

a) Secondary design (two segments):

a1) • Transformer placement with "lots-to-transformer" assignment.

• Transformer sizing.

a2) • Defining secondary circuitry routes (including crossings and handholes).

• Secondary circuitry sizing.

b) Primary design (one segment):

b1) • Identifying source points and defining number of phases.

• Defining routes for primary circuitry

• J-box placement and looping considerations.

• Primary sizing.

c) Street lighting (one segment):

c1) • Street light placement.

• Determining light to source connection routes.

• Lamp size determination and fusing.

The structure and tasks of the complete plat design as well as the tasks and structure of each segment of the design are presented in Figures 1 to 4.

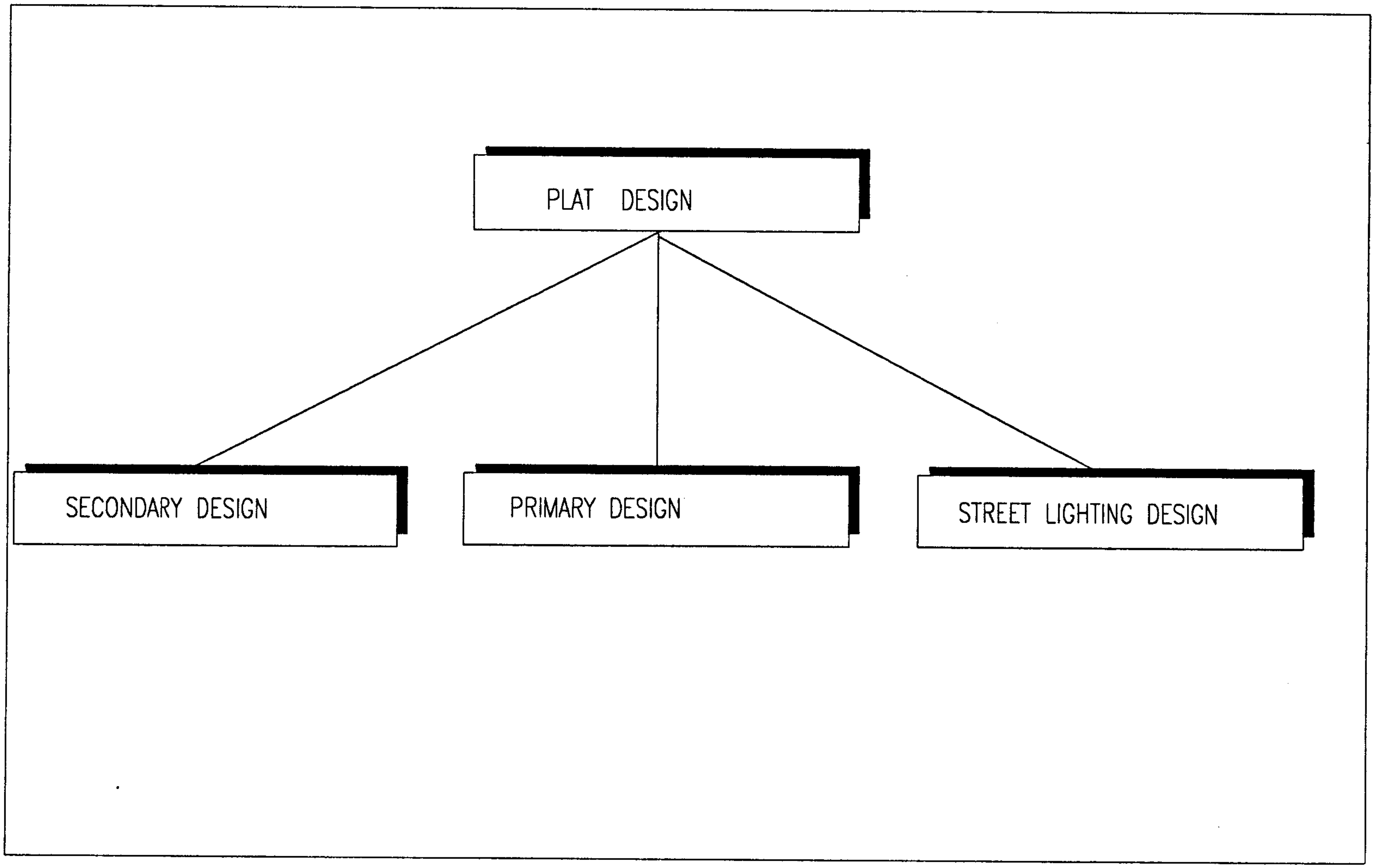

Figure 1. Plat design tasks and structure

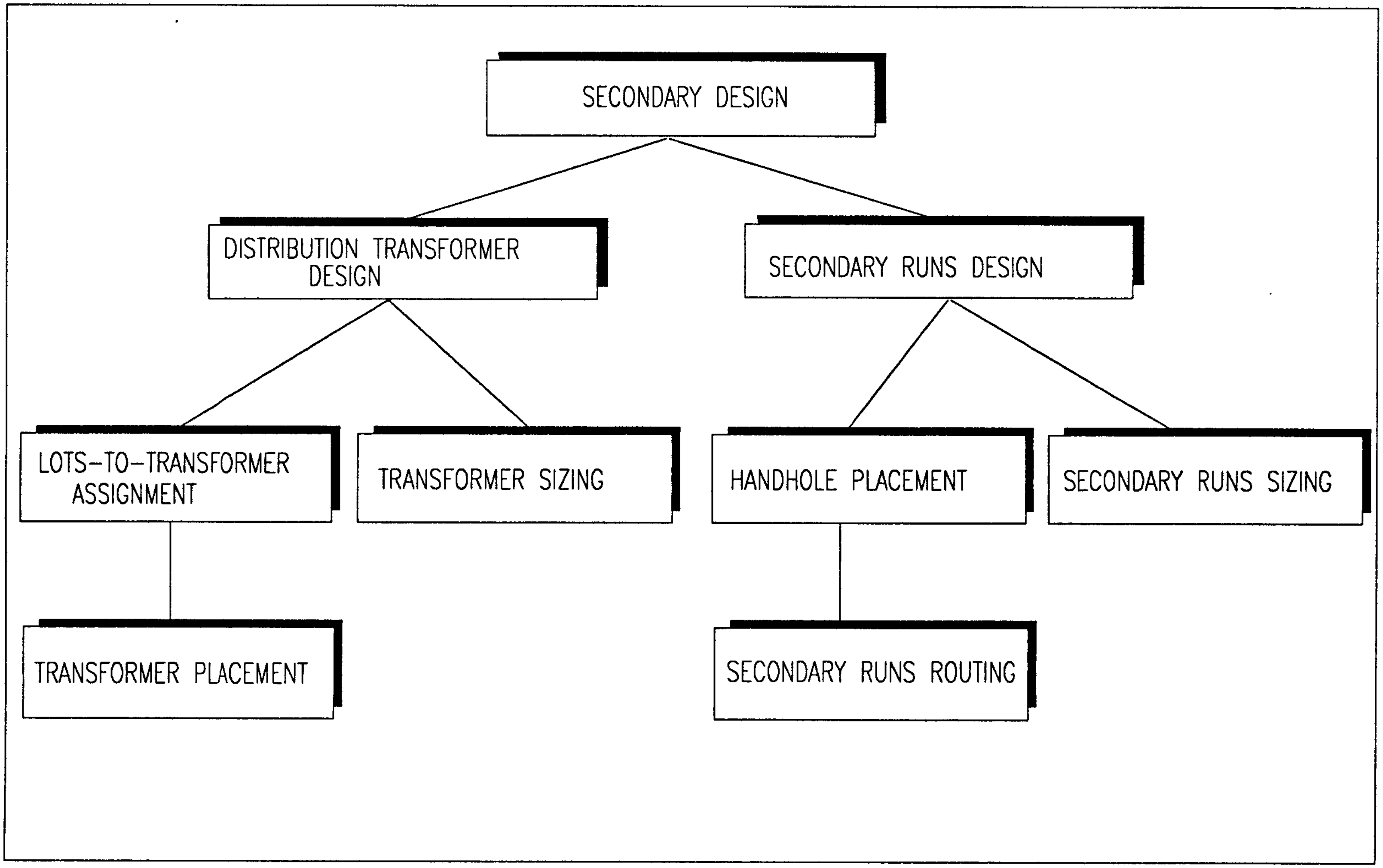

Figure 2. Tasks and structure of the secondary design

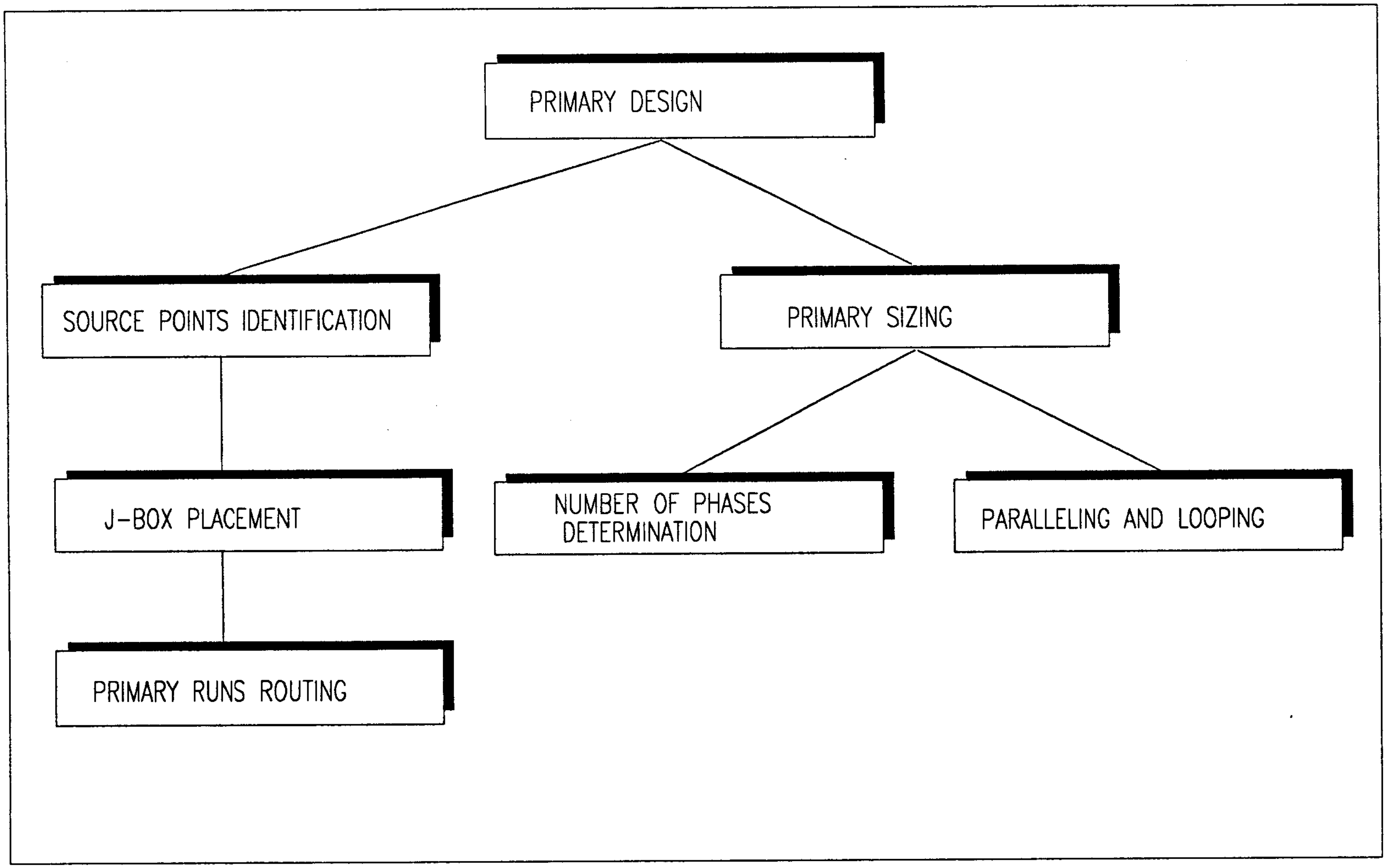

Figure 3. Tasks and structure of the primary design

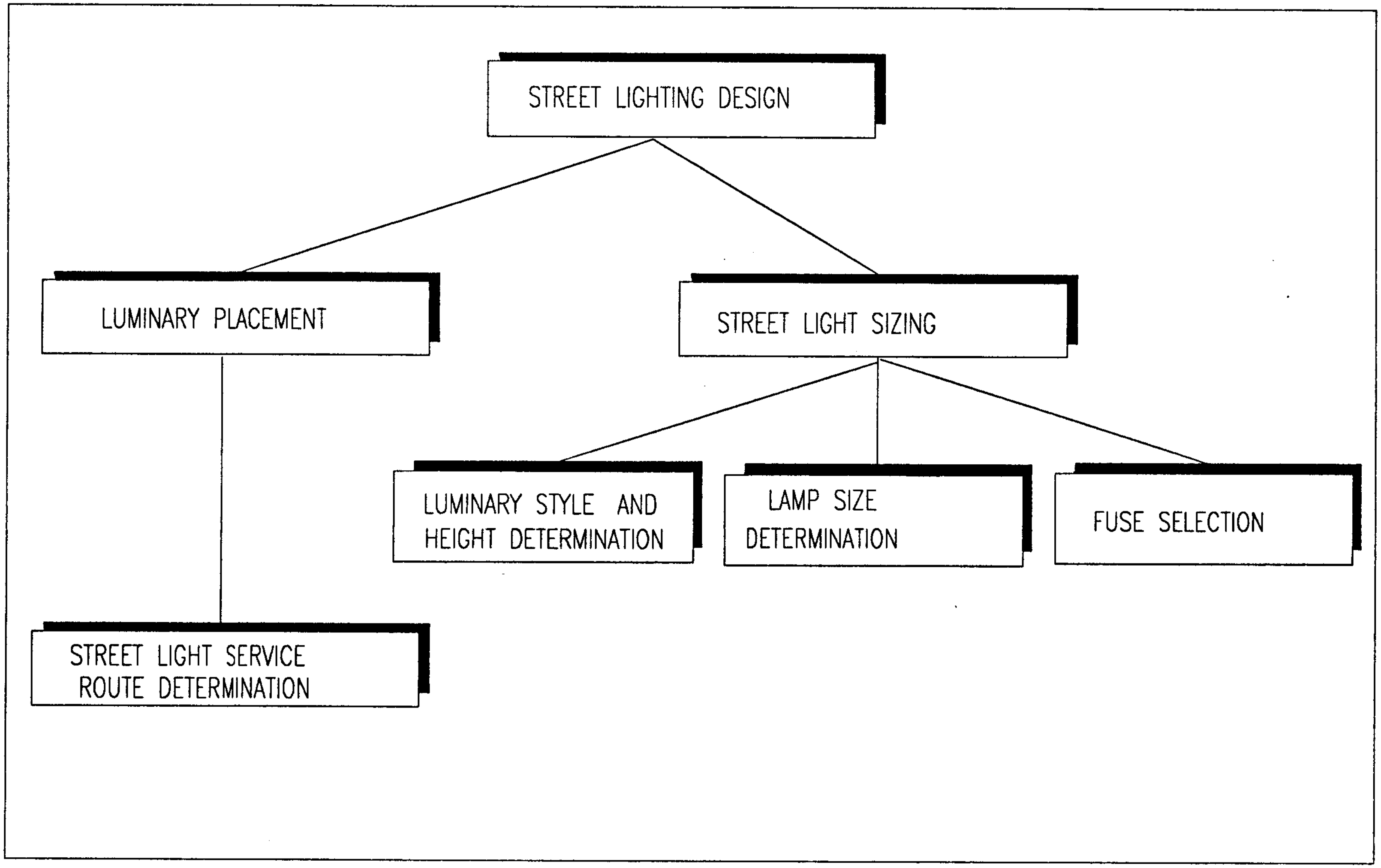

Figure 4. Tasks and structure for the street lighting design

Within each segment, the design process can be further divided into two subprocesses: one concerning conductor routing or equipment placement determination and another concerning equipment sizing.

Whether the design process is carried out automatically or not, the conductor routing and equipment placement subprocess is more creative and much harder to handle. Conductor routing is based on spatial reasoning and requires the ability to distinguish among different geometric shapes and objects. If a computerized approach is considered, a procedure similar to pattern recognition is required in order to apply an appropriate set of the rules such as: "Do not put a transformer at the end of the cul-de-sac." Equipment sizing, on the other hand, is a quite routine and almost a straightforward process after the routing and placement part of the design is complete.

2.3 Design Data

In order to come up with an automated "optimal" design, a more accurate, reliable and consistent design database has to be available than which is needed in the case of "manual" design which relies basically on engineering judgement and rules-of thumb. Using their expertise and common sense reasoning humans are capable of coming up with a "good solution" even if the available data are incomplete and unreliable. On the other hand, as a general rule, it may be stated that the more sophisticated a computerized design method is, the more accurate and comprehensive the data must be. The data required for the plat design can be divided into:

a) Equipment data

b) Plat data provided by the developer

c) Load data

a) Equipment data consist of transformer name plate data, conductor ampacity, vaults dimensions and so on. These data are available in the standard practices, requirements, rules, codes and regulations used in the process of the plat design. Some of these data, such as cost for a particular operation or equipment, can be extracted from a corporate database. This set of data is well defined, consistent and accurate, provided the corporate data base is well maintained.

b) Data provided by the developer basically consists of information concerning physical layouts and the presence of other utilities (such as gas, water, sewer etc.) in the plat, and data concerning any special service required (such as three phase load, heat pump, commercial load, etc). The second group of data provided by the developer contains information concerning anticipated load size, type of heating, lot size and other useful information. From the accuracy point of view these data are less accurate and can be incomplete, or even inconsistent.

c) Load data [20] are essential in order to come up with "optimal" design. These data cannot be directly provided by the developer and they have to be estimated by the designer based on the given information such as a lot size, availability of gas in the plat, anticipated major type of heating, panel size, anticipated home size and "the type and quality" of neighborhood. Based on the acceptable, reliable load data furnished, the system can be designed to operate much closer to its operating margins. Using these data, voltage drop calculations can be made to determine proper conductor sizes instead of using conservative rules-of-thumb.

2.4 Transformer Design

The distribution transformer design consists of:

a) transformer placement including lots-to-transformer assignment

b) transformer sizing

a) As a general rule the number of transformers utilized in the plat should be minimized which in turn means a given transformer has to serve as many lots as possible. The primary restriction on the number of lots that a transformer can serve is the tolerable voltage drop (distance), rather than the total load size. The usual number of lots that are served by one transformer is eight to twelve, the upper limit being valid for urban areas with gas service available. The transformer placement process basically consists of identifying lot clusters that can be served by each transformer. During the transformer placement process lot corners with sanitary sewer stub-outs, narrow lot frontages and the turnarounds of cul-de-sacs should be avoided.

b) Transformers typically are sized based on the actual (anticipated) type of residential heating. In the transformer placement process, the lots that have to be served with one transformer are already determined in step a). Using the number of lots determined in the lot-to-transformer assignment process and the anticipated type of load (heating), transformers are sized taking load diversity into account.

2.5 Secondary Runs Design

The design of secondary circuitry follows the transformer placement and sizing procedure. It can also be divided into two parts:

a) Secondary route determination

b) Selection of secondary conductors

a) In the process of transformer placement, it is already determined which lots have to be served from a particular transformer (transformer-to-lots assignment). Secondary as well as primary runs utilize 10-foot utility frontage easements for routing. Secondary route determination is a cost optimization process in order to minimize secondary conductor length, and more importantly the trench length. One should note that trenching is an expensive operation. In serving lots on the opposite side of the road, the number of crossings as well as the number of handholes and additional trenching have to be kept minimal, but generally reducing one will increase others. Careful economic evaluation based on the actual costs will dictate the preferable way.

b) Secondary runs typically are sized based on the assumed "total electric household" in contrast to transformers which are sized for anticipated load. The main consideration in sizing secondary runs is the allowable 3% voltage drop from the transformer to the service entrance.

2.6 Primary Design

In this dissertation, the term primary distribution is used to denote primary laterals [21,22,23] which supply the high voltage (HV) side of the distribution transformers at the plat. The primary distribution design can be seen as the optimization problem of connecting all transformers in the plat while keeping additional trenching rather than conductor length at a minimum (taking advantage of already identified trench segments for the secondary runs). At the same time the primary distribution design has to satisfy a set of technical, geographical, as well as functional constraints.

The process of primary design can be divided into several subproblems:

a) Determining the number of phases.

b) Identifying possible source points from already existing feeders in the plat vicinity.

c) Primary route determination.

d) Paralleling and looping considerations.

These subtasks are tightly interconnected and decisions made in one subproblem will influence reasoning in the other. For example, the determination of the number of phases will influence the looping and paralleling consideration. Similarly, the number of possible source points will have an impact on the routing and looping of the primary circuitry. Some of the consideration during each of these subtasks are:

a) The number of phases used depends on the size of the total anticipated load within the plat in order to avoid imbalance.

b) Before proceeding with the primary design, the available source points should be identified. In order to increase the service reliability, multiple source points should be identified.

c) As far as routes for the primary are concerned, they must satisfy the same or similar constraints that the secondary routes do. Primary routes should be placed on the one side of the street as much as possible rather than cross from side to side.

d) The general approach for multiple primary phases is to find several sources and try to backup one phase with the same phase from another source. Usually the less favorable looping solution is to run parallel conductors from the same source for backup purpose in the same trench.

2.7 Street Lighting Design

For street lighting design, the principal parameters are defined by the developer, the billing agency responsible for the development, or the maintenance of the street lighting system. With a limited number of lights to be installed, street lights should be installed at intersections first, and then near the neck of each cul-de-sac. The remaining available street lights should be evenly spaced throughout the plat. From the load size point of view, street lights represent negligible load. Furthermore, serving a street lights from a transformer or a handhole is not affecting the number of customers to be served from those points.

In order to keep additional trenching minimal, routes for street light services should utilize as much as possible trenches already defined for primary and secondary circuitry. With the same goal in mind, street lights should be placed on the side of the street that is used for the major electric conductor route.

Similar to the design of other components of the plat, the street lighting system design can be divided into two parts:

a) Luminary placement and service route determination.

b) Street light sizing including style and type identification, mounting height determination and type of fuse selection.

2.3 Designers' Problem Solving Techniques

The designers' problem solving technique was carefully analyzed during the knowledge acquisition process. The findings are in close agreement with the results observed by the authors who have studied general design processes from the cognitive science perspective [17,24-30], and can be stated as follows:

a) In order to reduce problem complexity, designers employ the 'divide and conquer' method. With hierarchical division, the problem of dealing with everything at once is avoided. The overall design task is divided functionally into subproblems that are much easier to deal with (transformer placement, transformer sizing, secondary runs routing and sizing, primary conductors routing and sizing). In addition, some subproblems are made manageable by spatial reduction. An example of spatial reduction is "lot clustering." After "lot clustering" has been done, secondary routing can proceed separately for each cluster of lots served by one transformer.

b) Although nearly independent, subproblems interact with each other. (For example, transformer placement will influence secondary routing, which in turn will influence primary routing etc.). A way to cope with and exploit interconnections is by constraint posting where constraints are used as communication media between subproblems [24-29]. This amounts to the propagation of constraints in a design, and it enables a designer to coordinate the solution of subproblems. An example for that type of problem solving is to constrain the routes for the primary to trenches already defined in the secondary runs routing subproblem.

c) Due to the complexity of the design process, designers are "satisficers" [17], which means they are finding solutions that are "good enough" rather than optimal. This is not because they do not want to find the optimal solution but because exact optimal solutions are simply not within the reach of the planners, or they are too costly to obtain.

In order to find a method that will best suit the specific requirements imposed by the character of the problem and the designers' problem solving techniques, several possible approaches namely Operational Research (OR), Computer Aided Design (CAD), and Artificial Intelligence (AI) were examined. Findings on literature search for each of these areas, and comparison among them are presented in the next chapter.

Chapter 3

REVIEW OF PLANNING AND DESIGN METHODOLOGIES

3.1 Review of Existing Literature

It is well recognized in the power community that distribution, as a research field, has not received as much attention in the past as it deserves. This is especially true for distribution system facilities planning and design problems. Though distribution systems, in particular secondary distribution systems, represent the base of the pyramid of the largest man-made technical system in the world, papers concerning distribution system facilities design are very scarce. For this reason an overview of the papers that concern with methods and approaches used in related areas is presented. This overview includes also papers concerning methods and approaches which, in the author's opinion, can be used to automate distribution system design.

Based on the approach they employ, these papers are broadly classified into three categories, namely Operational Research (OR), Computer Aided Design (CAD) and Artificial Intelligence (AI). Instead of discussing papers listed in a particular area, a general discussion on the particular methodology they use is presented. The emphasis in the discussion is placed on the suitability of the each methodology for Automated Electrical Plat Design (AEPD). Special consideration is given to the several AI methodologies, due to their abilities to accommodate problem solving procedure for the ill-structured tasks. After the review is performed, the need for a better approach to automate the design is justified.

An extensive list of related references is given at the end of the dissertation.

3.2 Operational Research Approach

Methods based on Operational Research (OR) approaches have a long history of application to distribution system planning and design problems [8-16]. The methods employed include linear programming [8], branch and bound [9-13], mixed integer programing [14], dynamic programing [15], and their derivatives. Traditional algorithmic methods are intended to address problems that are well defined and can be expressed by sufficiently accurate mathematical models. As discussed in section 1.2, it is not possible to derive an objective function for the AEPD without sacrificing the salient decision factors. In addition a solution methodology employed by the human designer involves many heuristic and "rules of thumb." As such this methodology is not capable of formulation in an algorithmic form. For these reasons OR methods cannot be efficiently used as an overall approach for an open-ended design problem such as AEPD. Nevertheless, OR based methods can be adequate for some subtasks within the AEPD.

3.3 Computer Aided Design Approach

The CAD methods [31,32] during the past decade have evolved from being a way to automate the production of 2D mechanical drawings to a way to automate the design of parts and products. The earliest forms of CAD were generally tools for entering, storing, and retrieving designs. The CAD methods mainly capture geometry and assume that the users already have a somewhat clear idea of their equipment and design needs. The lack of "intelligence" and inability to automate the creative part of design make the CAD approach unattractive for distribution system design. On the other hand, CAD features such as user friendliness in the form of menu driven graphic environments with window facilities and advanced Graphic User Interface (GUI) functions are fairly desirable.

Recent papers published in this area show a shift toward the use of an AI based approach [33-46]. The CAD methods which employ some type of "intelligence" are usually referred to as Intelligent Computer Aided Design (ICAD) and are discussed in the next sub-section as a part of the AI approach.

3.4 Artificial Intelligence Approach

Artificial Intelligence (AI) [4-7,17,24-29,48-53] is a reemerging technology that has recently attracted considerable publicity although it has been around since the emergence of digital computers. One simple view of the field is that it is concerned with devising computer programs to make computers smarter. In other words, the computers perform decisions like human beings with reasoning analysis.

The computer programs with which AI is concerned are primarily processes involving complexity, uncertainty, and ambiguity. These are, in other words, the typical type of problem solving and decision making that humans continually face in dealing with the world.

In the past decade AI techniques gained considerable acceptance in the power system community. Most of the work in that period has been geared towards the development of expert systems as an operator's aid in energy control centers for power transmission systems operating under abnormal conditions. Alarm processing, fault diagnosis, system restoration, and voltage/var control are a few key areas where significant work has progressed to date [54,55,56].

Power system planning and especially the design areas have not received as much attention from the AI researchers, although some progress has been made in this field [57-66,81]. In particular, Bujko's work [58] and Ramesh's work [81] cover problems that are related to the design of the residential underground electrical supply system. In his paper Bujko proposed an expert system whose structure combined both algorithmic and heuristic approach for the problem of industrial power network design. The proposed expert system is aimed at helping the designer in settling upon the design strategies, analyze obligatory standards and regulations, and determine selection criteria. In [81] Ramesh et al proposed the use of decision support system methodology for distribution engineering applications. The suitability of such a methodology is illustrated on the problems of distribution transformer sizing and recloser-fuse coordination.

In this dissertation, the author has limited his discussion only to those aspects of AI that in his opinion have prospects suitable for AEPD. From the AEPD perspective, relevant AI methodologies are: Expert Systems [67-70], Knowledge Based Systems [48,53,71] and Intelligent Decision Support Systems [76-79]. Although they have striking similarities, each of these methods is used as a vehicle for different problem solving strategies. Furthermore, each of the above mentioned methodologies has strengths and weaknesses. Some of them are discussed in more detail in the following subsection.

3.4.1 Expert Systems

An Expert System (ES) [49,67-70] is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require human expertise for their solution. The knowledge necessary to perform at such a level together with the inference procedures used, can be thought of as a model of an expert in a specialized field or domain of interest.

The basic components of an ES are:

- Knowledge Base
- Inference Engine
- Database
- User Interface

From the programming point of view, expert systems can be based on rule-based, logic-based or heuristics-based programming paradigm. Any of these techniques can be used to solve problems that have not been automated previously. Problem solving control strategies employed by rule based expert systems are forward chaining, backward chaining or combination of both. The forward chaining inference control strategy is intrinsic for planning and configuring problems, whereas backward chaining is well suited to diagnostic problems. The reasoning process of an expert system can be retrieved and used for explanation facilities. The replacement of manual problem solving with an automated tool is the main benefit that an ES can offer.

An inherent feature of the expert system technique is to guide a problem solving process through a prescribed computational approach. Thus, they are not ideally suited to handle open-ended problems associated with multiple alternatives.

A careful examination of the design procedure in the plat design process indicated that some problem aspects can be better solved through other problem solving techniques not employed by designers. Domain knowledge can be used in some part of the plat design to guide the search in ways that differ from an expert's approach. This means that a knowledge-based system rather than a "pure" expert system would be more appropriate as a tool for the design task.

3.4.2 Knowledge Based Systems

Expert systems basically mimic the problem solving behavior of experts using domain knowledge acquired during the knowledge acquisition process. A Knowledge Based System (KBS) [48,53,73] goes beyond that in the sense that they enrich the problem solving strategy with methods that are not originally employed by human experts. As a result, procedural optimization routines and other number crunching may be used in the solution stage. Although the search process can be different from the one used by an expert, it is still strongly based on the domain knowledge.

Knowledge based systems also can be thought of as having several different experts each of whom has specialized in their specific domain, cooperating to achieve a solution. The problem solving control structure of the knowledge based system is more advanced and usually employs "knowledge about knowledge" or "metaknowledge" [25] to guide the overall solution process. Blackboard systems [41,59,72-75] and agenda based systems [30] are the two most frequently used types of knowledge based system architectures.

The inherent feature of the ES and KBS is that they both guide a problem solving process through a prescribed decision path. This is treated by many [79-81] as a drawback of these approaches to engineering design. What designers would ideally like to have is an intelligent computer tool that would enhance and support their judgement and thinking stage of design, rather than have a computer tool that would only automate the design. In that case the human partner would preserve a leading role in the design process while "less creative" tasks would be automated by the computer.

3.4.3 Intelligent Decision Support Systems

A Decision Support System (DSS) [81-83] is a computerized tool derived from decision theory used to enhance the user's ability to make decisions efficiently. DSSs are intended to explore and seek alternate solutions rather than to offer the final solution. The ultimate decision is left to the discretion of the user. They are well suited for open-ended problems and are mainly employed in all types of planning areas. Conventional decision support systems are used for retrieving, manipulating, or summarizing data in a way that assists decision makers. Some common decision support systems are spreadsheets and database management systems.

An Intelligent Decision Support System (IDSS) [76-78,84-90] adds intelligence to an existing decision support system in order to enhance the problem solving ability and to help maintain a broad range of knowledge about a particular domain. Intelligent Decision Support Systems are used for capturing, organizing, and reapplying knowledge including decision rules and criteria.

According to Fiksel [77],

> *An intelligent decision support system is a computer program that helps users to apply generic decision-making procedures, including analysis, inference, and optimization methods, to their specific knowledge about a decision problem.*

Unlike ES and KBS an IDSS does not attempt to discover complete solutions, instead they play a support role, leaving the user in charge. It can monitor the data that is being entered or retrieved by the humans, and make helpful suggestions. It can evaluate the implications of alternative decisions based on users' beliefs and assumptions. It can manage other software applications and expedite routine tasks, and it can help to enforce consistency and standardization in problem solving procedures in large organization. In addition, IDSS is a good way to help decision makers to incorporate knowledge processing capabilities into their everyday work.

IDSSs typically are expected to have the following capabilities:

- Sophisticated database management with ability to maintain consistency of knowledge.
- Plan maintenance and validation on the basis of current knowledge.
- Qualitative logical analysis with ability to identify unproven or invalid assumptions and determine implication of alternatives.
- Plan monitoring and revision which means the ability to recognize violated constraints and assumptions.
- Plan recommendation and evaluation of the plan evolution.

Contrary to ES and KBS, an IDSS shifts emphasis from a search procedure to more basic support functions such as knowledge browsing and alternate hypothesis testing. The IDSS enhances human judgement and thinking ability rather than solely recommending actions through a prescribed computational approach. In the interactive, symbiotic mode of operation with the human partner, the IDSS principal contributions are speed, deductive power, and systematic application of all available knowledge, while the user's principal contributions are creative exploration and common sense interpretation of the problem situation. The quality of the user interface assumes a paramount role, since the user is actively involved in the problem solving procedure during the run time.

3.5 Summary of Review

From the discussion of existing methodologies presented in Chapter 3, it can be concluded that none of them can be used as an exclusive way of dealing with such a complex task as AEPD. The IDSS as a methodology appears to be the best approach for embedding the problem solving strategy employed by plat designers. Furthermore this approach is capable of handling multiple alternatives, which are encountered during the electric plat design. Some parts of the plat design problem are well structured so that conventional OR algorithmic approach can be used for them.

In order to get an efficient AEPD tool, a hybrid IDSS must combine the user-friendliness from CAD methods, the robustness from OR algorithmic approach, and the ability to integrate different problem solving techniques from KBS.

In addition, the AEPD tool must operate with GIS stored data and within the GIS environment. For this reason Chapter 4 contains an brief overview of the Geographic Information System.

Chapter 4

GEOGRAPHIC INFORMATION SYSTEM

The Geographic Information System (GIS) as a part of the corporate database management system forms a repository where relevant information is drawn for the design purpose. In addition, spatial analysis capability of the GIS can be used to implement part of the AEPD problem solving procedure. For these reasons an overview of the GIS, and the role of the GIS for automated distribution system planning within the electric utility AM/FM system, is given in the following subsections.

4.1 An Overview

A Geographic Information System (GIS) can be loosely defined as an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze and display all forms of geographically referenced information. Although the term GIS originally includes more than just software, in this dissertation it primarily refers to the software part of the Geographic Information System.

In the last decade the GIS [18,91] has emerged from a stage of exploratory development of computerized mapping to the mature technology used in many diverse applications that require spatial information processing. The main difference between a GIS and other graphic software packages is that a GIS integrates database management, computer graphics, and spatial modeling into a software environment for managing geographic features. GIS is used to build a model of the world as it exists ("real world"), whereas CAD is used to represent new objects. The data necessary to represent the world as it is are much larger and more complex than the data required to represent a new product [92]. This fact is a main difference between CAD and GIS, and makes database the most important aspect of the GIS. Instead of storing maps in the conventional graphical sense, a GIS stores the data from which a user can create the desired view, drawn to suit a particular purpose. Thus GIS is an analysis tool that allows the user to identify spatial relationships between map features.

There are two basic types of map information that a GIS is dealing with:

- spatial information describing the location and shape of geographic features and their spatial relations to the other features
- descriptive (thematic) information about the features

Integration of these two types of data, and the ability to maintain the spatial relationship between the map features, open the variety of ways for an advanced, automated map data processing.

Regarding data handling within the GIS, two types of spatial data models exists, namely vector and raster [18]. In vector representation data are organized as geographic object like points, lines or polygon. In raster representation data are organized according to spatial address, and displayed using the grid. Vector model is related more closely to the traditional cartographic practice and it is usually chosen when the data are interpreted as a geographic feature so that feature's component can be easily accessed. Raster format, on the other hand, is more inherent to the modern ways of map creation by satellite/aerial sensing. It is convenient for region-type feature manipulation but it is inefficient for processing line-type features. Comparing to vector data processing, raster type data processing is usually much slower. As more detailed features can be discerned from satellites, the amount of the raster type information will increase. However, vector type model will remain a choice for the analysis intensive GIS applications. The GIS used in this dissertation is based on the vector data model so this model is described in more detail.

In vector representation, a point is recorded as a single (x,y) location in the Cartesian coordinate system, lines are recorded as a series of ordered (x,y) pairs, and polygons are recorded as line segments that enclose an area. For the spatial analysis, besides creating representation for geographic objects (points, lines, and polygons), a way of representing relationship among the objects, whether they belong to the same or different classes, must be provided. Topology, defined as a mathematical procedure for explicitly defining spatial relationships, is used for that purpose. The spatial relation among the primitive geographic objects are defined using the concepts of:

- connectivity (lines connect to each other at nodes)
- contiguity (each line has direction and left and right side)
- area definition (polygon is defined by lines that surround an area)

Based on these concepts, locational data are represented with a topological model that is stored in separate files managed by a Database Management System (DBMS).

Thematic data, used for the geographic feature attributes description are stored in the form of records and items. These feature attribute tables are also managed by the relational DBMS. The link between the feature and the record is maintained through the unique identifier stored in the files containing (x,y) coordinates and corresponding record in the feature attribute table. This unique identifier is used to perform relational operation on feature locational and thematic data within the DBMS.

Complete map information is often logically organized into sets of layers or themes of information. Each layer is called coverage and has features with one common attribute, such as lines representing all roads in one area, or polygons representing lot division of residential plat development. A coverage is the basic unit of map information storage in vector representation. It consists of topologically linked geographic features and their associated descriptive data stored as an automated map. Physically all data contained in the coverage are stored in one directory as a set of binary files containing feature attribute tables, coordinate and topology files, and cross-reference files used by relational DBMS. Information contained in various layers can be analyzed separately or combined creating new coverages to assist the user in decision making.

A typical GIS software system is organized in hierarchical form containing the following subsystems:

- subsystem for cartographic data inputting,
- subsystem for cartographic data displaying,
- relational DBMS used to analyze and describe locational data and feature attributes,
- subsystem containing spatial library system for managing large cartographic database,
- fourth generation language with a set of functions and macros for performing spatial analysis and cartographic data manipulations,

- related software modules capable of performing special tasks such as geographic network analysis or three-dimensional surface analysis.

The GIS was originally developed for use in interactive mode to support the user in identifying relation among the geographic features. This approach probably resulted in such a structure with a set of analysis tools spread out among the several subsystems. However commands, functions and macros, provided within the GIS fourth generation language (4GL), enable automatic communication among subsystems. With this possibility a fairly sophisticated spatial analysis can be obtained automatically in the noninteractive batch processing mode.

4.2 Electric Utility AM/FM System

Automated Mapping and Facilities Management is the terminology used to denote a subset of GIS. When a GIS is being used by an electric utility it is often referred to as an AM/FM system [93-95].

Computerized distribution planning, as a part of a broader Automated Distribution System (ADS) concept [3,65,96-98], requires the availability of digitally stored and automatically retrieved data. Geographically referenced data, which represent circuit map and records of electric utility entities such as transformers, switching devices and fuses, are easily stored and manipulated within the GIS environment. Besides providing data consistency and increasing productivity, a GIS based AM/FM system enables automated modeling for a host of engineering applications used in distribution system planning and design. Using an AM/FM system, the abstract model for distribution power flow calculations may be constructed automatically from digitized geographic maps and associated facilities data of the physical system. With such a capability, a utility AM/FM system provides a platform upon which a wide variety of applications can reside. Many of these applications will significantly free the user from time consuming and redundant tasks of manual data preparation. With an AM/FM system that supports spatial analysis, a whole new set of problems in distribution system can be automated. Automated Electrical Plat Design is representative of this new class of problems from Automated Distribution System area that will benefit from application of the GIS technology in the electric utility industry.

Chapter 5

INTELLIGENT DECISION SUPPORT SYSTEM FOR AUTOMATED ELECTRICAL PLAT DESIGN

5.1 Conceptual AEPD Tool Design Issues

An Intelligent Decision Support System (IDSS) [76-79,84-90] with the capability to suggest and evaluate different alternatives concerning different equipment placement locations, load size and type, as well as variation of any other design criteria, appears to be the best approach for the residential underground distribution facilities design tool. This requires a hybrid problem solving environment [29,30,41,59,73] with the capability to combine different methods of the computer aided design and engineering (CAD/CAE) approach, the knowledge based system approach (KBS) and the decision support system approach (DSS) [81,82]. The well-structured optimization tasks and basic technical and economical calculations are carried out by procedural algorithms [29]. Ill-structured synthesis tasks, in charge of a "creative" part of the design, are carried out by a rule-based programming paradigm. Methods for "what-if" analysis found in decision theory are in charge of the decision making part due to multiple alternatives in the design process.

The need to integrate diverse sources of knowledge and artifact representations in a useful manner also requires a special type of knowledge based system architecture. A blackboard architecture [41,48,49,59,72-75] offers good ability to integrate different types of problem solving strategies among knowledge sources (KS) encountered in the distribution facility design problem. Communication among the knowledge sources is solely carried out through the blackboard which acts as a global database. A human partner is interactively included in the run time process with his expertise as an independent knowledge source. In addition, during the exploration of the alternative design options he acts as a high priority task scheduler.

As far as the user interface is concerned, the design aid must provide user friendliness with windowing capabilities and use of advanced Graphic User Interface (GUI) methods.

5.2 Problem Solving Architecture

Based on issues discussed above, the conceptual IDSS problem solving model has the blackboard architecture shown in Figure 5. As can be seen from this figure, the complete automated plat design process can be divided into two modes:

a) off-line mode consisting of preprocessing after which the initial set of information is posted on the blackboard. These information contains description of the relevant spatial relation and possible device placement sites, routing corridors and possible street crossings.

b) interactive mode during which the real design process in symbiotic cooperation between human designer and knowledge sources takes place.

The generic software tools and environments needed for the AEPD are presented in Figure 6.

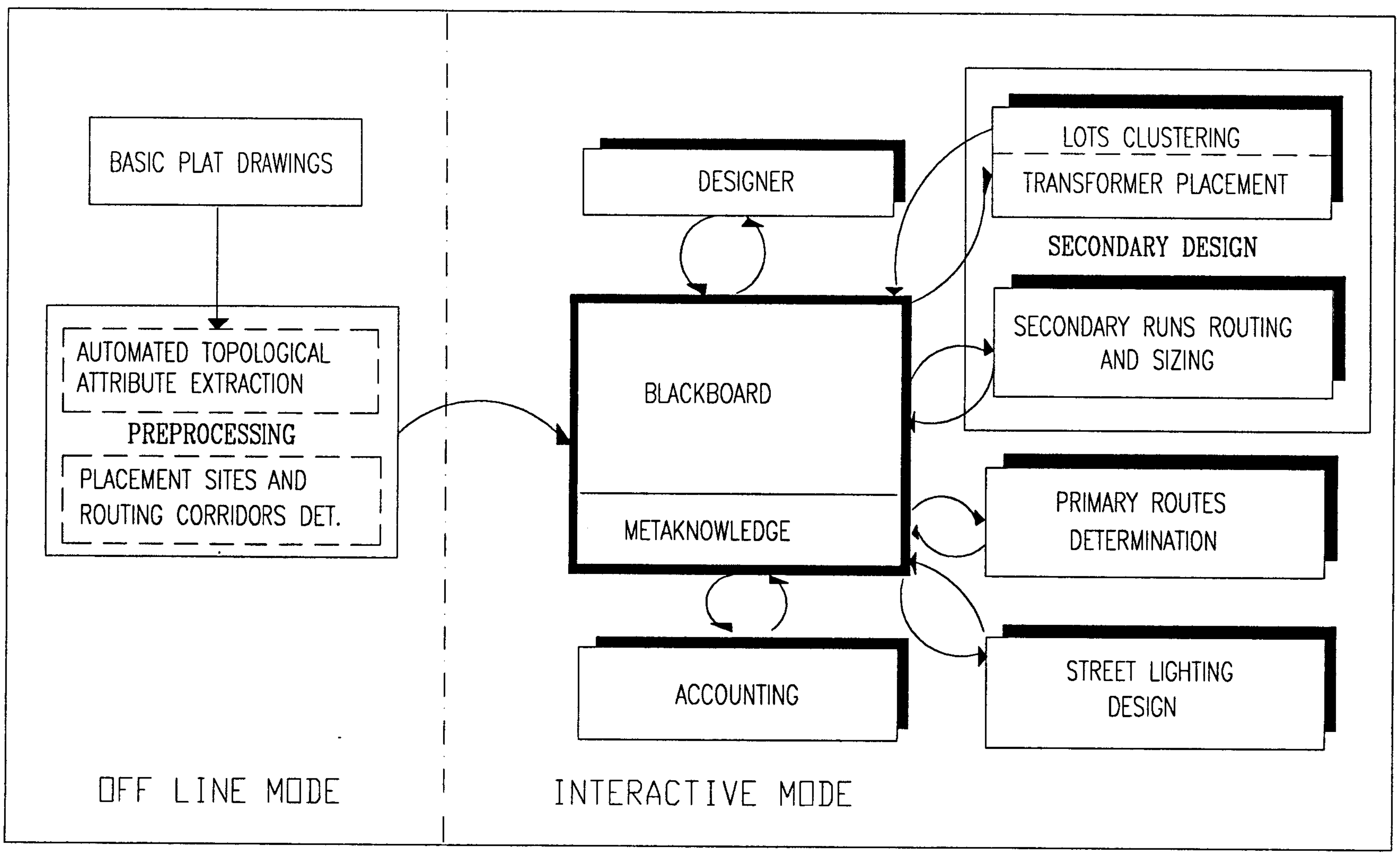

Figure 5. Intelligent Decision Support System for AEPD
Conceptual Blackboard Based Problem-Solving Model

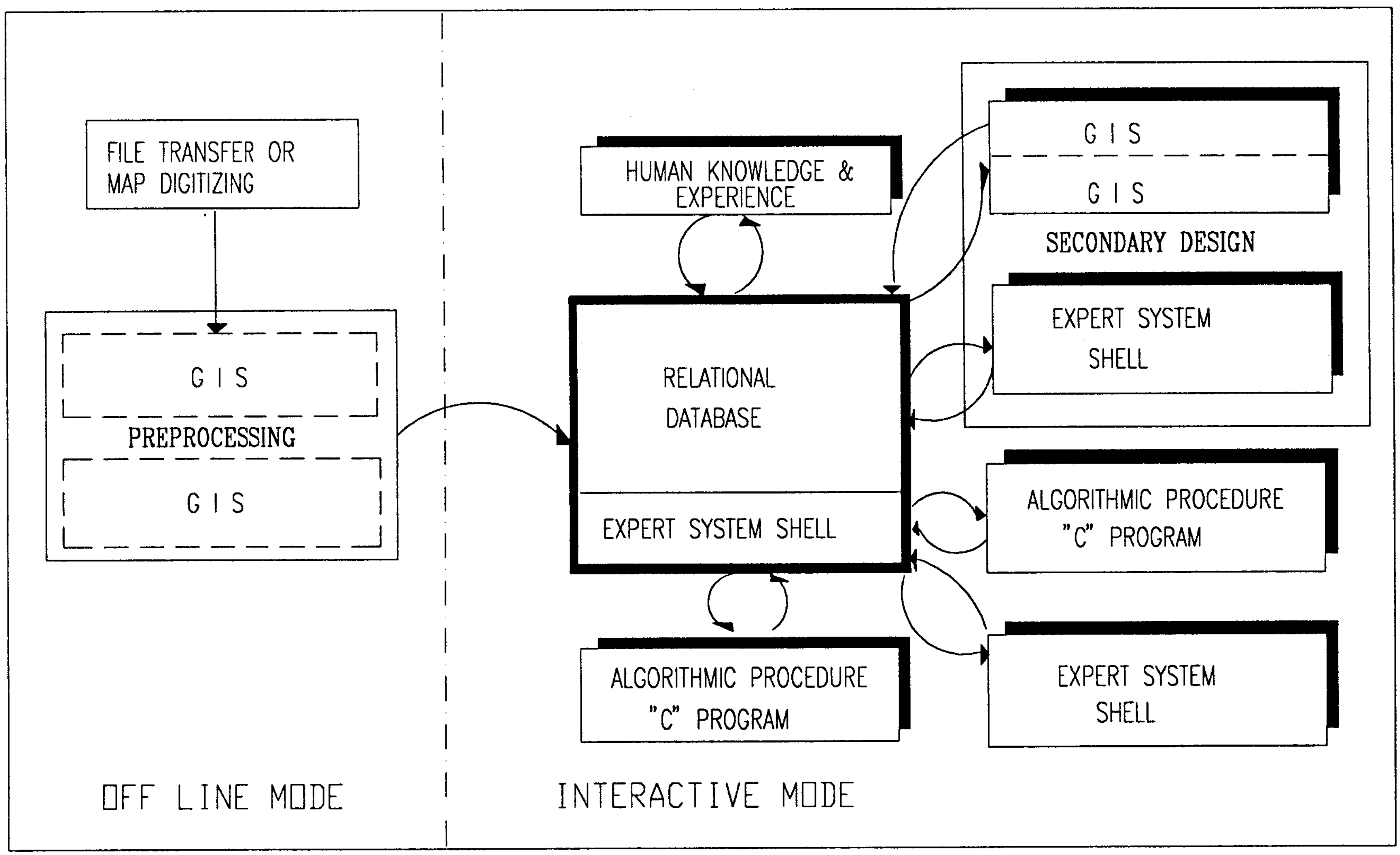

Figure 6. Intelligent Decision Support System for AEPD
Software Tools and Environments

A description of the tasks performed by the preprocessor in the off-line mode, and the tasks performed by each knowledge source in the on-line mode, is presented in the following subsection.

5.3 Plat Preprocessor

An additional requirement is imposed on the AEPD tool by the specific type of data encountered in the distribution system facilities design. A significant amount of information is stored in the form of a GIS (geographic information system) type database [18]. As stated earlier, the GIS basically integrates database management, computer graphics, and spatial modeling into a software environment for managing geographic features. The spatial data model of the commercially available GIS environment which is used in the AEPD tool is based on vector representation. In vector representation, geographic objects are represented by nodes (points), lines (arcs) or regions (polygons). Each of these entities has an appropriate attribute table, stored in the relational database. Examples of these entities for the AEPD problem are: transformers represented as points, secondary runs represented as arcs, and residential lots represented as polygons. At the start of the design process, basic engineering maps with geographically referenced information are contained in the form of different coverages containing layouts of the street and lot division, placement and layouts of other utilities such as water and gas mains, sewer mains and stub-outs, telephone lines and TV cables.

The geographic information system as a part of the corporate database management system forms a repository wherefrom relevant information are drawn for the design purpose. For this reason the IDSS for AEPD must have provisions for operation within the GIS environment.

The routing and placement part of the plat design process can be simply formalized as a composition of elementary operations described with the following symbolic model:

what the designer sees on the map

+what the designer knows

=what the designer does

Successful repetition of these elementary operations moves the design process from the initial state to the goal state.

As it can be seen from the above description, visual perception is crucial for the electric plat design process. To computerize the plat design, spatial reasoning with a form of pattern recognition is required to apply rules such as: "Place street light at the street crossing first", or "Do not put transformer at the end of the cul-de-sac". In order to automate plat design, without employing sophisticated pattern recognition or computer vision methods which are beyond the scope of this work, a sufficient set of information must be provided. This information must include relevant geographic and topological features of the plat layout and relations among the objects present in the plat. After the basic engineering maps have been digitized, relevant information must be stored in the attribute tables of the appropriate elements in the database part of the GIS. Examples of these attributes are:

- "polygon id number" of the left side neighboring lot,
- "side of the street" where the particular lot is placed (Left/Right),
- is a particular lot in the cul-de-sac ? (Yes/No).

During the preprocessing part of the AEPD, these attributes can be entered manually, or what is much more efficient, can be extracted automatically from the spatial representation of the digitized maps, with available GIS macros and functions. In the preprocessing part of the design, the GIS is used to substitute for the eyes of the "blind" designer implemented in the rule based programing paradigm, who knows how to operate, but does not see the world he has to operate on. The GIS ability to structure the "real world" representation required for the spatial reasoning part of the AEPD tool, without need for human intervention, enables automation of the design process. During the preprocessing part of the IDSS process, the coverage-layers data model inherent to the GIS spatial processing, has to be altered to an object oriented data model more suited for the knowledge processing within the expert system (ES) environment.

In addition, in the preprocessing part of the plat design, a set of spatial constraints are applied which are defined in the form of rules such as:

a) Transformers should be placed on the front (street) corner of the lot that is not used for sewer stub-out.

or

b) Secondary runs should utilize trenches located on the front (street side) of the 10' utility easement.

The application of these rules prune the search space, and make the overall search process manageable. Though these spatial constraints are not influenced or altered by any part of the design process, an early-commitment strategy [24-28] is employed. Spatial rules (constraints) are applied using the GIS macros and functions. As a result of spatial rules application, possible routing corridors and placement locations are identified and stored as attributes in the database part of the appropriate objects. This use of constraints as elimination rules in the preprocessing part of AEPD yields a small, feasible set of the design placement and routing alternatives to be explored during the run-time process. Thus with this approach, after plat spatial reduction, the search space is reduced so that even an exhaustive search of the possible design options is feasible.

5.4 Knowledge Sources

In the following subsections the role, software environment, programing paradigm and problem solving approach of the various knowledge sources in charge of different parts of the overall designing process is described.

5.4.1 Transformer Placer

This knowledge source operates within the GIS environment and takes advantage of existing macros and functions to determine best transformer location. To do that:

1) a cluster of lots with determined size must be identified.
2) among the possible locations for transformer placement, defined in the preprocessing part, the site that is closest to the center of gravity of that cluster is identified.

The clustering process is a crucial one for the success of automated transformer placement and it later influences all parts of the AEPD process.

The number of lots in the cluster is determined based on anticipated load and average lot size, which basically determines maximal conductor length to maintain allowable voltage drop. That number is provided by the user and can be used as a good way to explore the consequence of future change of the load type on design solutions. From the economical point of view it makes sense to keep each cluster size similar and close to the maximum number of lots. This strategy reduces the number of transformers used, and consequently the capital investment on residential underground distribution systems. In addition, this approach results in transformer magnetizing losses reduction as well. In order to maintain approximately equal cluster size, a complex procedure containing backtracking readjustment is employed in the clustering process [99-101].

The lots clustering procedure, based on the designers' approach, is implemented using the GIS' fourth generation programming language. Each cluster starts to grow automatically from an identified origin such as end of the cul-de-sac and main street entrances at the plat, and continues until the predetermined number of lots are incorporated in the cluster. During this process some of the original clusters are merged together, and some new cluster origins are created. New lots that are added to the cluster are identified based on their distance from the cluster origin and the existence of path segments through corridors or street crossing.

Since the lots clustering results significantly impacts the design, at the end of the clustering process the user is prompted for his/her approval. If the user disapproves, he/she can request an appropriate cluster reconfiguration before actual transformer placement can proceed.

From the data model point of view, clustering is a point where for the first time object oriented "real world" structuring is introduced. Instead of coverages containing layouts of the engineering maps with plat division, street layouts, utility mains and physical obstacles, which are used as a basic data model in GIS, a plat is represented as a set of objects called clusters, each of which is treated independently in the process of transformer placement, the secondary runs design, and the street light design. The detailed description of the object oriented database model for the rule-based knowledge processing is given in Chapter 8.

After lots clustering is completed and approved by the designer, a transformer placement is obtained using the minimization principle which states that an optimal location for the source point must be in the vicinity of the lots cluster center of gravity [19,64]. This principle, explained in Appendix B, is valid both for the capital investment reduction (trench length and secondary conductor length), and for the operational losses reduction ($\mathbf{I^2R}$ losses). In the Transformer Placer knowledge source this minimization principle is implemented in two steps. First, a center of gravity is found for the particular cluster, assuming each load point is in the lot centroid. Then the available site which is closest to the center of gravity is used as an optimal transformer location and suggested to the user. The user can accept this suggestion or change the transformer location to explore different design alternatives.

Once the transformer location is accepted by the designer, a transformer site is established as an origin for that cluster, and spatial attributes with regard to the transformer are created and assigned to each lot for further processing. In regard to the transformer, lots are classified as those on "the left side" or on "the right side" of the transformer, as well as lots on the "same side" or on the "other side " of the transformer. This classification creates attributes, assigned to the lot's record, which later facilitates the routing process during the secondary runs design.

A similar procedure as for the transformer placement is used to place handholes on the "other sides" of the streets in one cluster. After the transformer and the handholes are placed, spatial relations among connecting devices and lots are automatically established and stored in the attribute tables of the appropriate coverage.

A sizing for a particular transformer is based on the anticipated type of heating and "lots-to-transformer" assignment determined by the Transformer Placer. The transformer sizing is implemented in rule-based programing paradigm using a commercially available expert system shell.

5.4.2 Secondary Runs Designer

Secondary runs routing and sizing is done for each cluster of lots served by one transformer independently. This knowledge source is also implemented in a rule-based programming paradigm using a commercially available expert system shell.

In order to find the optimal routing for secondary runs using feasible corridors and street crossings, a plat layout with available information obtained after corridors and crossings determination and transformer placement, are structured in the object oriented "real world" representation.

More details about this knowledge source and problem solving method employed are given in Chapter 8.

5.4.3 Primary Runs Designer

After the user determines the number of phases to be used and chooses one or more among the possible power supply points from the existing feeders in the plat vicinity, this knowledge source is used for the primary conductor routes determination.

This step assumes that the transformer placement and secondary routing segments of the plat design have been accomplished. After that, the primary routing can be seen as an optimization problem of connecting all transformers in the plat, while keeping additional trenching rather than conductor length at a minimum (taking advantage of already determined trench segments for the secondary). For this purpose an algorithmic procedure, based on a modified branch and bound method need to be employed. The distances among terminal points for each cluster secondary network, that are required for this procedure, can be obtained automatically using the GIS.

The development of Primary Runs Designer knowledge source is beyond the scope of this dissertation.

5.4.4 Street Light Designer

This knowledge source needs to combine the GIS fourth generation programming language and a rule-based programming paradigm. The GIS environment can be used for the placement part of the street light design, while the rule-based part can be applied within the commercially available expert system shell. The required domain knowledge has already been acquired in the plat design knowledge acquisition process. Street light design involves two steps:

a) luminaries placement

b) street light connection

In the first step, a predetermined number of the luminaries are placed on appropriate locations such as the intersections. For this purpose some elementary pattern recognition process has to be done to distinguish among possible placement sites those that are near the street intersection. Within the GIS environment the closest source point for the each luminary needs to be determined also.

In the second step, each street light is assigned to the nearest connecting device (transformer or handhole) if a path exists (corridor or street crossing) that can be utilized for street lighting wiring.

The Street Light Designer development is also beyond the scope of this dissertation.

5.4.5 Accountant

The cost minimization is one of the basic objectives of the AEPD tool. The AEPD tool is designed, with the idea in mind that it should provide a "minimal cost solution" for the given values of user controlled variables, which are number of lots in the cluster, type of heating utilized, maximal conductor length to be used, types of conductor to be used, transformer site within the cluster, and so on.

A knowledge source, named Accountant, is intended to provide a mechanism for evaluation of the different design options and load scenarios. In order to determine the cost-effectiveness of a particular design option, this knowledge source does not only keep track of the bill of materials and basic labor and equipment cost, but it takes into account the operational cost required for a given option, too. Thus it is also used for the evaluation of both the capital investment and the operational costs.

This knowledge source is also not currently implemented in AEPD prototype.

5.4.6 Human Designer

The role of the human designer in the interactive on-line mode of design is twofold:

a) Using his knowledge and expertise, the designer acts as an independent knowledge source for the hard tasks such as: determination of the best source points among the ones identified and offered by the computer, or defining paralleling and looping policy. In difficult and conflicting situations the human designer is asked to provide appropriate input if the computer cannot come up with a particular solution. In the same manner, the human designer is asked to provide missing data or to supplement inconsistent and incorrect data, so it enables the automated design process to proceed even in that situation. In addition it makes sense to use human ability for common sense reasoning and to utilize his/her ability to easily identify some spatial features such as street intersections or the end of the cul-de-sac. With such an approach optimal labor division between two agents, human and computer, are obtained. This enables each partner to play their individual roles effectively.

b) The human designer also acts as an overall task scheduler while trying to generate and explore alternative design options. In so doing, the overall control embedded into the metaknowledge posts the assignments for the knowledge sources on the blackboard in order to fulfill the designer's requests. For example, to check the cost differential if a transformer is moved from one place to another, the secondary runs knowledge source must be invoked by the overall control, then the primary router knowledge source, and finally the accountant knowledge source must be invoked.

5.5 Blackboard

The characteristics of the blackboard approach to problem solving are independent operation of knowledge sources and globally shared information. In the blackboard problem solving architecture, the blackboard is the communication medium through which the knowledge sources communicate their findings to each other. The blackboard is:

a) the source of all data on which a knowledge source operates,

b) the destination for all conclusions from a knowledge source.

Thus, the blackboard can be thought of as a global database. The blackboard is implemented using a commercially available relational database. A bridge developed to interface the GIS database with the chosen Relational Database Management System (RDBMS) is not released yet and it is expected to be released in the 1991. Due to this reason, for the prototyping purpose object oriented "real world" structuring, instead within the relational database, is implemented in the "flat file format." The expert system shell, used in AEPD to accommodate rule-based reasoning, among the several relational database bridges contains a bridge for the "flat file" form database structure. With that bridge, SQL-like queries are embedded as RHS actions of the IF THEN rules [102]. For the prototyping purpose, SQL-like transaction are used for the "flat file" data retrieval and update. More details of the expert system shell-database transactions are given in Chapter 8.

5.5.1 Metaknowledge and Overall Control

In order to guide the overall solution process and to respond to the designer's requests, a special knowledge source called metaknowledge must be developed. The metaknowledge is usually presented as a part of the blackboard. The metaknowledge in the AEPD tool is embedded in the rule-based programming paradigm. The control strategy employed by the control knowledge source is request driven. The control knowledge source selects the domain knowledge source that is likely to provide the requested information. In addition, control knowledge source acts as an agenda scheduler in determining which KS to use and when to invoke it to fulfil the particular need for the any design scenario. Thus, in the example of moving a transformer from one place to another to determine the cost differential, the control mechanism defines which knowledge sources must be used and in what sequence they must be employed.

5.6 AEPD Prototype

To check the feasibility of the proposed problem solving architecture, an AEPD prototype is developed in this dissertation. The AEPD prototype functionally covers the area of GIS plat preprocessing and a secondary design which refers both to the transformer and the secondary runs design as shown in Figure 2. The Plat Preprocessor, the Transformer Placer knowledge source, and the Secondary Runs Designer knowledge source, developed in this dissertation for the AEPD prototyping purpose, are fully operable and can be used later as elements of the complete AEPD tool. These AEPD elements are used for the prototyping because they represent the two major ingredients, namely GIS and AI, that form the Blackboard Based Intelligent Decision Support System for AEPD. The third ingredient, a Relational

Database Management System (RDBMS), as a medium for Blackboard implementation, is not included in the AEPD prototype, because of the absence of a bridge between the GIS database and relational database. The data required to bridge the gap between the GIS and the ES shell is manually transmitted by the user. Thus the GIS and Es shell are not coupled in the AEPD prototype.

The structure of the prototype developed in this dissertation for the AEPD concept feasibility evaluation is given in Figure 7. The development of the AEPD prototype modules, and the obtained results are presented in the following chapters.

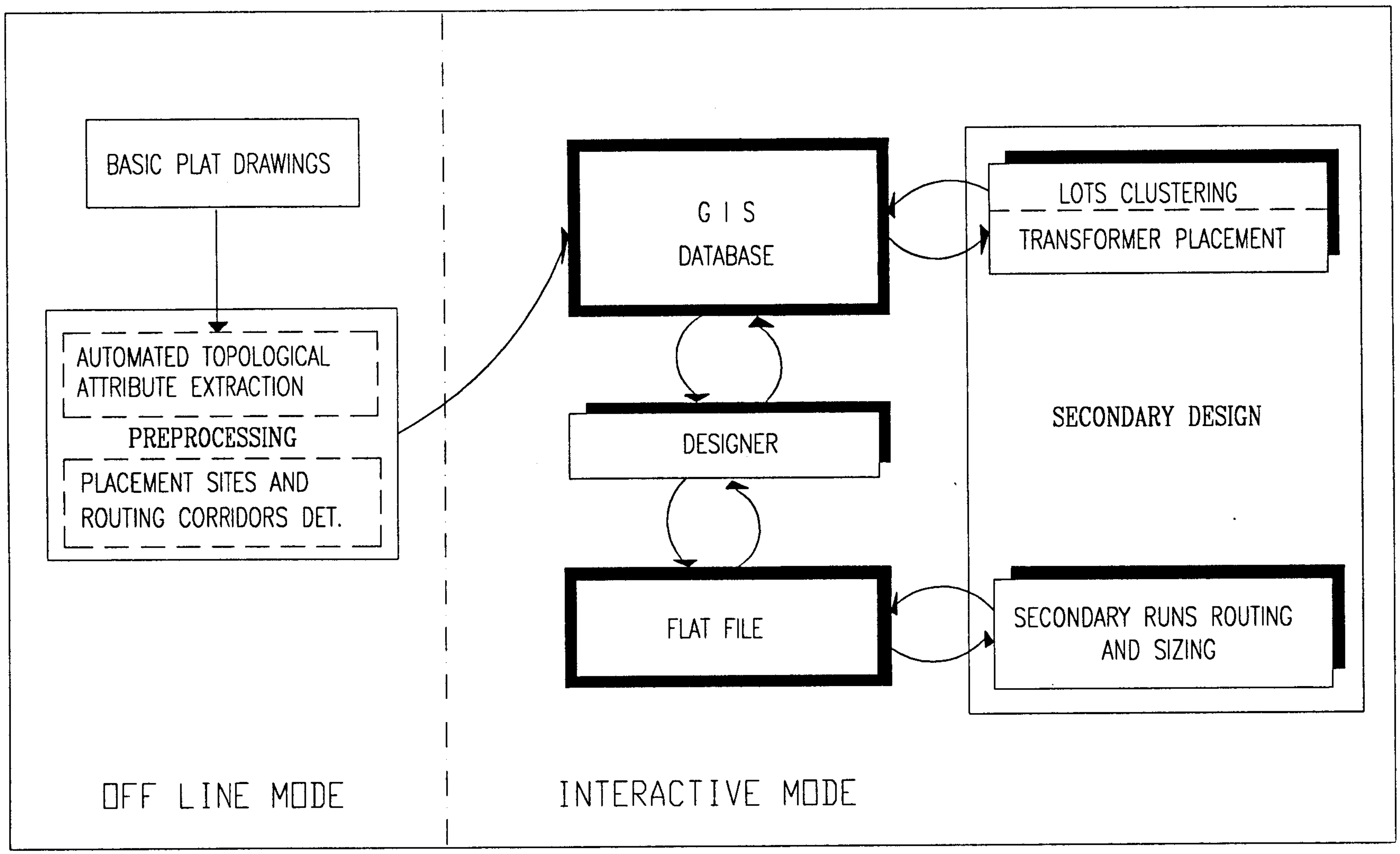

Figure 7. STRUCTURE OF THE AEPD PROTOTYPE

Chapter 6

PLAT PREPROCESOR

6.1 Secondary Runs Routing and Sizing Prototype Developed in LISP Programming Language

The results of the knowledge acquisition process [19] and review of existing methodologies reported in the literature suggested that an Artificial Intelligence based approach might be appropriate for automating electrical plat design. For the purpose of exploring the feasibility of this concept, the expert system prototype for the secondary runs sizing and routing, based on acquired rules, is initially implemented in the Lisp programming language [110]. The prototype is developed based on the assumption that in the GIS preprocessing part of the AEPD, required topological attributes containing spatial description of the plat, had been extracted. Furthermore, it is assumed that spatial constraints had been applied within the GIS in order to create possible placement sites, routing corridors, and street crossings. It is additionally assumed that the lots clustering had been done, and that transformer and handholes had been placed. Thus, the prototype had to deal with secondary routing and sizing for only one cluster of the lots at the time.

Lisp Cond forms were used to embed 40 routing, sizing and checking rules employed by plat designers. Atom's property list is used for the expert system working memory emulation. The source code of the Lisp prototype, including control structure and structure of the working memory elements, as well as the results, are given in Appendix C.

In addition to the feasibility study for the AI approach to AEPD, the prototype is used for the identification of the necessary topological features that must be extracted during the preprocessing part of the AEPD. In addition, Lisp prototype helped in identifying tasks, such as defining possible placement sites, corridors, and crossings that must precede the rule based reasoning part of an AEPD. Based on the experience obtained with the Lisp prototype, the role of GIS in the "real world modelling" is identified.

6.2 Data Required for Automated Electrical Plat Design

The goal of the AEPD tool is to automate routine tasks and provide suggestions for most of the creative tasks encountered in the electrical plat design. It is important to note that the tasks that are routine from the human point of view, are not necessarily routine and easy to automate with a computer program. This is especially true for the class of the tasks that requires computer vision or pattern recognition type of processing, such as automatic street identification, automatic cul-de-sacs identification, or automatic street intersection identification. All these tasks must be performed at the beginning of the design process, either by a human being or by a computer, in order to proceed with the AEPD. The ultimate goal is to have these tasks automatically performed by computer. In the first stage of AEPD development, results of some routine tasks that are very involved for computer processing can be interactively supplied by the user, before the start of AEPD. A good example for such a task is street identification, something which is obvious for the user from the map representation of developing a plat. If this task must be done by the computer, a complex processing in the GIS fourth generation language is required. This processing may employ the distinctive feature of the street polygon contiguity with remaining polygons that represent housing lots.

According to the results of knowledge acquisition, prior to the beginning of the design, the developer provides the designer with maps containing basic street layouts of the area to be developed including the plat division into housing lots. Originally this information can come from either map manuscripts on paper, maps drawn electronically and stored in the form of CAD .DXF format file, and digitized or scanned map in the form of several different standard GIS file formats. For the AEPD process, data containing street and lots division are stored according to the GIS data model into one coverage called LOT, which has only a polygon feature. Except for the basic topological attributes that are automatically created by default during the GIS coverage creation, no other thematic data are associated with this coverage at the beginning. If the original plat data are supplied by a municipal agency, it may contain additional descriptive data stored into LOT coverage polygon attribute table (LOT.PAT) such as a parcel number, owner name and other which are not needed for the AEPD process. Thus, with each polygon contained in the LOT coverage representing either a lot or street, there is a record associated in LOT.PAT containing initially only four basic topological attributes as shown in Table 1. All other descriptive data about spatial arrangement of the plat's lots, relation between the lots and street, neighboring lots and similar, which are needed for the future processing, are later either automatically created and stored in LOT.PAT using the GIS fourth generation language, or supplied by the designer upon request and stored, in an interactive mode. Data supplied by the designer may contain information about lots that do not require electrical supply, or lots that need a special type of electric supply (three phase). The description of required attributes and an explanation of how thay are created are given in following subsections.

The initial structure of the LOT polygon attribute table, at the beginning of the AEPD process is given in Table 1. The table header contains "Name" which denotes the field name, "Width" indicates width of the field in bytes , "Output Width" is the width in which the field is presented to the user , "Type" specifies a data type (numeric, float, binary, character, date, integer), and "Decimals" used to denote the number of decimals that are used .

Table 1. Initial Structure of the LOT.PAT

Name	Width	Output Width	Type	Decimals
Area	4	12	Float	3
Perimeter	4	12	Float	3
Lot#	4	5	Binary	-
Lot-id	4	5	Binary	-

Besides the information about street and lot layouts on the plat, usually the designer has at his/her disposal information about the presence of other utilities on the plat. Information about water and sewer mains and stub-outs, gas mains, storm drainage, and telephone and TV cables, can facilitate the design process. Except for the TV and telephone cables that usually share the same trench with an electric utility, the rest of the facilities present on the plat should be avoided. This is particularly true for the sewer stub-outs, which are placed in the lot frontage corners so that the same corner cannot be used for the transformer placement. Although these data are obtained from different sources and are originally contained in different maps, for the AEPD purpose they are combined into one GIS coverage with line feature. This coverage is called LINEOBSTACLE.

In addition to the obstacles that have line feature, there is another group of obstacles that are present on the plat, such as big rocks, ponds or some man made objects which the designer should avoid during the placement or routing process. These obstacles have polygon features and are stored in the GIS coverage called POLYOBSTACLE. The POLYOBSTACLE coverage may contain polygons representing areas with very steep terrain that cannot be used for the device placement or conductor routing. These areas can be also automatically identified using a GIS subsystem capable of processing maps that include information about plat elevation.

For the reasons explained earlier, the line feature representing utility lines is expanded into the "zone of influence" using spatial operation called buffering. The buffering operation converts a line feature into a polygon feature, so that buffered lines from LINEOBSTACLE can be unified with polygons from POLYOBSTACLE coverage into a unique coverage called OBSTACLE that has only polygon feature. For the AEPD purpose OBSTACLE polygon attribute table (OBSTACLE.PAT) does not need to contain any thematic data except basic topological attributes created by default.

The OBSTACLE coverage is used during the spatial processing within the GIS for constraint placement to reduce the number of possible placement sites, routing corridors, and street crossings. Using this coverage, rules such as "Do not place transformer in the lot corner occupied by sewer stub-out," are implemented.

At the beginning of the AEPD process all information about plat is stored in two GIS polygon feature coverages, called LOT and OBSTACLE. Except for the basic topological attributes, initially no other descriptive data are associated with these coverages. Before the start of the AEPD processing a substantial amount of data must be generated and prepared. This automated data preparation within the GIS environment is referred to as the **preprocessing**. To enable future automated processing, a host of required attributes must be created and stored in the LOT.PAT.

In addition, three new coverages containing possible equipment placement sites, routing corridors, and street crossings ought to be automatically generated. The programs for the automatic attributes and coverages generation, require a significant time for execution, but it can be performed without user intervention. The preprocessing is done as a first step of the AEPD in an off-line batch mode, so that computational time required for preprocessing is not of major concern.

The GIS preprocessing for the given plat is done only once, unlike the other knowledge sources (KS) in AEPD Blackboard Based IDSS problem solving architecture, which may be invoked several times during the one session.

The tasks of the GIS preprocessor are described in the following subsections in greater detail.

6.3 Automated Basic Spatial Relation Extraction

The first basic spatial relation that is automatically extracted from the existing LOT coverage and stored into LOT.PAT is "Side of the Street," which is introduced to identify a set of the lots that can be served without crossing the street. In order to enable consistency when dealing with cul-de-sacs where lots on the opposite sides of cul-de-sacs are served by crossing rather than going around, the bottom of the cul-de-sac is opened and lots in it are treated as being members of the two separate sets. This situation is presented in Figure 8 where each lot has an associated "Side of the Street" attribute, identified inside it.

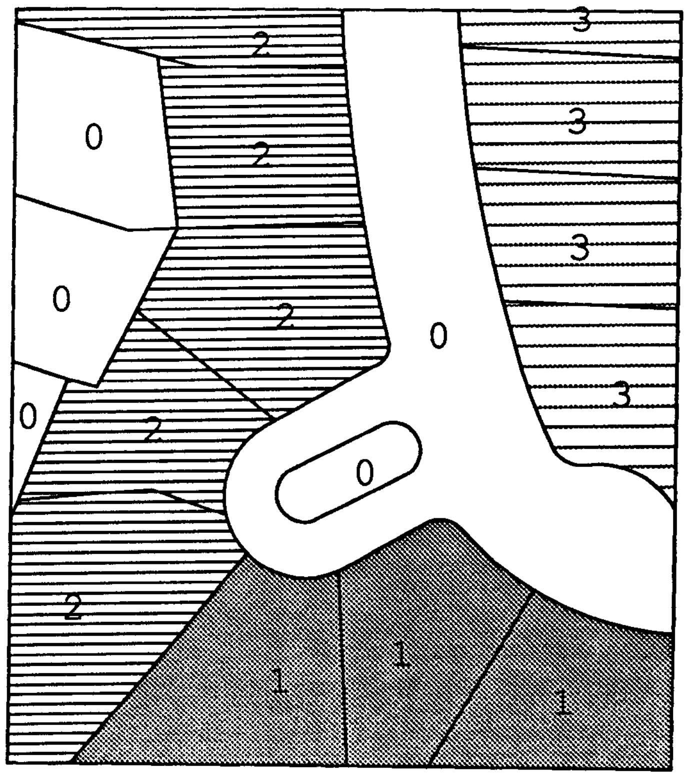

Figure 8. Side of the Street Identification: Cul-de-sac Case

Assigning the "Side of the Street" attribute to LOT.PAT is done in a spatial procedure which first uses the GIS contiguity concept to identify lot's frontages as arcs (lines) that have a street polygon on its left or right side (depending on arc orientation). After that, based on the GIS connectivity concept, among the previously selected arcs, those that are connected and form one "Side of the Street" are identified. The "Side of the Street" attribute is defined as an integer and all lots, which are members of the same "Side of the Street" set, have the same value for that attribute stored in their records in the LOT.PAT. Street intersections and cul-de-sacs introduce more than two "Sides of the Street."

The second task in basic spatial relation extraction is the identification of the left and right neighbor for each lot. This process is very important in enabling future processing and especially for making later rule based processor to be able "to see" spatial arrangement of the plat.

The neighboring lots identification is performed with a GIS macros and functions program. The program is based on a contiguity concept applied on the arcs that represent boundaries among the lots on the same "Side of Street". Left polygon id and right polygon id for each arc are topological attributes that are created by default during the GIS coverage creation. To find the left and right neighbor for each lot, its boundary arcs must be identified and all oriented in the same direction toward the street. After that lot neighbors can be found as left polygon id and right polygon id attributes, stored in the arc attribute table (AAT) of the LOT coverage. Thus, the main problem in neighboring lots identifications consists of identifying boundary arcs. As shown on the Figure 9, these arcs are incident to the nodes which are terminal nodes of the lot's frontage arcs. These are already identified during the "Side of Street" determination process, and their terminal nodes are easily obtained because they represent basic topological attributes. As such, they are stored by default in an arc attribute table (AAT), during the GIS coverage creation. Id numbers of the left and right lot's neighbor determined in this manner for each lot, are stored as integer value attributes "Left Neighbor" and "Right Neighbor," into appropriate record of LOT.PAT.

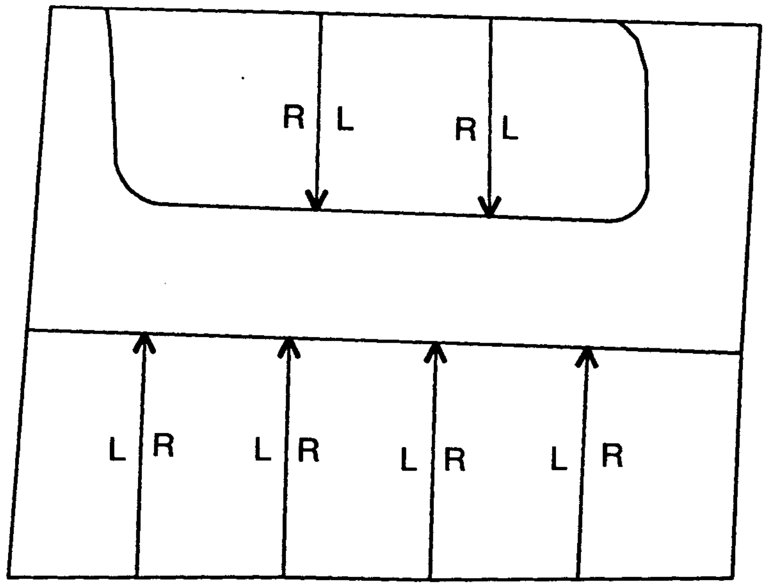

Figure 9. Neighboring Lots Identification

6.4 Possible Placement Sites, Routing Corridors and Street Crossings Generation

In addition to creating new attributes to be stored in the LOT polygon attribute table, during the GIS preprocessing new coverages are also created. To reduce the size and complexity of the electrical plat design problem, possible placement sites, routing corridors, and street crossings are predetermined in the preprocessing part of the AEPD. With such an approach during the interactive part of the design, only the possible design options, concerning transformer and handhole placement, as well as secondary and primary routing are explored.

A procedure for generating GIS coverage containing possible placement sites for the transformer and handholes is based on the rule that a transformer or a handhole can be placed at the front corner of the lot that is not used for sewer stubout [19]. In addition this site must be at the centerline of the 10 feet utility easement, and within an adequate distance from a lot boundary. To generate points that represents these possible placement sites, a buffering operation is applied to lot frontage arcs and lot boundary arcs.

The intersection points of the boundaries of these buffered zones, which fall within the lot polygon, as shown on Figure 10, represent possible placement sites. All possible placement sites obtained in a such way are stored in the form of new generated SITE coverage having point feature. The point attribute table of the SITE coverage (SITE.PAT), besides the default topological attributes for each site, contains a pointer to the lot where the placement site is situated, and an attribute that indicates if the site is in the left or right corner of that lot. Some attributes, containing information about relations between the placement sites and the crossings and the status of sites, are created and stored in the SITE.PAT in the subsequent parts of the later GIS preprocessing.

The secondary and primary runs of an underground electric distribution system are laid in trenches that are dug along the 10 feet utility easement in accordance with utility practice. The process of generating coverage that contains all possible secondary and primary runs routing corridors, is basically a process of identifying the centerline of the utility easement. To create the centerline of utility easement, lot's frontages arcs, already identified in one of the previous preprocessing task, are used. By performing a spatial operation called parallel, a set of new arcs 10 feet from lot's frontage arcs are created. These new arcs represent possible corridors for the trenches that must be dug on the plat. The process of corridor generation is presented on Figure 11.

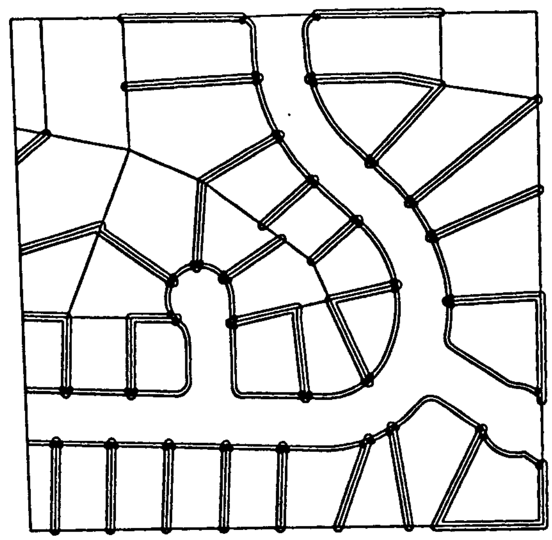

Figure 10. Placement Site Creation

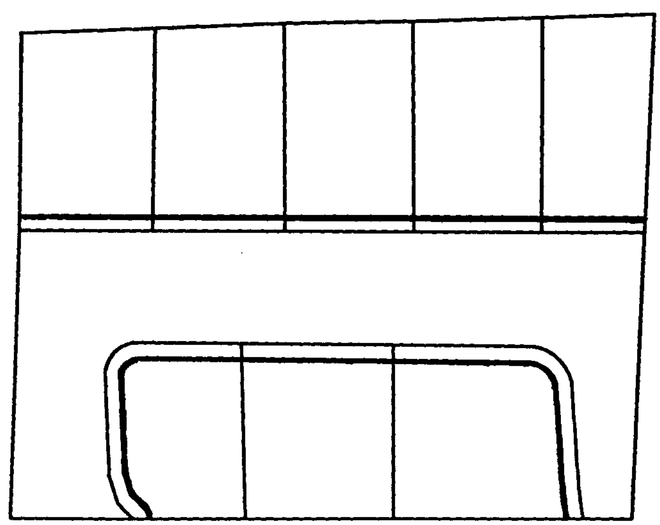

Figure 11. Routing Corridors Creation

All data concerning routing corridors in the GIS environment are stored in the CORRIDOR coverage. The arc attribute table, as a part of the descriptive data associated with this coverage, besides the basic topological attributes that are created during the coverage generation, contains an attribute that represents a pointer to the lot where a particular corridor segment is situated. A similar pointer from the lot to the associated corridor is stored as an attribute in the LOT.PAT. The remaining attributes for the CORRIDOR.AAT are later created and stored with forthcoming GIS preprocessing tasks.

The third coverage that contains all possible street crossings for the primary and secondary underground cables must also be created with a GIS preprocessor. According to the rules used in manual design (Appendix A), street crossings are automatically created for each site, connecting it to the nearest placement site that is not on the same "Side of Street". This procedure utilizes a built-in GIS function that finds the nearest point to the particular location. To make future processing as general as possible, a special procedure is implemented to take care of peculiarities encountered in determining crossing for the cul-de-sac lot arrangement. After the closest site to the particular placement site is found, the crossing is generated as an arc with these sites as terminal nodes. All data about street crossings are stored in GIS form as a coverage called CROSSINGS, having a line feature. In addition to the basic topological data automatically created during the CROSSING coverage creation, attributes relating crossing with the sites that are at the beginning and at the end of that crossing, are stored in CROSSINGS arc attribute table (CROSSINGS.AAT). An appropriate pointer to the site where the street crossing originates, is stored as an attribute in the SITE point attribute table (SITE.PAT).

Figure 12 shows the process of the street crossing determination.

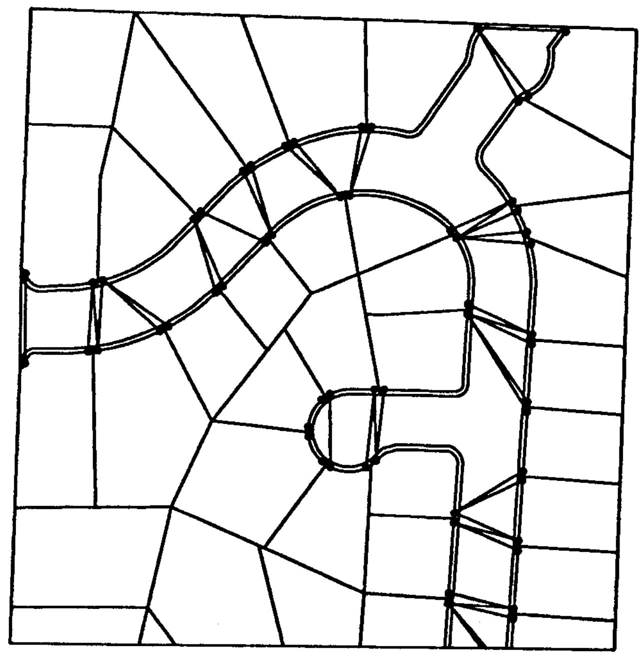

Figure 12. Street Crossings Creation

The overlay of the three coverages created with the GIS preprocessor over the basic LOT coverage creates a network of possible branches and nodes that can be utilized for the underground distribution system. Figure 13 depicts such a network pictorially.

6.5 Number of Sites, Corridors, and Street Crossings Reduction

During the placement sites, routing corridors and street crossing coverage creation, no concern has been given until now to the potential presence of obstacles on

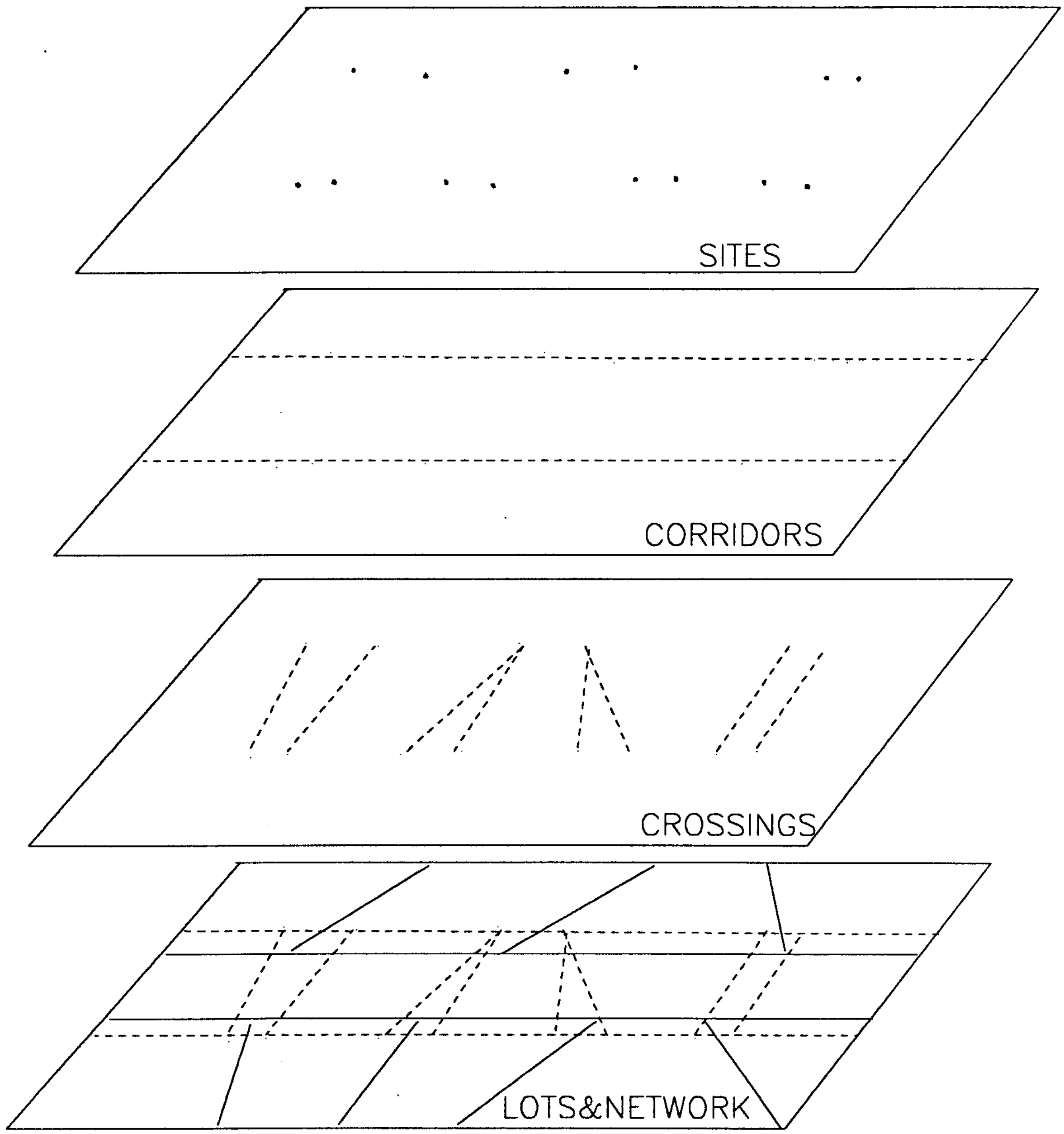

Figure 13. Determination of the Network of Possible Sites, Corridors and Crossings

these locations. To evaluate the usability of possible placement sites, routing corridors and street crossings, the OBSTACLE coverage created before the start of the AEPD process is used. The intersection of the network of the possible sites, corridors and crossings with the OBSTACLE coverage will indicate which element cannot be used due to the obstacles present on that location. This information is stored, as an attribute called Status, for each element in the appropriate coverage attribute table (SITE.PAT, CORRIDOR.AAT, and CROSSING.AAT). The value of this attribute is F if an element can be used for placement or routing, or the value is O if the obstacle is present on the same location. The operation of finding unusable elements is given in Figure 14.

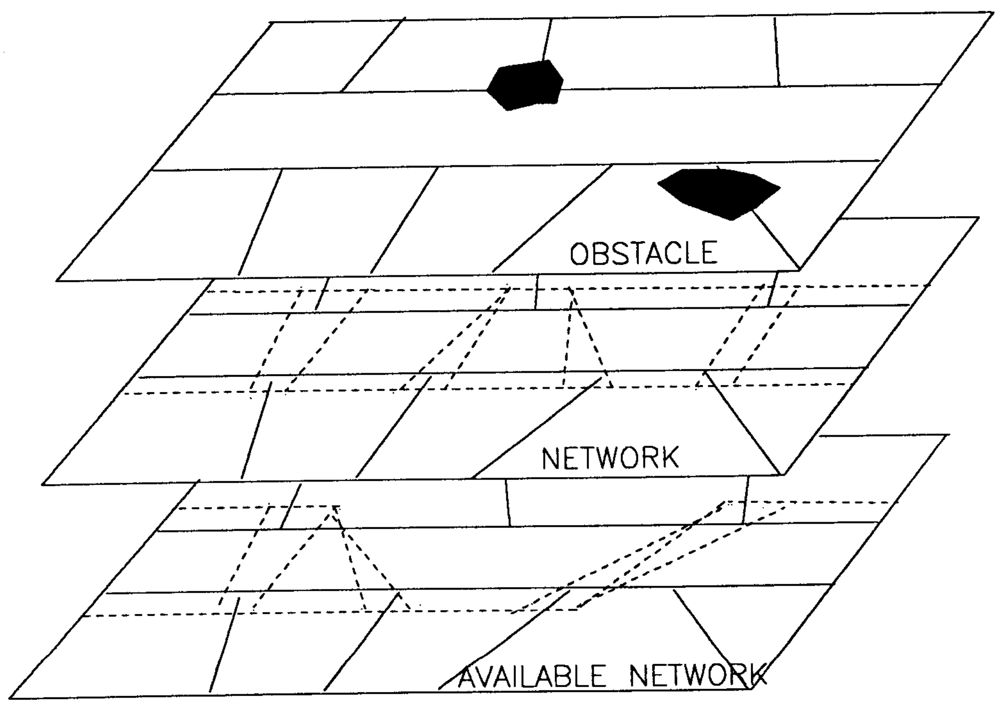

Figure 14. Unusable Elements Determination

Determination of the unusable elements for the device placement and conductor routing is the last task to be done by the GIS preprocessor. After these tasks have been performed, a set of information necessary for the future AEPD processing is available and can be posted on the blackboard. Descriptive data identified during the GIS preprocessing are posted on the AEPD blackboard as GIS coverage feature attribute tables described in next subsection.

6.6 GIS Coverage Feature Attribute Tables

The attribute tables for the LOT coverage, and newly created SITE, CORRIDOR, and CROSSING coverages, obtained after GIS preprocessing, are given in the Tables 2, 3, 4, and 5, respectively. The names of the attributes created with GIS preprocessor are printed in bold, to distinguish from the basic topological attributes that are created by default during the coverage creation. The attributes in the LOT.PAT that can be supplied by the designer, concerning anticipated type of load on a particular lot (usually single phase), or information about already existing electric supply for some lots (attribute Connected), are printed in italics. Also printed in italics are attributes in the LOT.PAT that can be entered by the user prior to the start of the designing process to avoid the need for pattern recognition type of processing (attributes "Street", and "Cul-de-Sac").

The attribute "Cluster" contained in LOT.PAT is created later in an interactive mode by Transformer Placer described in Chapter 7.

The attribute "Used" found in SITE.PAT, CORRIDOR.AAT, and CROSSING.AAT, which indicates that a particular element is used for placement or routing, is created and supplied by either Transformer Placer or Secondary and Primary Routing Knowledge Sources during the AEPD session.

Table 2. LOT Coverage Polygon Attribute Table (LOT.PAT)

Name	Width	Output Width	Type	Dec.	Description
Area	4	12	F	3	basic attribute
Perimeter	4	12	F	3	basic attribute
Lot #	4	5	B	-	basic attribute
Lot-Id	4	5	B	-	basic attribute
Load	1	1	C	-	Note 1
Connected	1	3	C	-	Note 1
Street	1	1	C	-	Note 1
Cul-de-sac	1	1	C	-	Note 1
SideStr	3	3	I	-	Side of the Street
LNeigh	4	5	B	-	Left neighbor id
RNeigh	4	5	B	-	Right neighbor id
LCorner	4	5	B	-	Left cor. Site id
RCorner	4	5	B	-	Right cor.Site id
Corridor-Id	4	5	B	-	Corridor id
Cluster	3	3	I	-	Note 2

Notes: 1) Data supplied by the user

2) Cluster number id created later by the Transformer Placer

Table 3. SITE Coverage Point Attribute Table (SITE.PAT)

Name	Width	Output Width	Type	Dec.	Description
Area	4	12	F	3	basic attribute
Perimeter	4	12	F	3	basic attribute
Site#	4	5	B	-	basic attribute
Site-Id	4	5	B	-	basic attribute
Lot-Id	4	5	B	-	Note 1
Crossing-I	4	5	B	-	Note 2
Opposite-Id	4	5	B	-	Note 3
L-R	1	1	C	-	Note 4
Status	1	1	C	-	Note 5
Used	1	1	C	-	Created later

Notes:

1) Pointer to the lot that contains that site
2) Pointer to the crossing that originates from that site
3) Pointer to the site on the opposite side of the crossing
4) L if the site is in the left and R if the site is in the right lot corner
5) F if the site can be used, O if the obstacle is present.

Table 4. CORRIDOR Coverage Arc Attribute Table (CORRIDOR.AAT)

Name	Width	Output Width	Type	Dec.	Description
Fnode#	4	5	B	-	basic attribute
Tnode#	4	5	B	-	basic attribute
Lpoly#	4	5	B	-	basic attribute
Rpoly#	4	5	B	-	basic attribute
Length	4	12	F	-	basic attribute
Corridor#	4	5	B	-	basic attribute
Corridor-Id	4	5	B	-	basic attribute
Lot-Id	4	5	B	-	Note 1
Status	1	1	C	-	Note 2
Used	1	1	C	-	Created later

Notes:

1) Lot id of the lot that contains that corridor

2) F if free for use, O if obstacle is present on that location

Table 5. CROSSING Coverage Arc Attribute Table (CROSSING.AAT)

Name	Width	Output Width	Type	Dec.	Description
Fnode#	4	5	B	-	basic attribute
Tnode#	4	5	B	-	basic attribute
Lpoly#	4	5	B	-	basic attribute
Rpoly#	4	5	B	-	basic attribute
Length	4	12	F	-	basic attribute
Crossing#	4	5	B	-	basic attribute
Crossing-Id	4	5	B	-	basic attribute
Site1-Id	4	5	B	-	Note 1
Site2-Id	4	5	B	-	Note 2
Status	1	1	C	-	Note 3
Used	1	1	C	-	Created later

Notes:

1) Site Id of the site where crossing originates

2) Site Id of the site where crossing ends

3) F if crossing can be used, otherwise O

Chapter 7

TRANSFORMER PLACER

All procedures performed with a Plat Preprocessor to create the required attributes and objects as the initial data for an AEPD session, are performed in an off line batch mode without the need for the designer to intervene, or guide the preprocessing. On the other hand the GIS tasks performed by the Transformer Placer knowledge source, need the designer's initial input, result approval, or sometimes a suggestion to proceed. Thus, the GIS processing in Transformer Placer is done in an on line interactive mode, where a computer recommends the initial solution on the basis of current knowledge, monitors the designer's suggestion and constraint violation, presents intermediate results, and asks for his/her approval. The human partner in this mode guides the overall design process, sets the value for control variables and defines different scenarios and design options. Besides, the designer approves the solutions offered by the computer or suggests alternate possibilities to be explored.

As presented in Chapter 2, the transformer placement plays a crucial role in the overall electric plat design problem. The transformer placement part of the plat design influences not only the secondary runs design, but through the mechanism of constraint propagation it influences the primary as well as the street lighting design. Due to the sensitivity of the cost of an electrical plat design on the issues how and where transformers are placed, this task requires special consideration, and constant approval and monitoring from both the human and the computer that are engaged in the design process. In addition due to this sensitivity, the Transformer Placer is the best origin to start exploring different scenarios and design options.

The first task performed by the Transformer Placer is lots clustering. This is a point in the design process where the complexity of the overall problem is reduced by spatial reduction. After the clustering is done, the other parts of the secondary design are performed for each cluster independently.

The transformer placement is also a source of necessary data for structuring the object oriented "real world" representation that is needed by expert system shell used for the secondary routing.

7.1 Lots Clustering

The idea of lots clustering, found in designer problem solving approach [19], is based on an attempt to identify a set of lots that are close by so that they can be efficiently served with one transformer. Though the need for lots clustering is easy to understand and justify, it is hard to implement in a manual electrical plat design, and an especially challenging one to automate with a computer [100,101]. Because the lot clustering concept is based on a spatial analysis, a GIS is chosen as an appropriate software environment for implementing this task.

Before the start of the clustering process a desirable size of the cluster with tolerable upper and lower limits for the cluster, must be provided by the designer. The size of the cluster expressed via the number of the lots, is based on the anticipated average size of the load and average size of the lots. The size of the cluster must be determined in a such way that it should minimize the number of transformers that would be used on the plat, while maintaining the tolerable voltage drop for the given secondary conductor size. Basically, the cluster size is determined by maximal length of a given conductor that for the given load still results in an acceptable static and dynamic voltage drop (say 3%). The size of the cluster, used as a rule of thumb by the designers in different areas, varies from four in low populated areas with electric heating, to fourteen in the densely populated urban area with available alternative heating sources. These rules of thumb are used as default value for the cluster size in the AEPD for each service area. Changing the maximal size of the conductor to be used, anticipated type of heating, and anticipated average load size, would change the desirable size of the cluster and consequently the cost of the plat design. Thus, these variables can be used as a vehicle for exploring cost benefits of different design alternatives. The average size of the lots in a particular plat can be automatically calculated and used to offset the desirable cluster size, if necessary.

After the cluster size has been determined, the clustering process implemented in a GIS environment can proceed. The overall clustering task can be functionally divided into the following subtasks:

- identification of cluster origin
- cluster growth
- cluster merging and reconfiguration

These three tasks are performed automatically, and at the end of the automated clustering the designer is prompted and asked for an approval or readjustment.

7.1.1 Identification of Cluster Origin

The origin identification is the first task to be done in clustering process. Based on the number of lots on the plat and desirable cluster size, an approximate number of resulting clusters is determined. Then the equal amount of cluster origins must be identified on the plat.

The first group of cluster origins is placed in the lots that are situated at the bottom of the cul-de-sacs, which are natural and easily identifiable for the designer but not for an automated procedure. For the sake of identifying these lots, the "opening" at the bottom of the cul-de-sacs performed for the "Side of the Street" attribute creation, as described in section 6.3, is used.

The second group of cluster origins is placed in the lots that lie at the street entrances of the plat. These points are identifiable as terminal points of the unsplit arcs that represent road curbs. Unsplit operation is one function provided by the GIS tools that eliminate intermediate nodes of several connecting arcs joining them into a single arc. Thus a set of connected lot frontage arcs can be unsplit to form one road curb. Using that method, at each street entrance of the plat, two lots are identified and one of them is used as the cluster origin.

The remaining cluster origins, if needed, are obtained by subsequent searching, using the branch and bound type of an algorithm, for the lot whose centroid is the farthest from the centroids of already established cluster origins.

An additional option built into the Transformer Placer, is to treat the origin placement as a way to control the design. In this mode the lots used for the cluster origins are defined by the designer in an interactive mode.

The identified clusters' origins for the group one, two and three are presented on Figure 15. Each group of origins have a different shading and group identifier written inside the lot polygon.

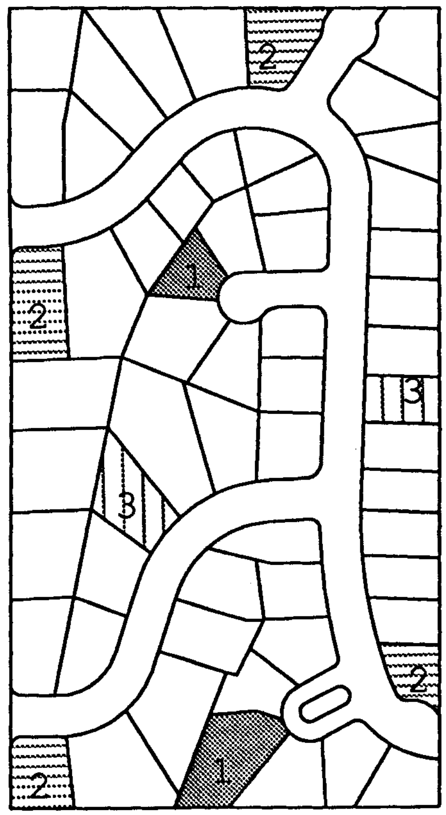

Figure 15. Cluster Origin Determination

7.1.2 Cluster Growth Process

For the cluster growth process, three different procedures have been attempted in order to find one that is the most efficient from the computational point of view, and that gives results which are similar to the clustering results obtained by the human designer. Due to the interactive nature of this task, computational efficiency must get more careful consideration than in the case of the GIS preprocessing task.

In this subsection, the description of the different procedures is presented, while more details concerning implementational issues of the algorithms that are used are given in [99].

The clustering methods can be categorized according to the point that they treat as the reference, into three categories:

a) a fixed reference point at the transformer placement site of the cluster origin lot,

b) a fixed reference point at the centroid of the lot that is a cluster origin,

c) a moving reference point at the center of gravity of the expanding cluster.

In all these three cases, the next lot to be added to the cluster among the unclustered lots is one that it is the closest lot to the reference point.

The notion of closest lot in the case a) means that the path going through the available corridors and street crossings from cluster origin to the available placement site is the shortest for that lot. This method of lots clustering relies on a network of placement points, corridors and crossing created by the GIS preprocessor, and finds a shortest path based on available elements. Though computationaly involved, this method makes an early pruning of the designs that are unacceptable due to the absence of possible paths for the conductor routing. As such, this method is recommended for the lots clustering where a considerable amount of obstacles are present at the plat, so that search space for the shortest path is reduced.

The closest lot determination with method a) is given in Figure 16. The lot that is origin of the cluster is denoted by one. The order in which lots are added to the cluster are printed inside the lot's polygon.

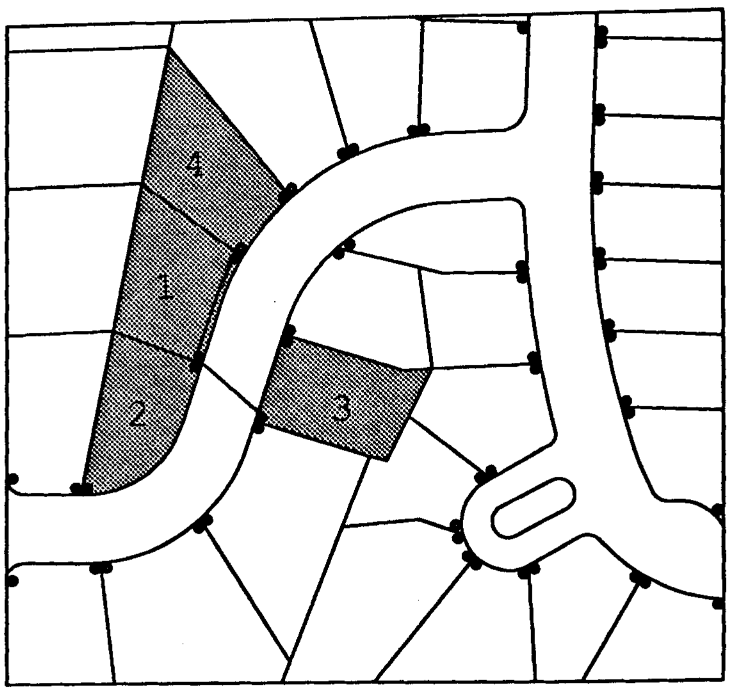

Figure 16. Closest Lot Determination: Method A

In the case b) the closeness is determined based on distance between the reference point, in the centroid of the lot that is the cluster origin, and centroid of the lot that is a possible candidate to be merged into the cluster. This process is shown in Figure 17, with the order in which the new lots are added to cluster printed inside the lot's polygon. The coordinates of the lots' centroids are automatically determined during the coverage creation, and stored as a part of basic topological attributes in the polygon attribute table. Thus determining the distance between the lot centroids and finding the shortest distance among them is a routine computational task and can be performed very efficiently.

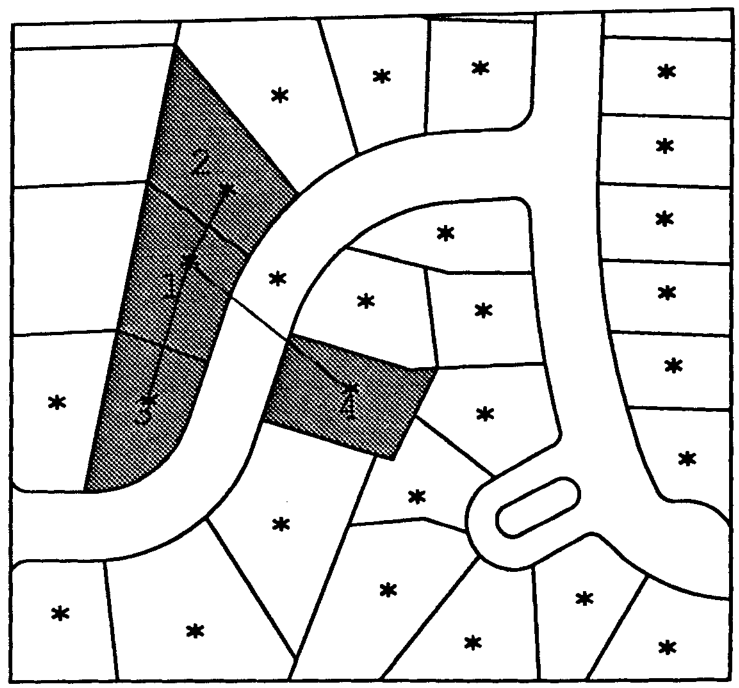

Figure 17. Closest Lot Determination: Method B

Though computationaly efficient method b) exhibits two drawbacks:

- the clustering is not done according to the real requirement for the transformer placement clustering where the distance is expressed by path using the corridors and crossings, rather than "crow fly" distances.
- this method does not examine automatically the existence of the feasible path among the lots, so that an additional routine for that checking must be implemented to ensure connectivity among the lots in the cluster.

In the case that there is no obstacle present in the plat, this method can be used directly without path availability checking.

With methods a) and b), both of which use the fixed reference point approach for the clustering process, the transformer site is inherently predefined in advance with cluster origin identification. Except for the street entrance origins, the only difference between the identified cluster origins and final transformer placement sites is caused by the process of cluster merging.

The method c) does not suffer from the transformer sites predetermination because it dynamically changes the reference point after the new lot is added to the cluster. In each iteration step after the new lot is added to the cluster, a center of gravity for the newly formed cluster is calculated and defined as the reference point for the next clustering step. The new lot to be added among the unclustered lots is chosen based on the shortest distance between its centroid and center of gravity of the expanding cluster. Adding the new lot and determining the new reference point for the method c) is given in Figure 18 for the two iteration steps. Starting from the same cluster origin lot (1) as in the Figure 16 and 17, the order in which lots are included into the cluster are printed inside the lot's polygon.

The method c) operates on " crow fly" distance rather than on length of the real path that utilizes the existing corridors and crossings. Thus it exhibits the same drawbacks as method b). Furthermore, more involved checking for the existing paths among the members of the cluster must be implemented in this method. The method c) is not recommended for plats with considerable obstacles present.

Although clustering methods a), b), and c) differ in the way they choose a new lot that should be added to the cluster, all of them use the same global iterative approach. At each step a new lot is added to all the clusters until the appropriate size for the clusters is reached or certain other conditions are met.

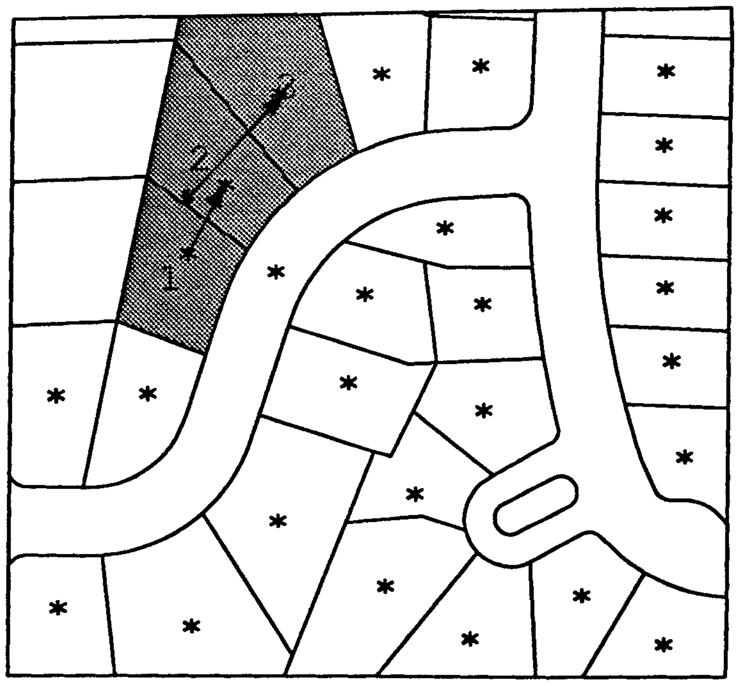

Figure 18. Closest Lot Determination: Method C

7.1.3. Cluster Merging and Reconfiguration

During the cluster growing process several different cases can be encountered before the clusters reach a proper size. The most frequent case is that one cluster tries to include a lot that is already a member of another cluster. That case can be avoided simply by introducing a flag that would distinguish clustered lots from unclusterd ones, so that prospective cluster members can be chosen only from the set of unclusterd lots. This practically means that a lot cannot be released from the cluster after being once included. Though this requirement appears to be reasonable, choosing only from the set of unclustered lots may result in irregular and spatially unconnected clusters that do not satisfy requirements originally imposed by the transformer placement problem. Thus instead of keeping lots "forever" in one cluster, once they have been picked up, a strategy of releasing lots from one cluster and merging them with another, must be implemented to obtain acceptable results.

In conflicting situations when one cluster tries to merge a lot that is already a member of another cluster, two questions must be answered. First, which cluster takes precedence over the other, and which one will be desintegrated ? Second, what will happen to the lots that are members of the cluster that must be disintegrated ? Although these questions require more careful study and are one of the directions for future work in this area, it is observed that different cluster growing method requires different cluster merging strategies. For example with cluster growing method c) it makes sense to merge all lots from the desintegrating cluster to the one that takes over. On the other hand in the cluster growing method a), only the lot closest to the reference point of the cluster that takes over is merged with that cluster, but the remaining lots are released.

The process of merging clusters and cluster disintegration eliminates some cluster origins, but in order to keep desirable size of clusters new origins should be dynamically defined during the clustering procedure. For that purpose, a new origin is determined as the lot whose centroid is the farthest from the all existing cluster origins.

Based on the description above, one can realized that the clustering procedure is subjective and complex. It is especially hard for implementation with the GIS fourth generation language, which does not include all the capabilities that possess a conventional programming language such as FORTRAN, PASCAL or C. The comparison of the results for two clustering procedures for the AEPD prototyping purpose is given in Chapter 9. The implementational aspects of the lots clustering procedures developed for the Transformer Placer are reported in a contemporary work under progress [99].

Due to the crucial impact of the quality of clustering outcome on the quality of the overall electrical plat design, the results of the lots clustering procedure are presented to the designer and his/her approval, suggestion or readjustment is requested. After the designer approves or rearranges the clusters their id numbers are created. These numbers are a unique cluster identifiers and they are assigned to all members of one cluster as the attribute "Cluster", and stored in the LOT polygon attribute table LOT.PAT (Table 2).

With this attribute available, the next segment of the Transformer Placer is ready to be processed automatically.

7.2 Transformer and Handhole Placement

The process of placing transformers inside the defined cluster is based on optimality principle, derived in Appendix B, which states: "For a given load arrangement, the optimal site for the transformer is in the vicinity of its load center of gravity for each cluster." This principle is also used in the problem of finding an optimal location for a distribution substation [64], which is a related area.

As a consequence of the clustering process, the problem of finding optimal sites for the transformers on the plat is reduced to the problem of finding the center of gravity for each cluster. After that, among the possible placement sites for each cluster, a site that is the nearest to that center of gravity, is chosen as the optimal. In this process each cluster is treated separately, one by one, so that spatial reduction of the problem makes the search procedure even more efficient.

For determining the "center of gravity," a load point for each lot is assumed to be placed in the lot centroid. The lot centroid coordinates are basic topological attributes of the label point, which are automatically assigned to each polygon during the coverage creation. Thus no additional calculations are required for the lot's load point determination in the GIS.

The anticipated load size of the each lot should influence the location of the "center of gravity." If all loads in the cluster are of the same type, and information about anticipated size of the load is not available, for the purpose of transformer placement all loads are treated as being the same size. In this case, according to Appendix B, load "center of gravity" coordinates can be determined using the formula:

$$x_t = \frac{\sum_{i=1}^{n} x_i}{n}$$

$$y_t = \frac{\sum_{i=1}^{n} y_i}{n}$$

where x_i and y_i are coordinates of the particular lot centroid

and n is the number of lots in the cluster.

If there is an established linear correlation between the lot size and load size for a given plat, that information can be used to guide a process of optimal transformer location determination. In this case, lot area, which is the basic topological attribute Area in the LOT.PAT automatically created during the LOT coverage generation, can be used as a weighting factor to move the center of gravity toward larger lots, according to formulas:

$$x_t = \frac{\sum_{i=1}^{n} Area_i * x_i}{\sum_{i=1}^{n} Area_i}$$

$$y_t = \frac{\sum_{i=1}^{n} Area_i * y_i}{\sum_{i=1}^{n} Area_i}$$

Finally, in the case that reliable data concerning anticipated lot's load size exist in the form of LOT.PAT attribute Load, the formula for the coordinates of the load "center of gravity" is given by:

$$x_t = \frac{\sum_{i=1}^{n} Load_i * x_i}{\sum_{i=1}^{n} Load_i}$$

$$y_t = \frac{\sum_{i=1}^{n} Load_i * y_i}{\sum_{i=1}^{n} Load_i}$$

After the "center of gravity" is determined, the optimal site for the transformer is found as the one of the available placement sites that is the closest to the load "center of gravity". The distances between the cluster's load "center of gravity " and available elements from the coverage SITE that lie in that cluster can be found easily. In the same way a search for the shortest, among these calculated distances, is an easy task also. Thus computational burden for the transformer placement is not difficult. The results of the transformer placement is stored as a value T of the attribute "Status" in the SITE coverage point attribute table (SITE.PAT record of the particular site Table 3).

Besides placing a transformer in each cluster, the Transformer Placer KS places the other necessary connecting devices called handholes in each cluster. The designer's practice concerning the use of handholes is different in different service areas [19], and the benefits as well as rules how and where to place the handholes are neither consistent nor straightforward.

The handhole placing strategy is based on the rule that each "Side of the Street" in one cluster must have one connecting device, either a transformer or a handhole. Thus for the handhole placement purpose, each "Side of the Street" that exists in the cluster and does not have a transformer on it, must obtain a handhole.

In the case of two "Sides of the Street" that are present in one cluster, a site for the handhole is determined as a terminal (end) node of the arc, element of CROSSING coverage, that originates in the site where the transformer is placed. This situation is presented on Figure 19, where the handhole site is determined by the crossing that originates from the site where the transformer is placed.

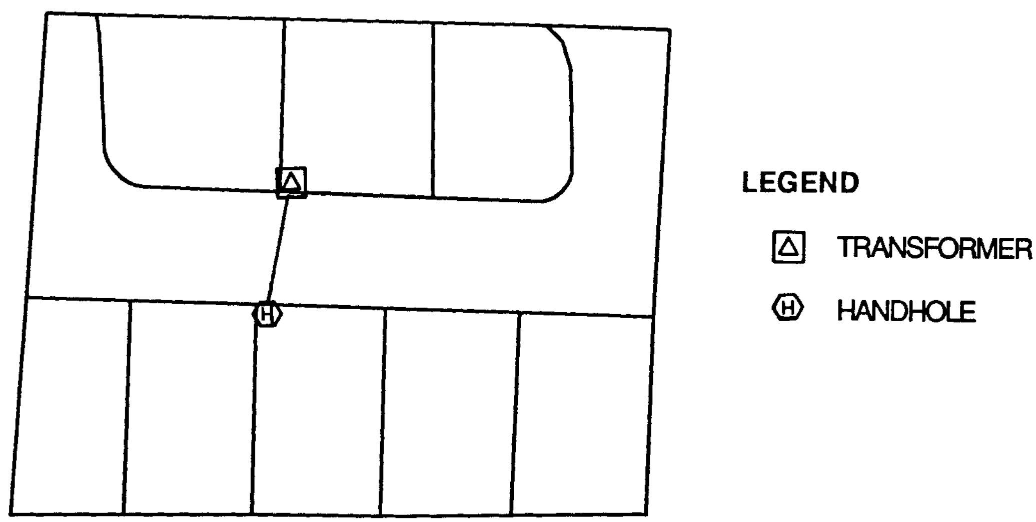

Figure 19. Handhole Placement: Two Sides of the Street

In the case that more than two "Sides of the Street" are present in one cluster, each additional handhole is placed on the site that is nearest to the load "center of gravity" for the lots that are on the same "Side of the Street". This case is given on Figure 20 where one handhole is placed on the opposite side of the crossing that originate from the transformer site, and other handhole is placed at the "center of gravity" for the lots which are on that "Side of the Street."

The handhole site is defined as the value H in the attribute Status of the point attribute table of the SITE coverage (SITE.PAT Table 3.) for the particular site.

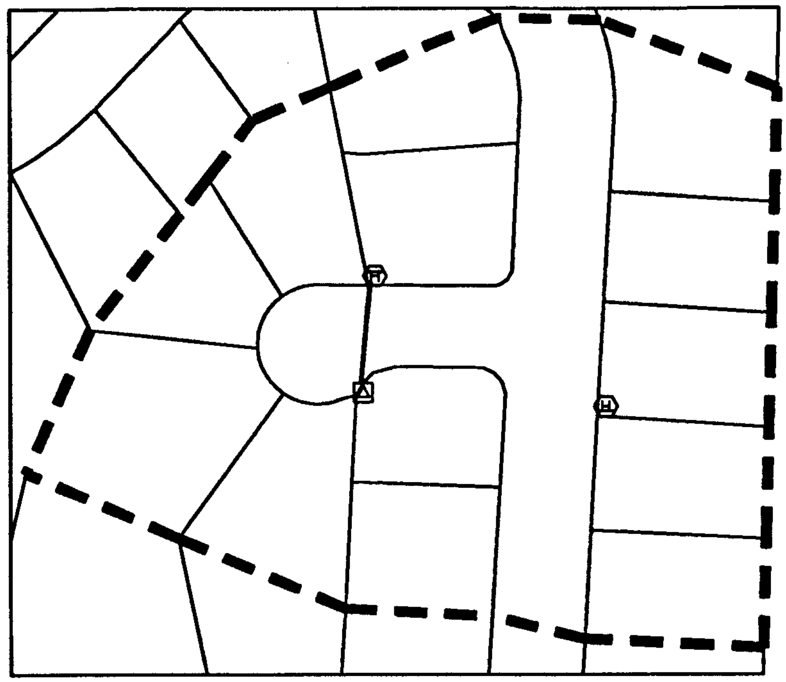

Figure 20. Handhole Placement: More Than Two Sides of the Street

The transformer and handholes placement sites provided by the Transformer Placer are presented to the designer for his/her approval prior to continuing the AEPD process. This point in the design is also a good control point for posting a request for various design options. Moving the transformer and/or handholes inside the cluster produces different designs for the given clustering of the plat. With this capability, the AEPD offers a way to explore a cost differential for different placement of connecting devices inside the cluster.

When the designer approves or rearranges the results obtained by the Transformer Placer, the set of spatial relation among the newly introduced objects (transformer, handholes) and previous plat elements contained in the coverage data model, must be established.

The spatial relations obtained with the Transformer Placer enable object oriented structuring of the plat representation, required for the subsequent rule based processing.

7.3 Establishing Spatial Relation Inside the Cluster

With transformer and handholes placement, all segments of the AEPD prerequisite for the rule based secondary design are done. In order to prepare the results in the form that is usable for Secondary Runs Designer KS, plat data spread out in the form of several GIS coverage feature attribute tables must be restructured in cluster oriented data representation. For that structuring, a relational DBMS acting as a Blackboard is used to provide a cluster based "view" of the plat data.

Before forming a cluster based view of the plat data for each cluster, the relation between the transformer and lots that are inside that cluster must be established. Similar relations must be established between each handhole and lots that are on the same "Side of the Street." For that purpose the attribute that define on which "Side of the Street" the lot is situated, and the attribute that define the lot position in regard to the connecting device on that "Side of the Street", are added to the LOT.PAT. Automated extraction of the values for these attributes is based on a spatial procedure that utilizes a lot's boundary contiguity concept. This procedure is similar to the one that is used for the basic topological attribute extraction done with the Plat Preprocessor.

Besides defining relational attributes between the lots and connecting devices, for the cluster data model representation, only those elements from the GIS coverages that are associated with a particular cluster must be identified. For example, a crossing that exists among the placement sites in different clusters is not assigned to any of them because it cannot be used for the secondary routing purpose. These elements of the CROSSING coverage must be eliminated from the set of the data used for secondary routing. However, those crossings can be utilized later for the primary routing.

With that spatial attribute creation and assignment of proper elements to each cluster for the purpose of cluster data structuring, the role of the Transformer Placer is exhausted, and all necessary data are available for the next Knowledge Source. Thus Secondary Runs Designer may take over the AEPD process.

Chapter 8

SECONDARY RUNS DESIGNER

The secondary runs routing and sizing part of the AEPD is done by the Secondary Runs Designer knowledge source. This knowledge source is implemented in a rule based programing paradigm, and it gives results based on mimicking the problem solving reasoning of an expert designer in this narrow domain. For this purpose information acquired during the knowledge acquisition process is embedded in a commercially available expert system shell.

The first task of this knowledge source is to find the optimal routes for the secondary runs within each cluster using a defined network of the allowable corridors, street crossings and transformer/handhole placement sites. After this task is done, based on the length of the particular secondary run and the anticipated size of the load that has to be served by it, a proper size for the each conductor is determined. In addition, the Secondary Runs Designer is used to size the transformer according to the number of lots that are served, and their anticipated load size.

8.1 Knowledge Processing

When using expert systems, the reasoning of an expert is modelled with the formalism of rules and an appropriate inferencing mechanism used to draw a valid conclusion. The rules represent the reasoning on the representation of the problem. For the computational model of problem solving it is required to have a representation of the world in relation to the reasoning. This means that information about "things" must not only be available but also must be formalized so that it can be efficiently used during a problem solving activity. During this process, an expert system focuses its attention on the point that represents an intersection of the two planes, the reasoning and the representation plane that form a cognitive space.

As discused in Chapter 2, the process of the secondary runs design is functionally divided into two parts, one concerning routing and another concerning sizing. The first part concerning routing within the plat, involves spatial reasoning [112,113,114], and cannot be performed without having sufficient information about the "real world" where the actual routing must be performed. To decide the secondary cable routing, a comprehensive set of information on the spatial arrangements of the lots in the cluster, the lot's relation with regard to a connecting device (a transformer or a handhole), the existing and available trenching corridors and street crossings, and other pertinent information are required. Besides their availability, this information must be structured in an appropriate way so that it can be efficiently used during the knowledge processing.

The second part of the secondary design includes sizing that does not require such extensive "real world" description. In fact, for selecting a "proper" conductor size, the designer needs to know only its length and the load served. Similarly for "proper" sizing of the transformer only the number of lots in the cluster and the size of their load must be known.

In the AEPD, starting from the basic data provided by the designer, the data that are required for the problem representation are created and provided by the Plat Preprocessor and Transformer Placer. These two GIS modules are sources of necessary information for solving the secondary runs routing and sizing problem. The difficulty with these data is that they are structured as a coverage data model, which is intrinsic for GIS environment but is not an appropriate way for structuring data for the rule based reasoning [114,115,116,117]. Thus GIS data must be restructured in the object oriented data form that is inherently efficient for the rule based reasoning.

8.1.1 Object Oriented Real World Representation

The overall plat spatial configuration from the point of view of an electrical plat design can be hierarchically decomposed into several levels as presented in Figure 21. The plat can be decomposed into several clusters each of which has several "Sides of the Street", which in turn consists of several lots. The lots are the basic constituents of the plat structure representation for the AEPD purpose. As such they are a natural choice for objects in an object oriented "real world" abstraction [116,117] required for knowledge processing within the expert system shell. All information needed by the Secondary Runs Designer, is encapsulated in the LOT objects as their properties. The object oriented data model for the Secondary Designer knowledge source is conceptually similar to the data model used for Secondary Router prototype (Appendix C). The Secondary Router prototype is initially developed to check the feasibility for the AI approach and for the identification of the necessary topological features that are needed for the spatial reasoning. In the Secondary Router prototype data model, a cluster is represented as a LISP list of atoms, each of which represents a lot. The data concerning a particular lot are stored in the atoms' property list. The objects in the data model used for the AEPD Secondary Runs Designer correspond to the atoms used in the data model of the Secondary Router prototype implemented in LISP programing language.

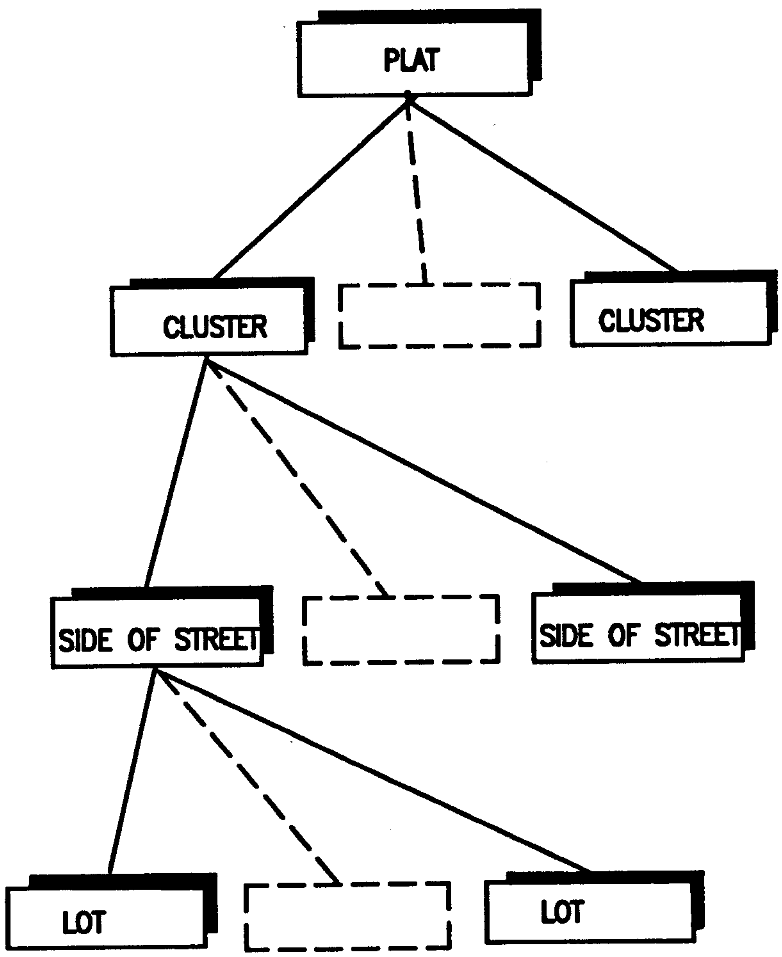

Figure 21. Hierarchical Decomposition of the Plat Spatial Structure

During the secondary design the human expert keeps his/her focus of attention on only one cluster at a time. In the same manner the Secondary Runs Designer knowledge source operates only on the set of lots that are members of one cluster at a time. For the problem under consideration, it suffices if the data that define relation among the elements in one cluster are available. The anatomy of the structured symbolic description called object LOT is given in Table 6. Thus, lots are the only objects that are present in the data model used by Secondary Runs Designer.

The overall cluster representation is given using the class of lots whose instance LOT has all required data stored as object's properties. In addition, the results of the Secondary Runs Designer are also stored in the form of the LOT object properties given in Table 6. The names of the properties that are created by the Secondary Runs Designer are printed in bold italics to distinguish them from the properties whose values are entered by the user (plain text) or provided by either the Plat Preprocessor (italics) or the Transformer Placer (underline).

8.1.2 Inference Control Mechanism

The rules used for the Secondary Runs Designer have a symmetric form. That means that for the knowledge processing depending on the inference procedure that is taking place, the same rule may be used for both a backward chaining or a forward chaining. This particular ability is based on augmented rule format. In this case besides the Left Hand Side (LHS) and Right Hand Side (RHS), which represents a standard condition-action form of rules that are usually found in production systems, the rules in an augmented format have in addition an Hypothesis part as described below:

IF (condition) **THEN**(hypothesis) **AND DO** (actions)

Table 6. Anatomy of the Object LOT

Name: LOT
Class: LOTS
Subobjects: None
Properties:

NAME	TYPE	DESCRIPTION
LID	INT	lot id number
SOT	CHARACTER STRING	lot position in regard to connecting device
SOS	CHARACTER STRING	lot side of the street (same, opposite) in regard to transformer
LNLID	INT	id of the left neighbor lot
RNLID	INT	id of the right neighbor lot
LOAD	FLOAT	anticipated lot's load in kW
CONN	CHARACTER STRING	status of lot's connection
CONL	FLOAT	conductor length in feet
CONS	CHARACTER STRING	conductor size in kcmil or AWG
SLC	CHARACTER STRING	status of the left corner
SRC	CHARACTER STRING	status of the right corner
SCOR	CHARACTER STRING	status of the corridor in this lot
CORL	FLOAT	corridor length in feet
NCON	INT	number of conductors in corridor
SCRL	CHARACTER STRING	status of the left crossing (lc)
CRIDL	INT	id of lot on the opposite side of lc
CRLL	FLOAT	left crossing length in feet
NCRL	INT	number of conductors in lc
SCRR	CHARACTER STRING	status of the right crossing (rc)
CRIDR	INT	id of lot on the opposite side of rc
CRLR	FLOAT	right crossing length in feet
NCRR	INT	number of conductors in rc

The hypothesis of this rule is a pseudo Boolean property assigned to that rule. The value of that property can be TRUE or FALSE, but also UNKNOWN and NOTKNOWN depending on the result of the rule evaluation. The rule evaluation consists of checking the value of the LHS conditions. If all the conditions are found to be satisfied the hypothesis is TRUE, if not the value of the hypothesis is FALSE. If the value of at least one of the conditions on the left side is not known at the time of a rule evaluation, the hypothesis value is NOTKNOWN. Finally the rule hypothesis value is UNKNOWN if that rule is not yet being evaluated.

The rule evaluation, while trying to find the status of the conditions on the LHS of the rule, leads to backward chaining as the default mode of the knowledge processing. In addition, the rule that has to be evaluated next can be determined in the forward chaining mode by the RHS action, or by the gates or context mechanism. The primary purpose of the gate mechanism is to expand the search intelligently. The gates are generated during the evaluation of the LHS of the rules, and contain all rules that share the same condition in the LHS. The rules that are linked at the runtime by the backward chaining, forward chaining or the gates mechanism, form the so called knowledge island. All links that connect the rules in one knowledge island, are called strong links. On the other hand, a context as a rule scheduling mechanism is defined by the knowledge engineer to link different knowledge islands that will not be automatically linked during the runtime. Thus the context is a weak link between the knowledge islands. To enable conflict resolution among the rules that are scheduled for evaluation, a rule priority can be assigned to each rule as a rule argument. Those priorities can be static or can be dynamically modified during the run time.

Contrary to the conventional programming where the order of the processing is determined by a stack status in a last-in first-out (LIFO) mode, the status of the stack in the expert system shell is dynamically modified according to the "conclusion" that is reached in the particular moment of knowledge processing.

That mechanisms of rules scheduling allow the implementation of a complex inferencing control procedure.

8.2 Expert System Database Bridge Issues

The places where the data required for the rule based processing physically reside in the AEPD are GIS database table of coverages that are used or created by the Plat Preprocessor or the Transformer Placer. Those data represent the facts that are input values for the rule based reasoning process.

Knowledge represented by rules describing the reasoning process and the set of objects that represent the world upon which the reasoning takes places is stored into several files, called knowledge base, in the expert system shell. Thus knowledge and facts are kept separately in the knowledge base and the external database respectively. During the runtime facts from the database must be mapped into the objects' properties, and result of the reasoning must be written back to the database. To enable this process a bridge that would allow a two way communication between the GIS database and the expert system shell must exist.

In the AEPD tool presented in Figure 6, the link is established via the bridge between the expert system and the relational DBMS that is used as a Blackboard medium. An additional bridge that exists between the GIS and RDBMS is used to post the data from the GIS on the Blackboard in the form of relational DBMS "view."

Instead of direct communication between the expert system and GIS database, the communication is established through the RDBMS Blackboard where the GIS data are structured to enable automatic record mapping into the object properties. The expert system/RDBMS [102] and RDBMS/GIS database [115] communication is a problem per se, and it is an AEPD area that requires further study.

The bridge required between the RDBMS and the GIS, that are used as AEPD software environments, is not released as yet. For this reason, the AEPD prototype does not allow automatic communication between the GIS and expert system via the RDBMS bridge. Thus for the prototyping purpose, the facts stored in the GIS database are manually transported to the database file in a flat file form. These data are then accessed directly by the expert system. The structure of the database file where facts used during the expert system reasoning reside and the expert system database file transactions are described in the following subsection.

8.2.1 Expert System Database File Transactions

The database file used for the facts storage in the AEPD prototype is basically an external file rather than a standard database, because data are accessed directly by the expert system instead of being accessed through a real database management system. Nonetheless, SQL-like queries are provided by the expert system for the database file/expert system transactions. When a RDBMS is adopted in place of the database file at a later date, no changes will be required for the expert system part of the prototype.

The database file is an ASCII "flat file," allowing easy manual data editing. This file has a tabular form consisting of records, with each record containing several fields. A record represents a logical unit of information and a field represents an attribute of the record. A particular datum in the database file is called a cell. The mapping between the database file table structure organization and the expert system object structure organization is done in a such way that database records are associated with objects, database fields are associated with an object's properties and a cell represents a value of specific property for the particular object called "Object .slot."

The structure of the AEPD prototype database file is defined by the object oriented "real world" abstraction for the expert system Secondary Runs Designer. The database file, as shown in Table 7, represents a cluster of the lots, with each record representing a particular lot and each field representing attribute with values provided either by the user, Plat Preprocessor, or the Transformer Placer. The values for some fields are created or updated during the knowledge processing by the expert system. The database file presented in Table 7 contains facts about one cluster with ten lots used for prototype testing. Comparison of this table with Table 6 shows that there is a one to one correspondence between the properties of the object LOT and fields in the database file.

During the inference process the facts from the database file can be retrieved or updated in a three different ways, as:

- group transaction,
- sequential transaction, or
- atomic transaction

A group transaction is a default strategy for interaction between the expert system and the database file. It represents the so called "loose coupling" [102] between

Table 7. Database File Example

LID	SOT	SOS	LNLID	RNLID	LOAD	CONN	CONL	CONS	SLC	SRC	SCOR	CORL	NCON	SCRL	CRIDL	CRLL	NCRL	SCRR	CRIDR	CRLR	NCRR
1	LEFT	OPP	0	2	0.0	YES	0.0		NOT	NOT	FREE	50.0	0	FREE	6	30.0	0	FREE	6	30.0	0
2	LEFT	OPP	1	3	0.0	YES	0.0		NOT	NOT	FREE	55.0	0	FREE	7	30.0	0	FREE	7	30.0	0
3	RIGHT	OPP	2	4	0.0	YES	0.0		HHOLE	NOT	FREE	45.0	0	FREE	8	30.0	0	FREE	8	30.0	0
4	RIGHT	OPP	3	5	0.0	YES	0.0		NOT	NOT	FREE	50.0	0	FREE	9	30.0	0	FREE	9	30.0	0
5	RIGHT	OPP	4	0	0.0	YES	0.0		NOT	NOT	FREE	60.0	0	FREE	10	30.0	0	FREE	10	30.0	0
6	LEFT	SAM	5	7	0.0	YES	0.0		NOT	NOT	FREE	50.0	0	FREE	1	30.0	0	FREE	1	30.0	0
7	LEFT	SAM	6	8	0.0	YES	0.0		NOT	NOT	FREE	55.0	0	FREE	2	30.0	0	FREE	2	30.0	0
8	RIGHT	SAM	7	9	0.0	YES	0.0		XFRM	NOT	FREE	45.0	0	FREE	3	30.0	0	FREE	3	30.0	0
9	RIGHT	SAM	8	10	0.0	YES	0.0		NOT	NOT	FREE	50.0	0	FREE	4	30.0	0	FREE	4	30.0	0
10	RIGHT	SAM	9	0	0.0	YES	0.0		NOT	NOT	FREE	60.0	0	FREE	5	30.0	0	FREE	5	30.0	0

the two. In this mode all records from the table (or all records selected by the query statement) are processed in one retrieve statement. In this case for each record from the table a dynamic object in the expert system working memory is created, and value of the field is assigned to the property slot of the dynamic object. The rules that are usually used with group transaction are based on pattern matching. The data are usually retrieved at the beginning of the session and written back at the end in this mode. Communication overhead is modest, but pattern matching rules that must be employed are less efficient than the simple rules that can be used with other modes of communication. In addition, a memory must be allocated for the dynamic objects in expert system working memory. Because of the way the knowledge is processed, the group transactions are not used by the Secondary Runs Designer.

A sequential transaction is an appropriate way of interfacing expert system and the database for inferencing that requires each record to be processed independently. Instead of retrieving all or a group of records, in a sequential transaction records are retrieved one by one. The values of the record fields are mapped to an existing object, and processed by the set of rules that usually do not require pattern matching. At the end of the processing, the result is written back to the database in a sequential mode to update the record which is being processed. The sequential transaction represents a "more tight" coupling with the database and demands more communication overhead. The design and global control of the application is more complex and it requires rules looping and resetting the working memory before any new record is retrieved. The advantage of this method is that simple rules without pattern matching are used which makes an inferencing procedure more efficient. In the Secondary Runs Designer, because of the way the lots are processed, the sequential transaction mode is preferred.

In an atomic transaction, only one record is selected by the query, and the datum from the particular cell can be retrieved and assigned to the value of "Object.slot," or the cell can be update by the "Object.slot" value. Atomic queries do not influence the overall design of the application, but do require the selective query criteria. Atomic transactions are also used by the Secondary Runs Designer.

8.3 Route Determination and Sizing Procedure

The procedure for finding the route for the secondary connection of the particular lot is based on the principle that each lot should be connected to the connecting device that is on its "Side of the Street." If there is no available path between the lot and the connecting device on the same "Side of the Street," a route must cross on the opposite "Side of the Street" utilizing available crossing and then proceed to find a way to the proper connecting device. Besides, during the routing process a set of rules must be used to satisfy standard practices employed by designers. If a suitable route cannot be found or a technical requirement cannot be met, the designer is prompted for his/her action or suggestion.

This simple principle of lot's connection finding is valid for each lot in the cluster so that the same set of the rules can be used for every lot. Lots are processed one by one, and facts required for the processing are retrieved from the database file with sequential transaction. During the connecting procedure, starting from the lot that has to be connected, whenever a route uses a particular corridor or street crossing, the number of conductors in that segment is increased by one. This number is then updated in the database file with an atomic write. At the end of the lot's processing the final result in the form of secondary conductor length and a flag showing that this lot is connected successfully, is sequentially written into the database file. In the looping mode facts for the new lot are retrieved again sequentially, and after resetting some rules the process continues until all lots in the cluster are connected.

The result of the secondary routing is presented in the database file as a length of the conductor for each lot, the number of conductors that are using a utility easement (corridor) that lay in a particular lot area, and the number of conductors that use crossings that originate in a particular lot.

After the length of a conductor for each lot is found, it is used with the anticipated load size to determine secondary conductor size. For the transformer sizing the total anticipated load on the cluster is used.

The knowledge base used in AEPD prototype Secondary Runs Designer consists of the two knowledge bases kept in two separate files:

- a larger one containing rules for routing and information about the structure of objects, and
- a smaller one containing rules for secondary conductors and transformer sizing.

The routing knowledge base contains fifty rules. It is not complete as yet, so the Secondary Runs Designer can successfully handle clusters with fairly simple spatial structure. The expansion of the rule base will enable handling more complicated clusters including the "deep" cul-de-sacs and the multiple intersections.

The sizing knowledge base has sixteen rules and provides a proper size for the secondary conductors and the cluster's transformer based on an anticipated lot's load size and obtained conductor length. If no information about load size is present in the database field "Load," a default value based on the designers' practice is provided by the expert system.

The results of the Secondary Runs Designer in the tabular database form (Tables 9 and 10) and their graphical interpretation (Figure 32 and 33) will be discussed later in Chapter 9.

Chapter 9

AEPD FEASIBILITY EVALUATION

To prove the feasibility of the automated electrical plat design concept and to evaluate performance of each knowledge source, the AEPD prototype is tested on an actual residential plat. The test plat is taken from the maps representing the City of Bellevue municipal area. These maps are provided to Puget Sound Power and Light Company (PSPL) by the City of Bellevue WA, and are used by Facility Management System project for the pilot map conversion.

In this chapter, the description of the test plat and the results based on the application of the Plat Preprocessor, the Transformer Placer and the Secondary Runs Designer knowledge sources are presented. For the sake of comparison a electrical plat design obtained manually by an independent human designer is also given. At the end a simplified economic evaluation of the three different solutions for the secondary system is given. These are obtained using variation of one from the number of possible AEPD control variables, namely the cluster size.

9.1 Test Plat

The plat used for testing the AEPD prototype is presented in Figure 22. As it can be seen from Figure 22, the plat contains four street entrances and two cul-de-sacs. This type of plat layout with multiple street entrance and multiple cul-de-sacs is particularly complicated and according to PSPL designers it is a challenging one for the underground residential electrical supply system design.

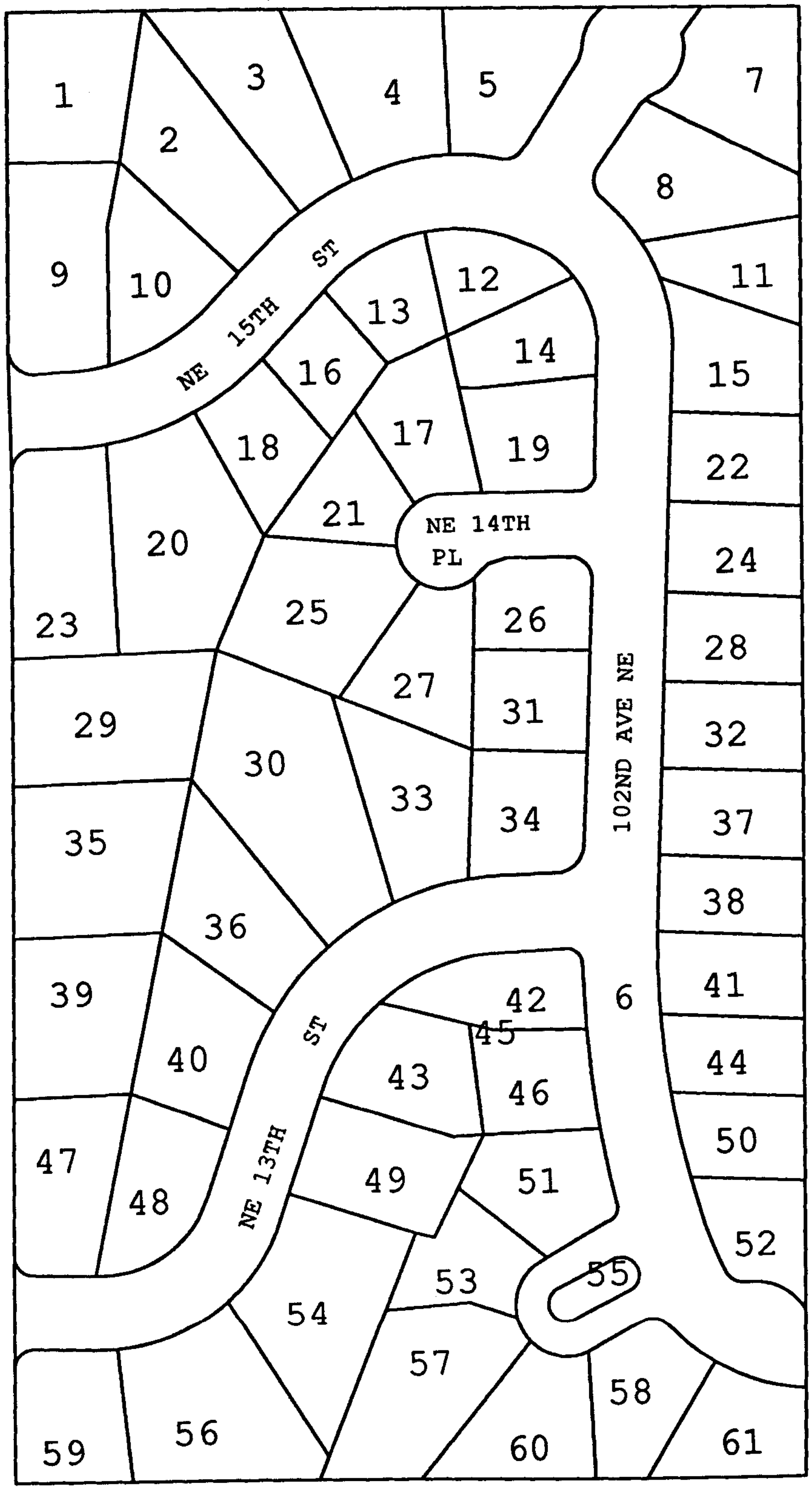

Figure 22. Test Plat

The test plat consists of fifty-seven polygons representing parcels and one polygon representing the street. According to the standard practice that secondary runs should utilize the lot frontage easement, only the lot polygons that have a lot frontage inside the plat (fifty three in this case) are considered for the electrical plat design. The database part of the GIS polygon coverage that represents a test plat is originally supplied with some additional thematic data such as parcel id numbers, parcel owner and so on. Because the AEPD does not require any thematic data in addition to the basic topological attributes for the start of processing, the redundant thematic data are ignored. The initial structure of the LOT coverage polygon attribute table required for the start of AEPD is the same as the one that is given in Table 1.

In order to facilitate the GIS preprocessing, before the start of the Plat Preprocessor, the attributes that define a street polygon and cul-de-sacs are manually entered in the database part of the LOT coverage.

9.2 Plat Preprocessor

Figure 23 shows the results of the first segment of the plat preprocessing, the basic attribute extraction. After the cul-de-sacs "opening," the Plat Preprocessor identifies six "Sides of the Street" present on the plat. Those lots that are members of the same "Side of the Street" are presented in Figure 23 shaded with the same pattern.

The second segment of the plat preprocessing is presented in Figures 24, 25 and 26. Figure 24 shows the sites that are available for the placement of transformers and handholes, which are generated by the Plat Preprocessor. Those sites are indicated as black points in the lots' street corners. Figure 25 contains the possible routing corridors within the centerline of the utility easement that are identified by the Plat

Preprocessor. In this figure corridors are identified as a thick lines that run parallel with the street curbs. Figure 26 shows the possible street crossings that must be used if runs should cross the street. These are also presented as thick lines. Finally, Figure 27 combines all these coverages created by the Plat Preprocessor in one coverage that shows the network of possible sites, corridors and crossings that can be used for the equipment placement, secondary, and primary routing.

Using the "join" command of the GIS database, attributes (items) that are created by the Plat Preprocessor are given in Table 8. The meaning of these attributes, the same ones as the ones printed bold in the LOT.PAT (Table 2), is given earlier in chapter 6. These attributes are prerequisite data for future automated processing of the subsequent knowledge sources.

9.3 Manual Electrical Plat Design for the Test Plat

In the preprocessing part of the AEPD a GIS acts as "plat describer" for the "blindfolded" designer. The preprocessing part is intrinsic to the AEPD concept and it is not present in the manual design where a "real world description" comes naturally by means of visual perception. Thus Plat Preprocessor does not have a counterpart in the manual design with which it can be compared. The quality of the Plat Preprocessor is embodied in the quality of the overall plat design and this is the only way that Plat Preprocessor performance can be measured. On the other hand the results of the individual knowledge sources can be compared with the results of their counterpart's segments in the manual design. The comparison of these two results gives a good insight into the quality of AEPD prototype.

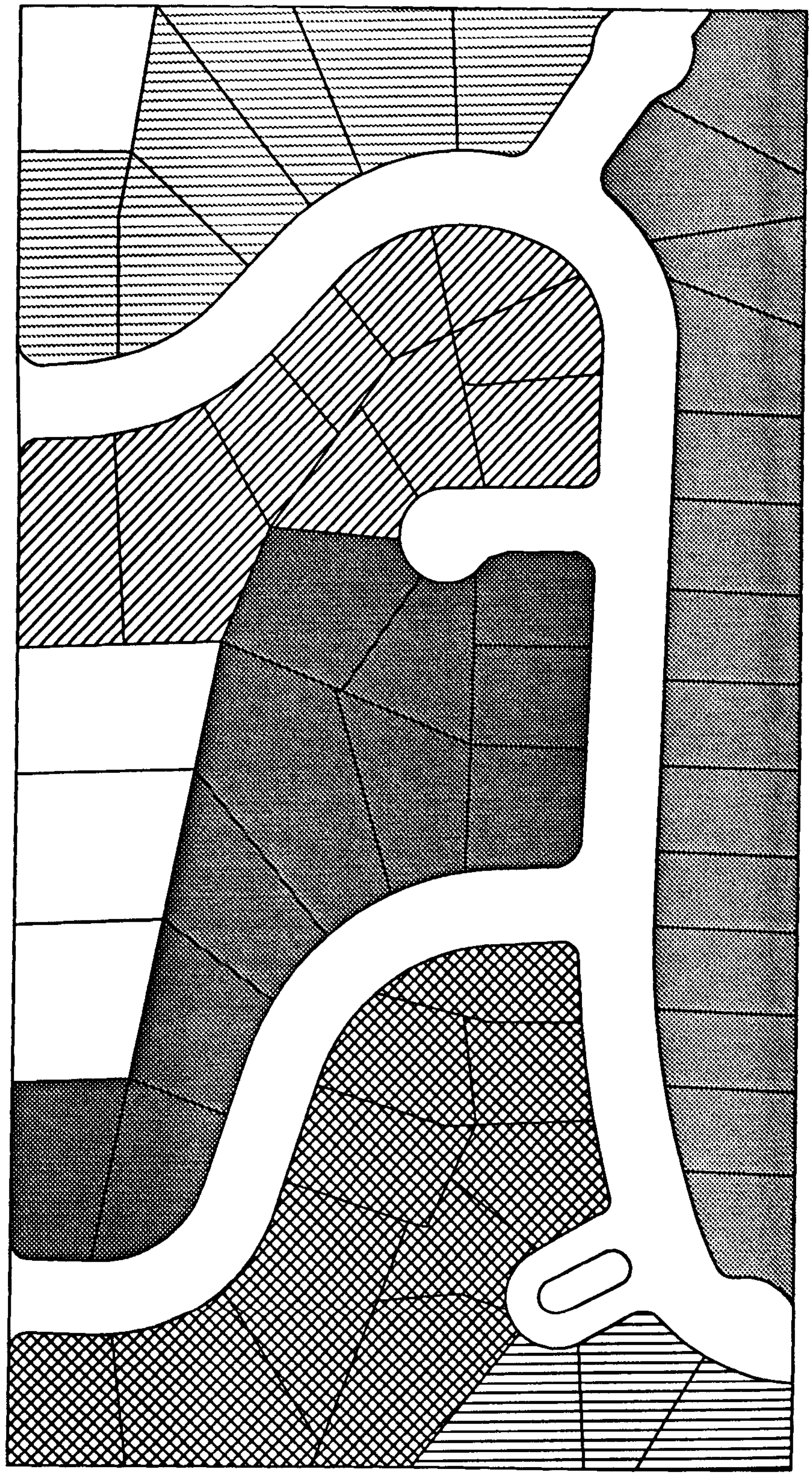

Figure 23. Plat Preprocessor: Side of the Street

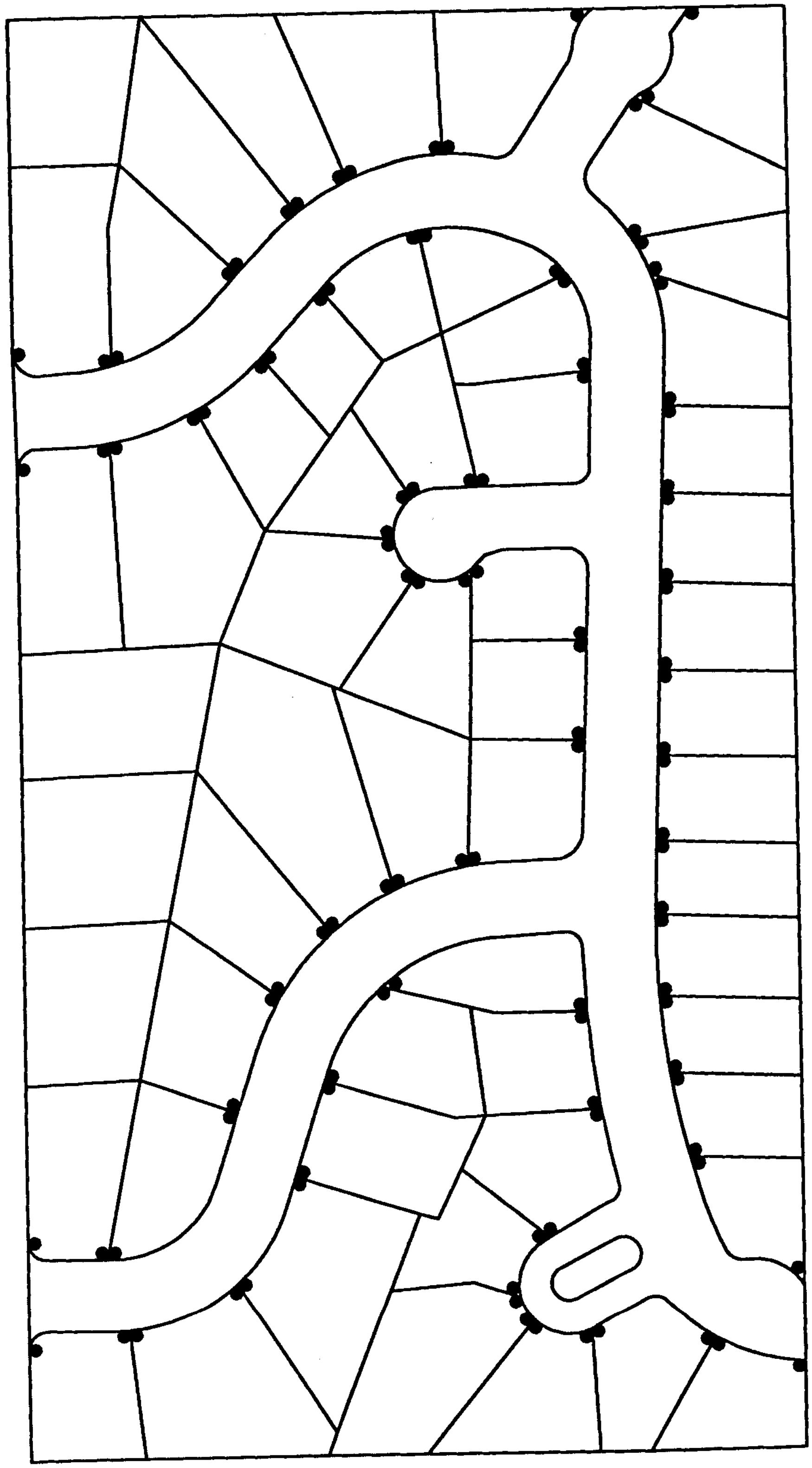

Figure 24. Plat Preprocessor: Placement Sites

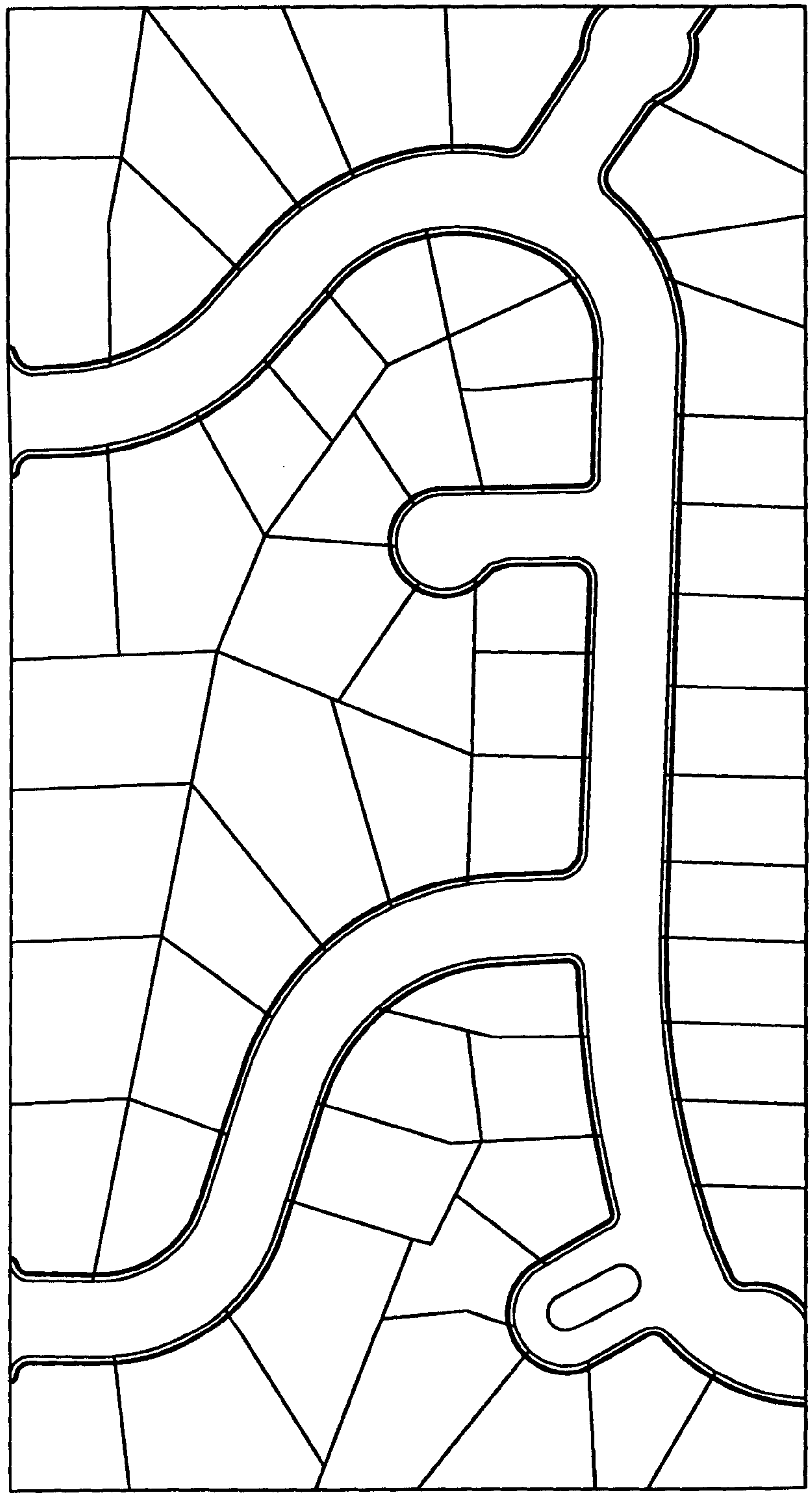

Figure 25. Plat Preprocessor: Routing Corridors

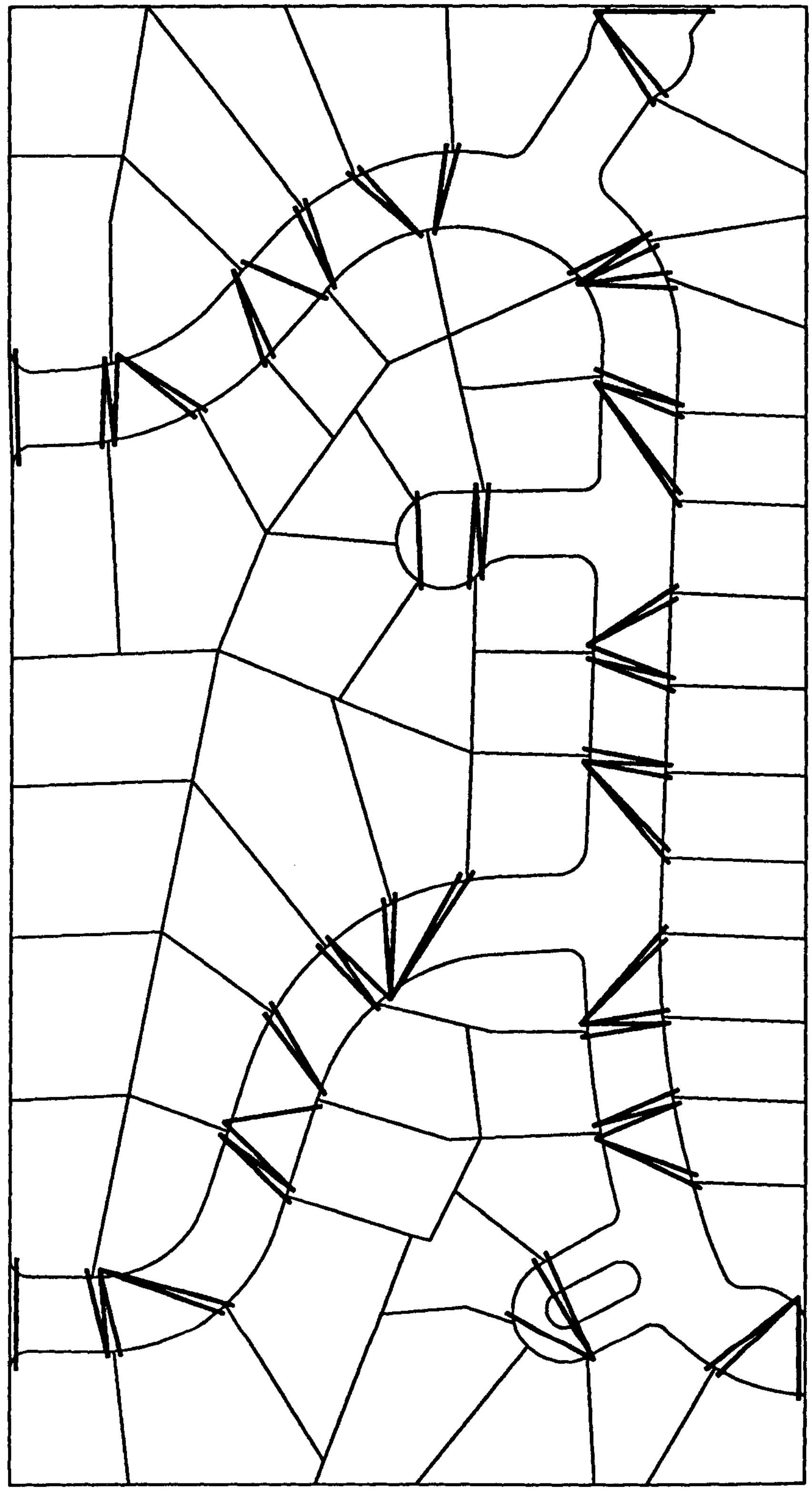

Figure 26. Plat Preprocessor: Street Crossings

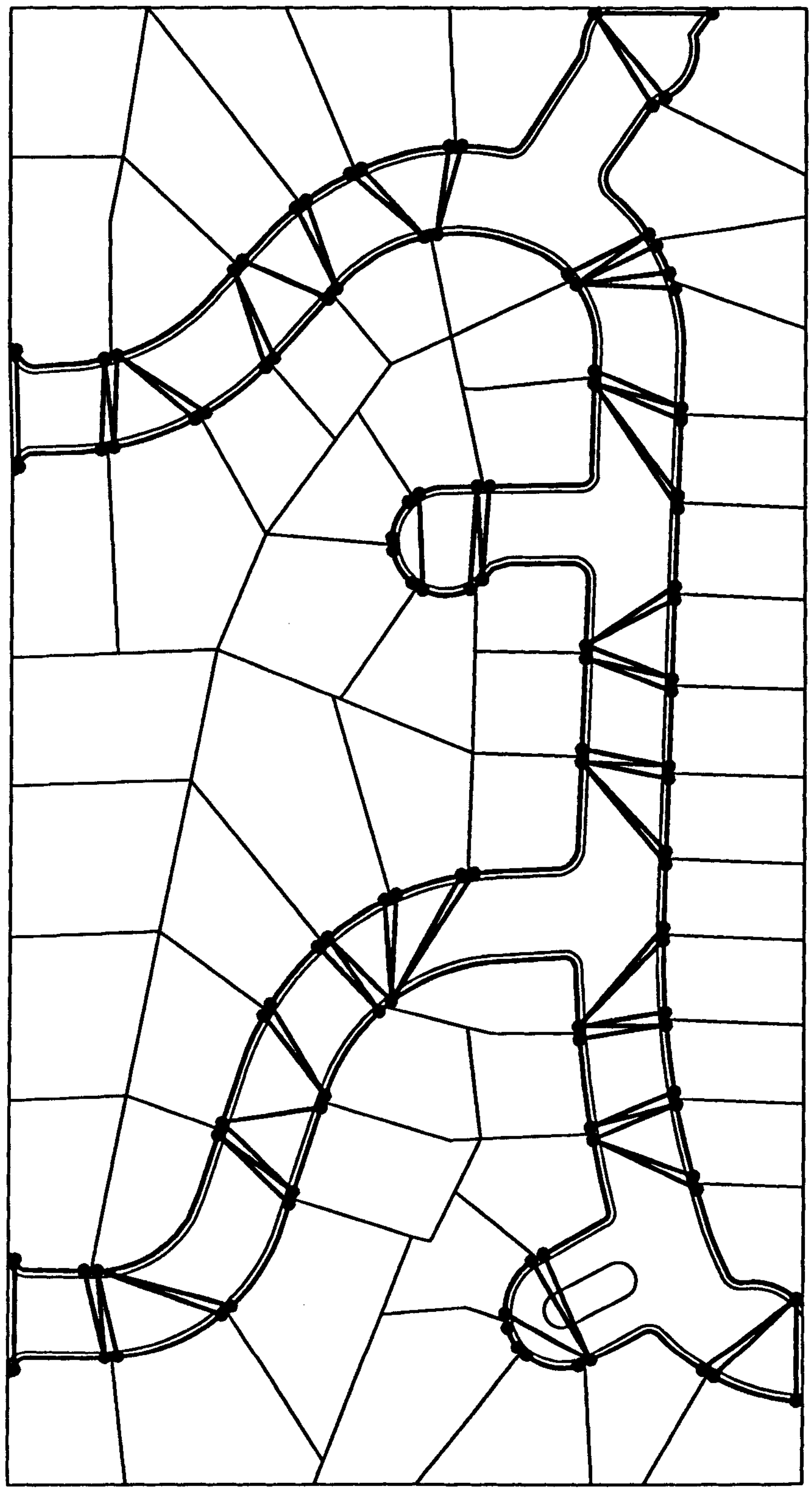

Figure 27. Plat Preprocessor: Network of the Sites, Corridors, and Crossings

Table 8. LOT.PAT Attributes Determined by Plat Preprocessor

POLY#	STREET	SIDESTR	CORRIDOR-ID	LNEIGH	RNEIGH	LCORRNER	RCORNER
3	N	1	3	4	2	8	9
4	N	1	4	5	3	6	7
5	N	1	5	0	4	1	5
12	N	2	12	13	14	11	17
13	N	2	13	16	12	19	12
15	N	4	15	22	11	32	21
16	N	2	16	18	13	26	22
18	N	2	18	20	16	30	27
20	N	2	20	23	18	34	31
21	N	2	21	17	25	40	43
22	N	4	22	24	15	41	33
23	N	2	23	0	20	36	35
24	N	4	24	28	22	49	42
25	N	3	25	21	27	44	46
26	N	3	26	27	31	45	51
27	N	3	27	25	26	47	48
28	N	4	28	32	24	53	50
29	N	0	0	0	0	0	0
30	N	3	30	33	36	64	66
31	N	3	31	26	34	52	55
32	N	4	32	37	28	57	54
33	N	3	33	34	30	62	63
34	N	3	34	31	33	56	61
35	N	0	0	0	0	0	0
36	N	3	36	30	40	67	70
37	N	4	37	38	32	59	58
38	N	4	38	41	37	65	60
41	N	4	41	44	38	73	68
42	N	5	42	43	46	69	74
44	N	4	44	50	41	78	75
53	N	5	53	51	57	92	97
54	N	5	54	56	49	94	88
55	N	0	0	0	0	0	0
57	N	5	57	53	60	98	99
58	N	6	58	60	61	104	106
60	N	6	60	57	58	102	105
61	N	6	61	58	0	107	108
1	N	0	0	0	0	0	0
2	N	1	2	3	10	10	15
6	Y	0	0	0	0	0	0
7	N	4	7	8	0	3	2
8	N	4	8	11	7	13	4
9	N	1	9	10	0	25	23
10	N	1	10	2	9	16	24
11	N	4	11	15	8	18	14
14	N	2	14	12	19	20	28
17	N	2	17	19	21	37	39
19	N	2	19	14	17	29	38
39	N	0	0	0	0	0	0
40	N	3	40	36	48	72	81
43	N	5	43	49	42	77	71
45	N	0	0	0	0	0	0
46	N	5	46	42	51	76	83
47	N	3	47	48	0	91	89
48	N	3	48	40	47	82	93
49	N	5	49	54	43	86	79
50	N	4	50	52	44	85	80
51	N	5	51	46	53	84	90
52	N	4	52	0	50	95	87
56	N	5	56	59	54	100	96
59	N	5	59	0	56	103	101

To run a simplified Turing test for the AEPD prototype knowledge sources, a human designer is asked to provide clustering and design of the secondary runs for the test plat. The manual design sketch as obtained by the human designer is shown in Figure 28. This design is used for comparison with the results of the AEPD knowledge sources.

9.4 Transformer Placer

The results of the automated lots clustering, a crucial part of the AEPD, are presented in Figures 29 and 30 for the two different clustering methods.

Figure 29 contains the results obtained with method a) that selects the next lot to be added to the cluster based on the shortest path between the placement sites, utilizing the existing network of corridors and crossings. Figure 30 presents the clustering results obtained with method b) where the next lot to be added to the cluster is determined based on "crow fly" distance between the lots label points. Both these methods use the same lots for the origins. These lots from where the cluster growth starts are identified at cul-de-sacs and plat street entrance. In addition, both methods use a fixed reference point approach so that similarity between the results can be attributed to that fact.

Though the test sample is not large enough to draw a significant conclusion about the order of preference between these two methods, the comparison of the clustering results for this test plat shows that method a) gives somewhat better result that later need less rearrangement by the user. However the results obtained with both of these methods are acceptable and with minor corrections agree with the manual clustering scheme given in Figure 28.

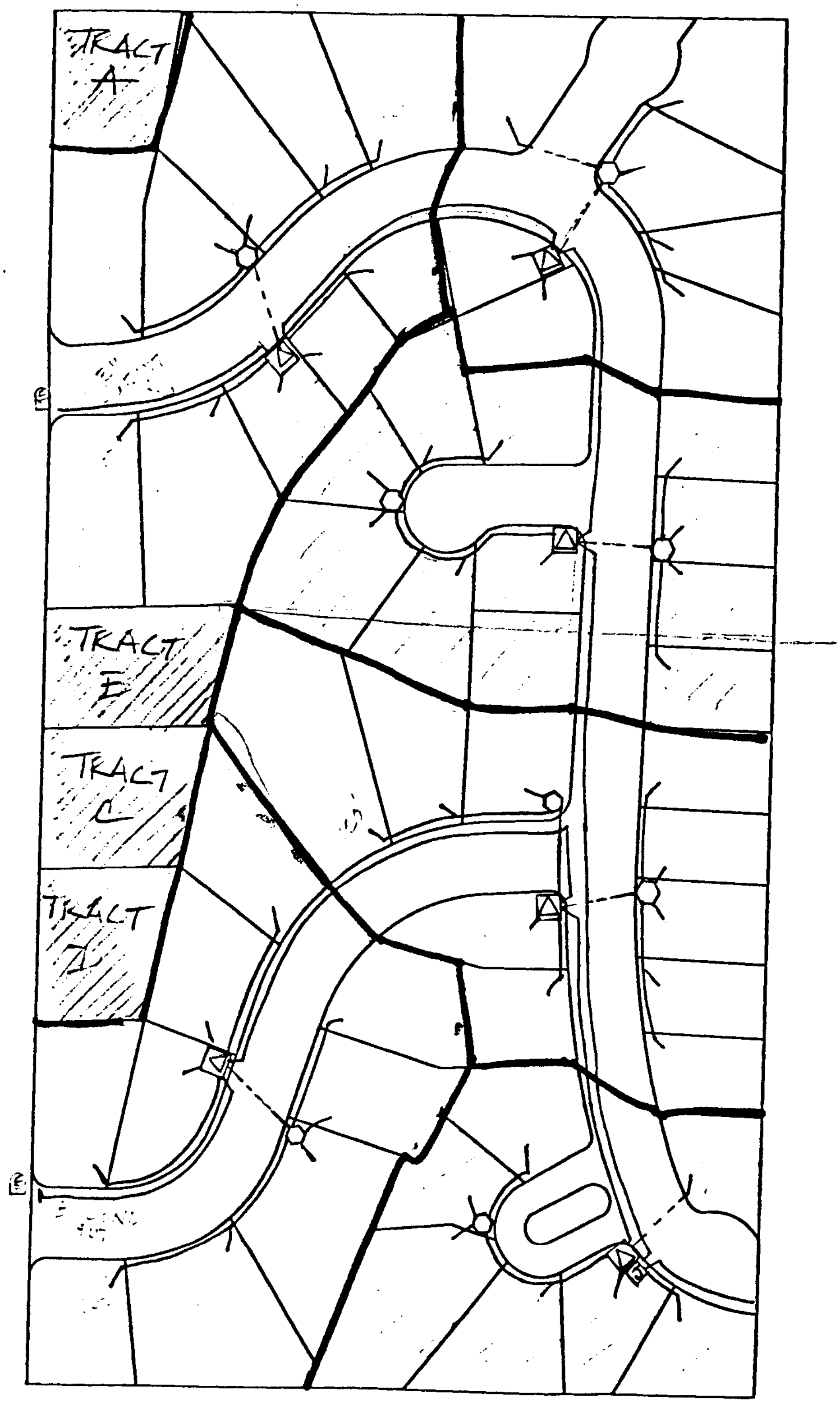

Figure 28. Transformer Placer: Manual Design

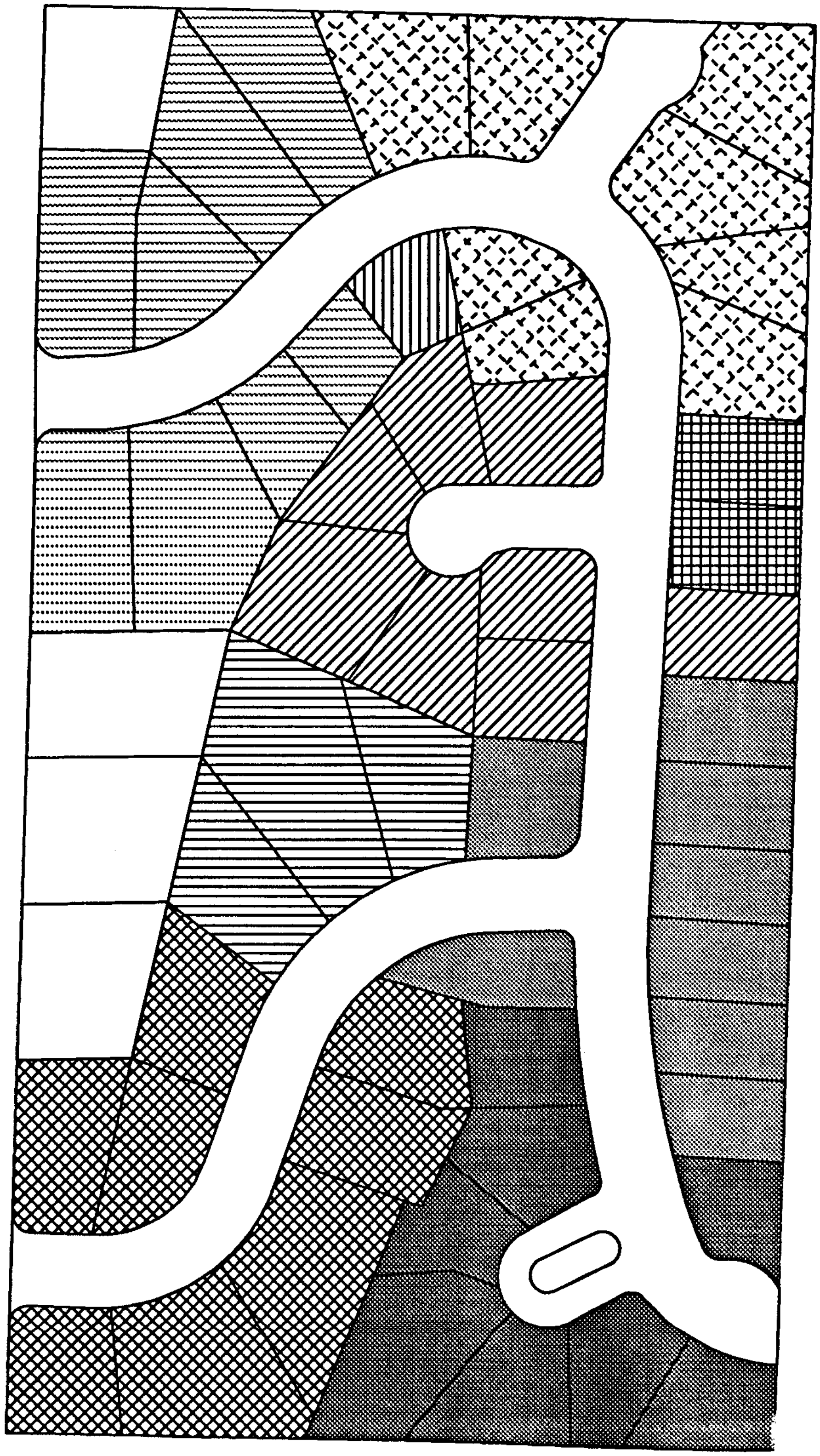

Figure 29. Transformer Placer: Clustering Method a)

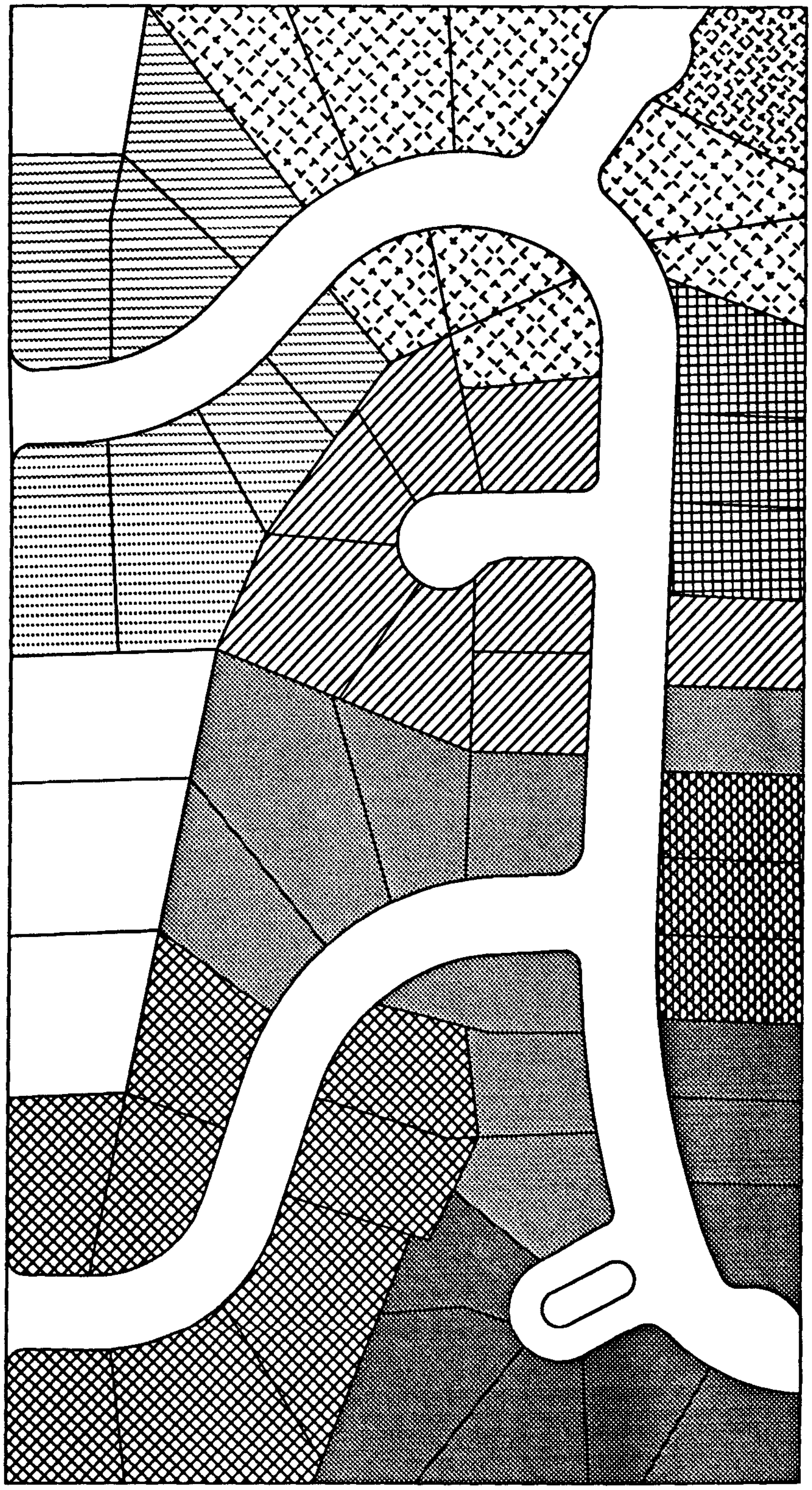

Figure 30. Transformer Placer : Clustering Method b)

The experiments with different clustering algorithms, especially with the methods that would include moving reference point approach on the large set of residential plats, are one of the future research directions in the AEPD area.

For the transformer and handhole placement, a set of clusters obtained by manual design shown in Figure 28, is used as a test bed. The comparison of the manually determined transformer and handholes sites with the corresponding results obtained automatically and shown in Figure 31 shows a close agreement. The one difference is that the human designer who provided the manual design did not apply the rule that the connecting device should not be placed on the corners of the intersection. Due to the higher risk of collision with vehicles, this rule is widely accepted by most of the designers. In the AEPD tool this rule is implemented in the form of a constraint that eliminates corners of the intersections as possible placement sites. A second noticeable difference in some clusters is in the reversal of the sites for the transformer and handhole, which in the manual design comes from optimizing the primary circuitry. This reversing of the sites in the AEPD can be taken care of, if necessary, during the primary design process.

9.5 Secondary Runs Designer

The result of the Secondary Runs Designer knowledge source is presented in detail for the lower left corner cluster of the test plat given in Figure 32. For this purpose, the transformer and handhole placement sites as determined by the Transformer Placer are used. The values for attributes required for the object oriented cluster representation are manually entered in the database file. The values for these attributes, which are properties of the LOT object, are provided by Plat Preprocessor

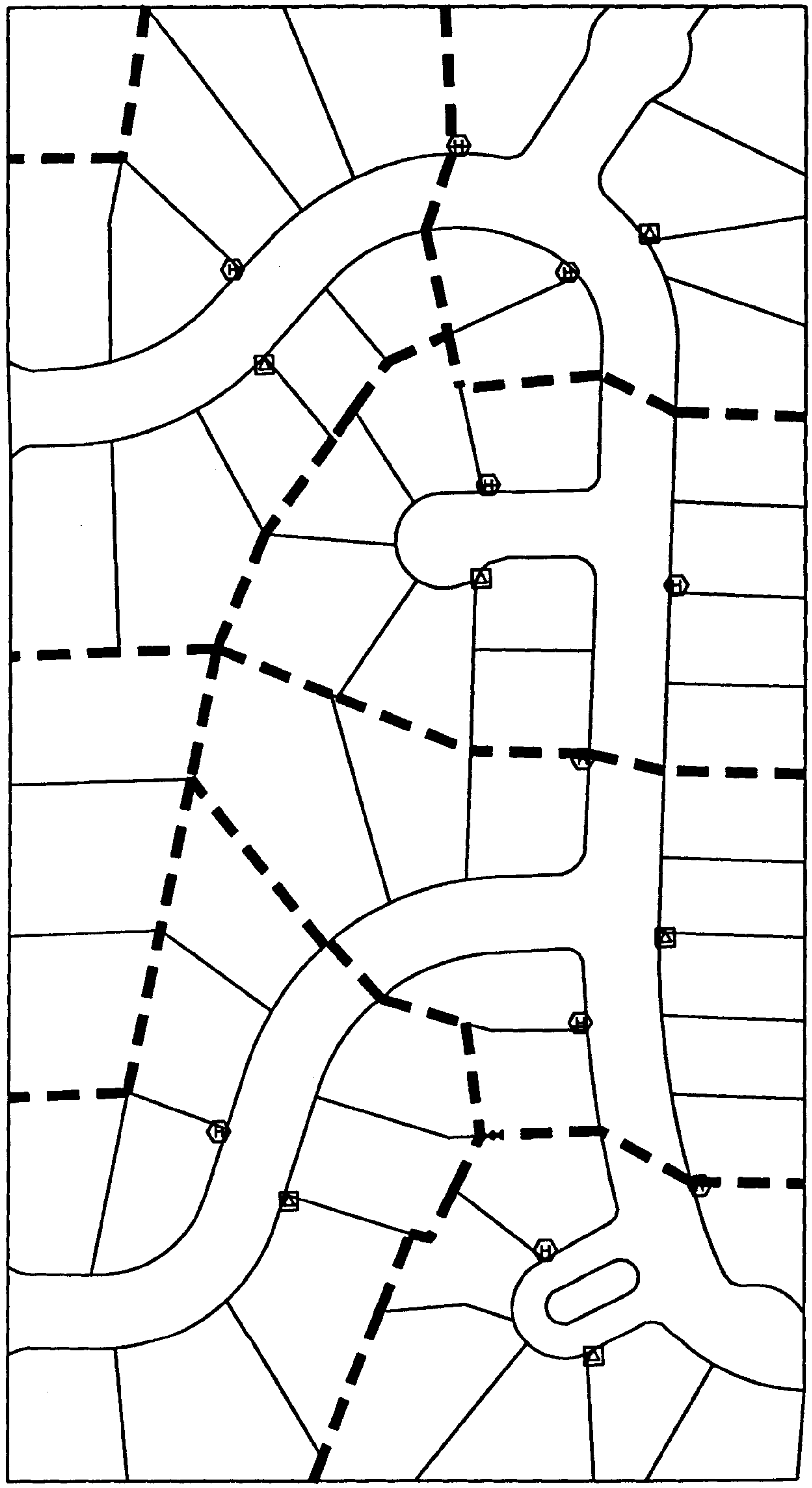

Figure 31. Transformer Placer: Transformer and Handhole Sites

and the Transformer Placer. The initial status of a database file used as a facts storage for this cluster is given in Table 9. The status of the database file after the expert system processing is given in Table 10, which contains the result of the secondary routing in the tabular form. The result of Secondary Runs Designer is written in the database file fields ***CONN*** (status of the lot's connection), ***CONL*** (lot's conductor length in feet), ***CONS*** (lot's conductor size in kcmil or AWG), ***NCON*** (number of conductors in lot's corridor), ***NCRL*** (number of conductors in lot's left crossing) and ***NCRR*** (number of conductors in lot's right crossing). A graphical representation of the obtained result is given in the Figure 33. The comparison of the manually obtained routes for the secondary conductors shown in Figure 28 with the routes that are obtained by the Secondary Runs Designer knowledge source shows practically no difference. Thus for the given placement of the connecting devices both automated and manual methods yield the same result.

9.6 Economic Evaluation of Different Design Scenarios

In order to see the impact of changing the desirable cluster size on the cost of the electrical plat design, three different secondary systems for the test plat are obtained using the AEPD prototype. The size of the cluster is just one of the many options which designer has on his/her disposal that can be used to explore the search space of the feasible electrical plat designs.

The desirable size of the cluster in the case A is 9, which is the same as used in the case of manual design. The desirable size of the cluster in the case B is 14, and desirable size of the cluster in the case C is 7. The results of the secondary design

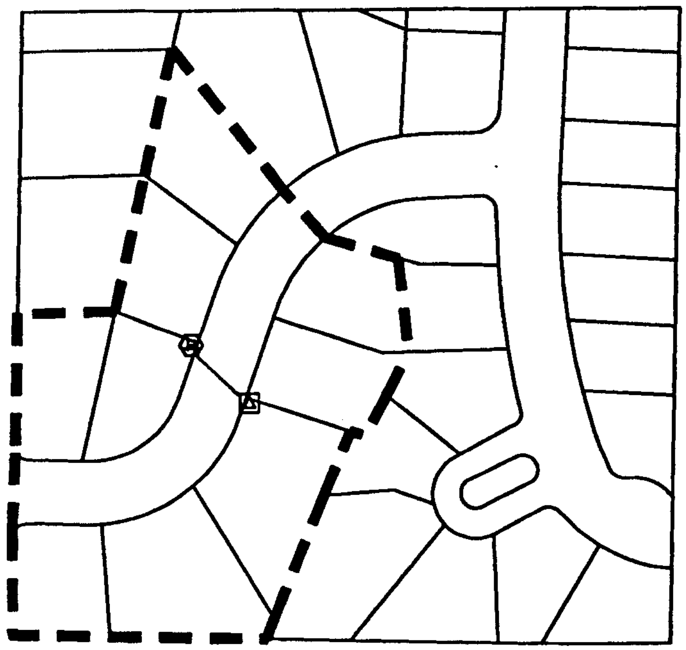

Figure 32. Secondary Runs Designer: Test Cluster

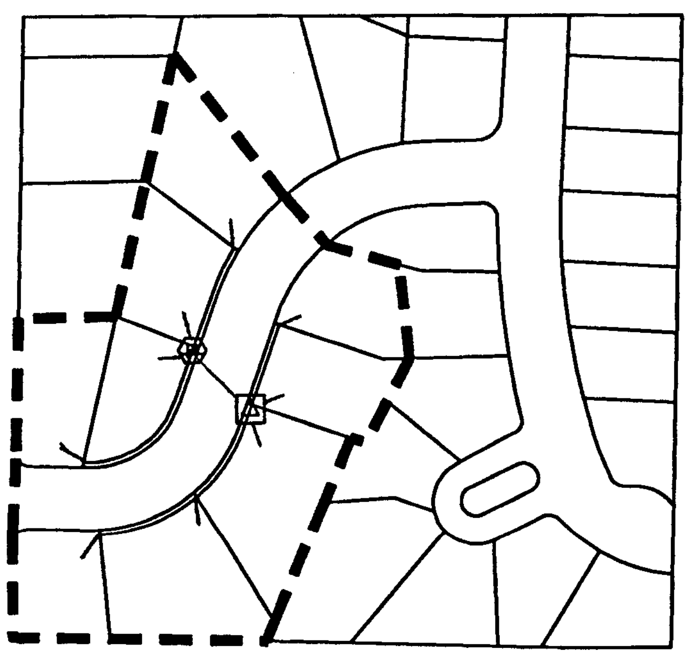

Figure 33. Secondary Runs Designer: Graphical Interpretation of the Result

Table 9. Initial Databse File for the Test Cluster

LID	SOT	SOS	LNLID	RNLID	LOAD	CONN	CONL	CONS	SLC	SRC	SCOR	CORL	NCON	SCRL	CRIDL	CRLL	NCRL	SCRR	CRIDR	CRLR	NCRR
48	RIGHT	OPP	49	0	0.0	NO	0.0		NOT	NOT	FREE	71.237	0	FREE	60	71.123	0	FREE	60	88.666	0
60	LEFT	SAM	0	57	0.0	NO	0.0		NOT	NOT	FREE	90.518	0	FREE	48	88.660	0	FREE	49	70.236	0
49	RIGHT	OPP	41	48	0.0	NO	0.0		HHOLE	NOT	FREE	166.348	0	FREE	50	71.193	0	FREE	60	71.034	0
57	LEFT	SAM	60	55	0.0	NO	0.0		NOT	NOT	FREE	99.491	0	FREE	49	71.204	0	FREE	49	108.394	0
41	LEFT	OPP	37	49	0.0	NO	0.0		NOT	NOT	FREE	100.738	0	FREE	44	79.203	0	FREE	50	78.309	0
55	LEFT	SAM	57	50	0.0	NO	0.0		NOT	XFRM	FREE	103.189	0	FREE	49	108.803	0	FREE	49	77.094	1
37	LEFT	OPP	0	41	0.0	NO	0.0		NOT	NOT	FREE	68.851	0	FREE	44	70.148	0	FREE	44	83.405	0
50	RIGHT	SAM	55	44	0.0	NO	0.0		NOT	NOT	FREE	80.113	0	FREE	49	70.193	0	FREE	41	78.149	0
44	RIGHT	SAM	50	0	0.0	NO	0.0		NOT	NOT	FREE	90.573	0	FREE	41	79.203	0	FREE	37	70.168	0

Table 10. Database File After Expert System Processing

LID	SOT	SOS	LNLID	RNLID	LOAD	CONN	CONL	CONS	SLC	SRC	SCOR	CORL	NCON	SCRL	CRIDL	CRLL	NCRL	SCRR	CRIDR	CRLR	NCRR
48	RIGHT	OPP	49	0	0.0	YES	166.348	4/0	NOT	NOT	FREE	71.237	0	FREE	60	71.123	0	FREE	60	88.666	0
60	LEFT	SAM	0	57	0.0	YES	202.680	350	NOT	NOT	FREE	90.518	0	FREE	48	88.660	0	FREE	49	70.236	0
49	RIGHT	OPP	41	48	0.0	YES	40.0	1/0	HHOLE	NOT	FREE	166.348	1	FREE	50	71.193	0	FREE	60	71.034	0
57	LEFT	SAM	60	55	0.0	YES	103.189	4/0	NOT	NOT	FREE	99.491	1	FREE	49	71.204	0	FREE	49	108.394	0
41	LEFT	OPP	37	49	0.0	YES	40.0	1/0	NOT	NOT	FREE	100.738	1	FREE	44	79.203	0	FREE	50	78.309	0
55	LEFT	SAM	57	50	0.0	YES	40.0	1/0	NOT	XFRM	FREE	103.189	2	FREE	49	108.803	0	FREE	49	77.094	1
37	LEFT	OPP	0	41	0.0	YES	100.738	4/0	NOT	NOT	FREE	68.851	0	FREE	44	70.148	0	FREE	44	83.405	0
50	RIGHT	SAM	55	44	0.0	YES	40.0	1/0	NOT	NOT	FREE	80.113	1	FREE	49	70.193	0	FREE	41	78.149	0
44	RIGHT	SAM	50	0	0.0	YES	80.113	4/0	NOT	NOT	FREE	90.573	0	FREE	41	79.203	0	FREE	37	70.168	0

obtained using the AEPD tool are presented in Figure 34, 35, and 36, for the case A, B, and C, respectively. These figures show the results of the secondary design after the author interactively corrected and rearranged the initial clustering proposed by the Transformer Placer. Table 11 presents the investment cost for the secondary system obtained by manual design and each of the automated designs.

The clustering method a) is used for the all three cases and the clock time requirement for automated clustering is in the order of 2-3 minutes for each case. The time required for establishing spatial relation inside clusters is in the order of 1-5 seconds. Thus the time requirement for the Transformer Placer on DEC 3100 workstation is 2-3 minutes for plats with the size of about 50 lots. The time required for interactive correction and rearrangement of the clusters initially proposed by the Transformer Placer depends on the quality of the initial result and the user skill, but satisficing result can be usually obtained within the 1-2 minutes. The Secondary Runs Designer needs 2-4 seconds for one cluster depending on the cluster size, so that total time requirement for the Secondary Runs Designer is in the order of 10-15 seconds. This estimate obviously does not include the time for manual data entering in the database files, because it will not be needed in the AEPD tool after the GIS ES shell coupling is completed. Thus the overall time required to come up with one design solution using the AEPD tool prototype is of the order of 2-3 minutes needed by the computer and 1-2 minutes of the user time, which means that each solution can be obtained within acceptable time of 3-5 minutes. The significant reduction in the computer time can be gained by optimizing the code for the lots clustering procedure. The communication overhead required for the future GIS/ES shell coupling is not

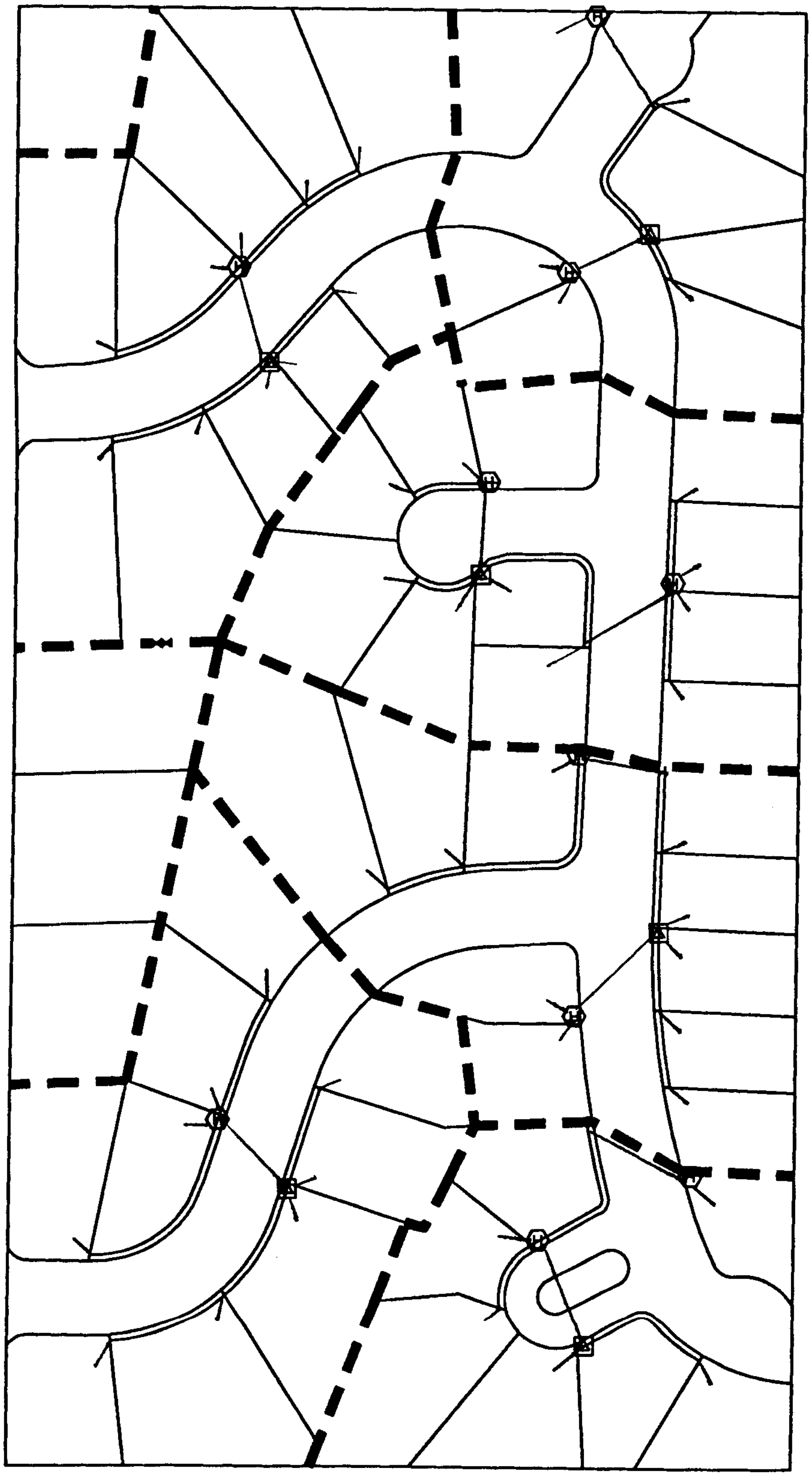

Figure 34. Secondary Design: Case A

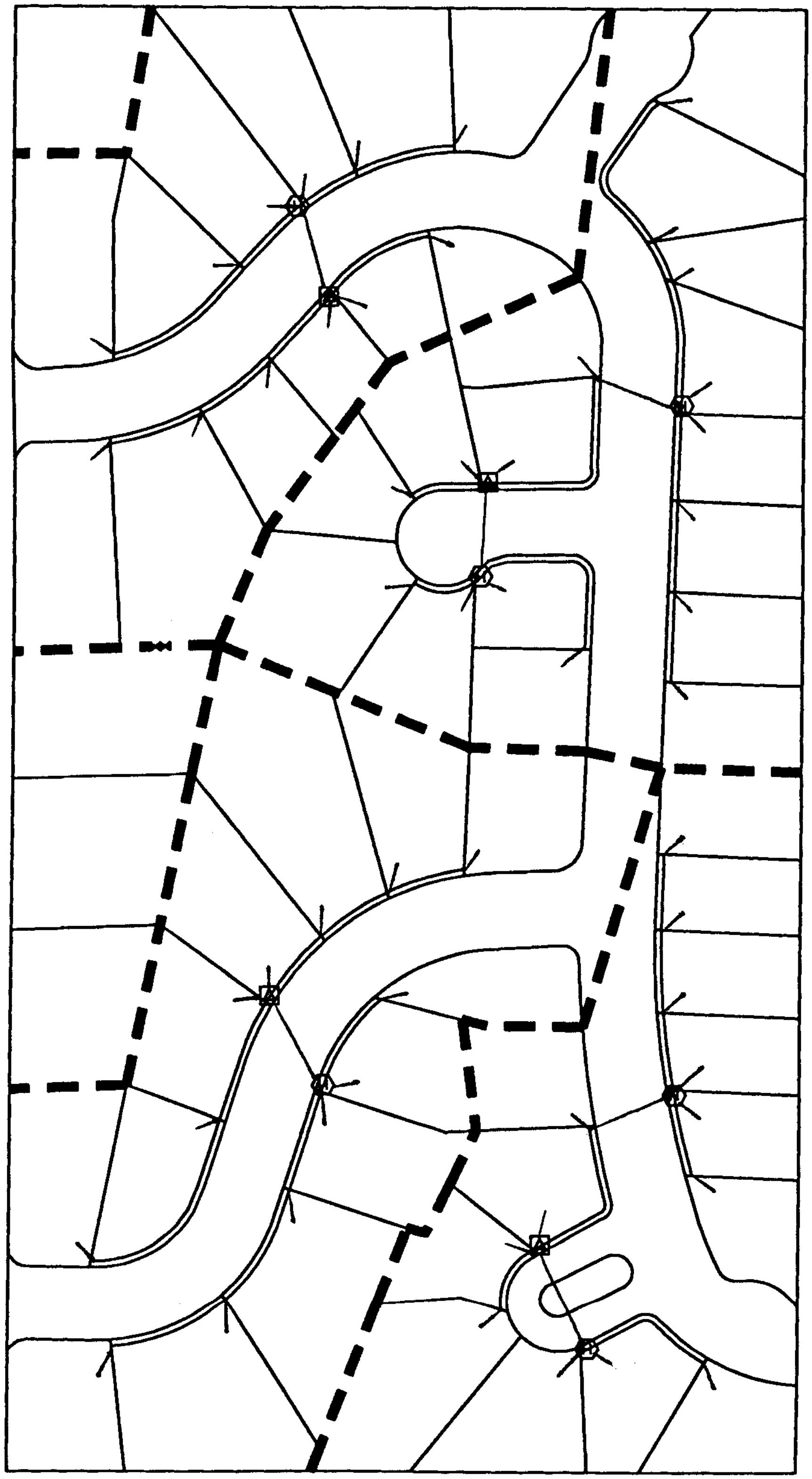

Figure 35. Secondary Design: Case B

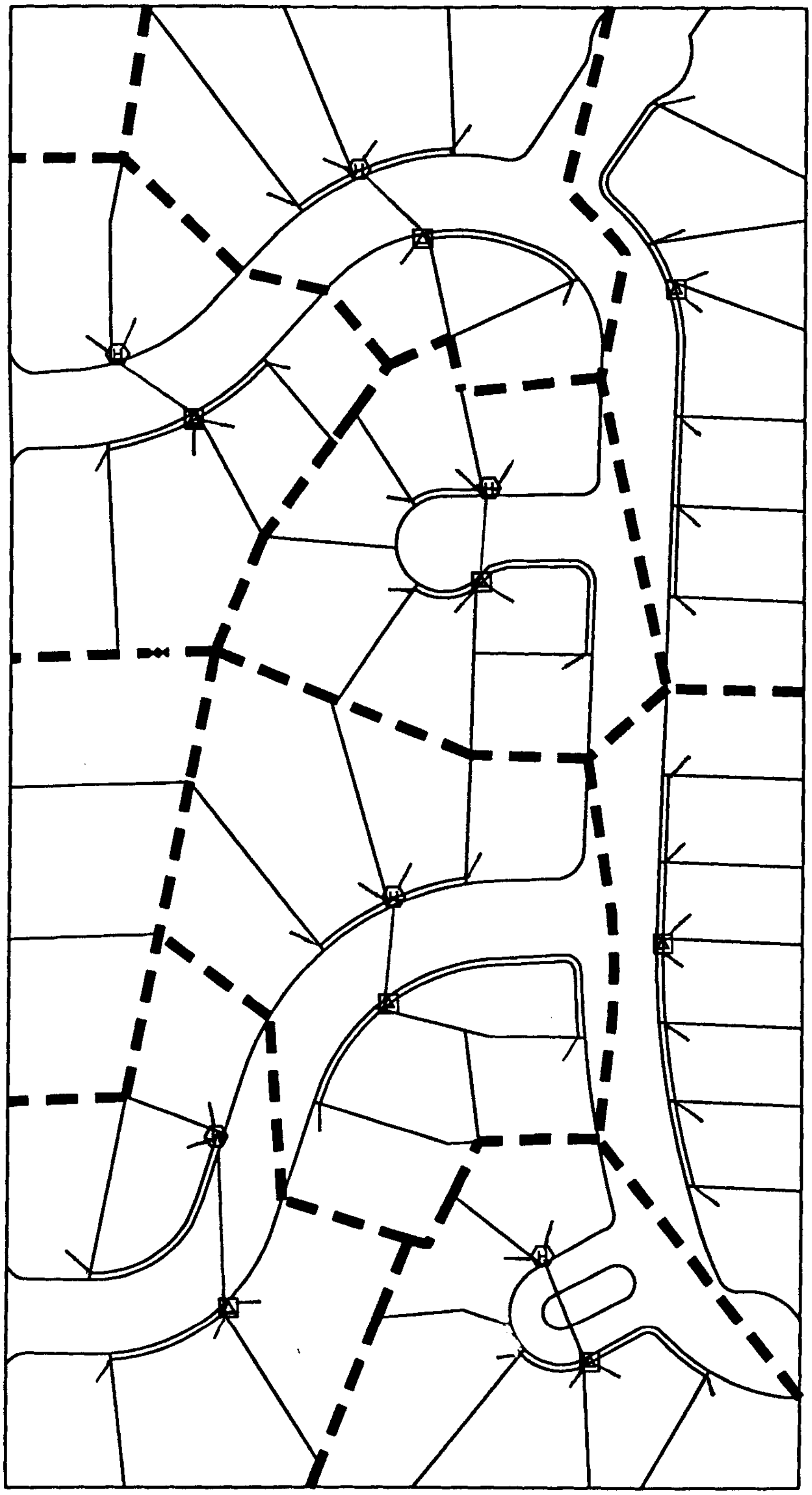

Figure 36. Secondary Design: Case C

Table 11. Capital Investment Cost for Different Design Scenarios

		MANUAL		CASE A		CASE B		CASE C	
TRANSFORMERS									
SIZE	COST	NUMBER	COST	NUMBER	COST	NUMBER	COST	NUMBER	COST
25 kVA	$910.52	0	0	0	0	0	0	8	$7,284
37.5kVA	$991.27	6	$5,948	6	$5,948	0	0	0	0
50 kVA	$1077.15	0	0	0	0	4	$4,309	0	0
HANDHOLES									
	COST	NUMBER	COST	NUMBER	COST	NUMBER	COST	NUMBER	COST
	$74.40	8	$595	8	$595	6	$446	6	$446
CABLES									
SIZE	COST	LENGTH	COST	LENGTH	COST	LENGTH	COST	LENGTH	COST
1/0	$0.62/ft	920 ft	$570	1,120 ft	$694	800 ft	$496	1,120 ft	$694
4/0	$1.03/ft	2,727 ft	$2,809	2,466 ft	$2,540	3,522 ft	$3,628	3,174 ft	$3,269
350	$1.43/ft	1,181 ft	$1,688	1,324 ft	$1,893	2,027 ft	$2,899	512 ft	$732
TRENCHING									
	COST	LENGTH	COST	LENGTH	COST	LENGTH	COST	LENGTH	COST
	$1.92/ft	2,990 ft	$5,742	3,148 ft	$6,044	3,361 ft	$6,453	2,827 ft	$5,429
CABLE LAYING									
	COST	LENGTH	COST	LENGTH	COST	LENGTH	COST	LENGTH	COST
	$0.83/ft	4,828 ft	$4,007	4910 ft	$4,075	6,349 ft	$5,270	4,806 ft	$3,989

TOTAL COST	$21,360	$21,789	$23,501	$21,843

included in this analysis, but it is expected that it will not affect the order of magnitude of the overall computational time.

The capital investment cost for the secondary system (Appendix B) consists of trenching cost, cable laying cost and cost of cables, transformers, and handholes. The cost of the secondary design is just one of the elements that must be taken into account during the quality evaluation of the electrical plat design. In addition, the cost of the primary design can sometimes alter the order of preference among the designs, that is being established based on the cost for the secondary system. Nonetheless, the cost of the secondary system can be used as a good illustration of the impact of different design scenarios on the cost of the underground residential electrical supply system.

The itemized capital investment cost for each of the secondary system designs realized using the AEPD prototype and the manual design are given in Table 11. This table shows that change of the design options, in this case the cluster size, leads to the different costs for secondary systems. Table 11 shows that costs for the manual and automated secondary design for the same cluster size (Case A), are in good agreement (less than 2% difference). The reason for the difference comes as a consequence of placing transformers in the corners of intersections in the case of manual design. This approach results in shorter trenches and shorter 350 kcmil secondary runs, but on the other hand it increases the risk of transformer - vehicle collision. The comparison of the costs for automated designs, in this particular case, shows that switching from 6 to 4 transformers results in +10% increase in cost for the secondary system. This paradox comes as a result of the need for a longer trenches and a more lengthily and more expensive cables that outweighs a saving incurred by reducing the number of transformers. However, as mentioned earlier, the need for trenching for the primary system can either increase or decrease the cost differential between these cases.

9.7 Summary of the Results

The results obtained by the AEPD prototype, and comparison with the results obtained by the human expert prove that the AEPD concept is a valid and viable way of automating the ill-structured, open-ended problem of electrical plat design. Although even in the case when humans are providing the design no two designs are expected to be the same, a close agreement between the manually obtained design and the results obtained by AEPD prototype indicates the appropriateness of the AEPD concept.

Though the cost of the primary circuitry and the operational cost are not included in this analysis, the comparison of the investment costs for the different secondary designs shows that considerable saving can be obtained by evaluating the different design configurations. The AEPD tool offers an automated way to explore the impact of different design scenarios. The nonexistence of such a capability in the case of manual design limits the options the designer can explore. Using the AEPD tool, the search for better solutions can be performed much easier and the search space contains only feasible solutions.

Chapter 10

SUMMARY, CONCLUSIONS AND DIRECTION FOR FUTURE RESEARCH

10.1 Summary

In this dissertation, the author has addressed the problem of Automated Electrical Plat Design (AEPD). This design is presently carried out manually resulting often in an overdesigned, costly, and nonstandardized solution. The comprehensive computerized tool that encompasses design of secondary, primary and a street lighting systems, which are components of the overall residential electrical supply system still does not exist. As an ill-structured and open-ended problem, the electrical plat design is hard to automate with conventional methods such as operational research or CAD. An additional complexity in automating plat design is imposed by the need to process spatial data such as circuit maps, records, and construction plans.

After a extensive knowledge acquisition the author has proposed an AI methodology, namely Intelligent Decision Support Systems (IDSS), to automate electrical plat design. In addition, to accommodate diverse software environments, data models, and problem solving paradigms that must be used for the AEPD, the author has proposed a conceptually new hybrid problem solving architecture. This architecture, called the Blackboard Based Intelligent Decision Support System, consists of different knowledge sources, including the human designer, concentrated around a global database. The environments in which the knowledge sources are implemented are: a GIS, procedural third generation programming language programs, and an expert system shell. In a such hybrid environment, the GIS principal task is to structure and formalize a "real world" representation required by other AEPD knowledge sources.

In order to prove the feasibility of the proposed concept for the AEPD, the author has developed an AEPD prototype that covers functionally the secondary part of an electrical plat design. The AEPD prototype employes two major ingredients used in AEPD, the GIS and the expert system shell. The GIS is used for "real world" structuring required by the Transformer Placer KS and the Secondary Runs Designer KS. In addition, the spatial analysis required for the Transformer Placer knowledge source is also implemented in GIS environment. The secondary routing task is implemented in an expert system shell, using the "real world" object oriented structuring provided by the GIS.

10.2 Conclusions

The results obtained by testing the AEPD prototype on the actual plat, and comparison with the results of the human expert's design, are encouraging and prove that the proposed AEPD concept is feasible. The AEPD offers an automated way to explore the impact of different design scenarios and the search for better solution can be performed much easier. The design tool, based on this concept, is expected to be accepted by designers because it supports and enhances the designer's thinking stage of design and judgements, rather than blindly automate the design process through a prescribed computation.

An additional outcome of this dissertation is the successful demonstration of the application of novel technologies, namely Geographic Information System (GIS) and Artificial Intelligence (AI) in the area of distribution planning. These are used for structuring the required data and capturing the designer problem solving technique respectively. The synergy of these two agents, one "being able to see," and another "being able to think," can provide the distribution system designers with a viable tool to support their decision making ability.

The concepts introduced in this dissertation are generic and can be applied for a host of problems in the distribution planning and design area that require spatial reasoning. It is the author's hope that he will establish a new standard for automating these problems with the concepts and ideas proposed in this dissertation.

10.3 Directions for Future Research

By no means is this dissertation the final word on the AEPD. As being the pioneer in this area the author has identified a number of problems and perspective research topics that deserve attention in the future. Some of the research area where the future focus of attention must be directed are:

- the different methods of clustering,
- the data model conversion,
- the GIS/expert system database bridges issues,
- the primary runs optimization procedure,
- the development of the remaining procedural knowledge sources,
- and the expansion of the existing rule base.

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GLOSSARY

Underground Distribution

ampacity	a cable load capacity given in amperes
CIC	a cable in conduit underground system where cables are placed in conduits, rather than directly buried.
FAST transformer	a "fused accessible sectionalizing transformer" is a single phase padmount transformer with a fused third primary bushing providing a convenient sectionalizing point in an underground system
handhole	a plastic, fiberglass or concrete box with a removable cover used to house secondary connectors and conductors when service length makes direct services uneconomical.
J-box	a three or four position junction device on the underground distribution system installed in vault and used for connecting multiple (three or four) primary conductors
leap frogging	a way of primary connection of transformers such that different phases pick up transformers in alternate mode.
padmount transformer	a single phase transformer, installed on a handhole with a concrete cover (pad), used to service single customers, residential plats, apartments and single phase commercial loads. Single phase padmount transformer has two primary (15kV) bushings.

primary lateral	a portion of a primary distribution feeder that is supplied by a main feeder or another laterals and extends through the load area with connections to the distribution transformers or primary loads.
secondary run	a 600 V rated cable used for underground residential 110-220 V electrical supply.
utility easement	an area with a right to access to construct, maintain and operate electric facilities such as transformers, secondary handholes, and conductors on the private property.

Geographic Information System

attribute	a characteristic of a map feature, stored in tabular form.
buffering	a form of proximity analysis where zones of a given distance are generated around coverage features.
coverage	a digital analog of a single map sheet forming the basic unit of data storage for most GISs.
feature attribute table	a table used to store coverage attribute information.
spatial data	information about the location, shape, and relationships among geographic features, usually stored as coordinates and topology.
thematic data	also descriptive data, a tabular and/or textual data describing the geographic characteristics of map feature.
vector	a coordinate based data structure commonly used to represent map features.

Appendix A

RULES ACQUIRED DURING THE KNOWLEDGE ACQUISITION PROCESS

Design Consideration

In order to design an optimal underground distribution system for the plat, according to designers' answers and Guidelines for Use in Developing a Specific Underground System Design Standard (IEEE Committee Report 1977) [23], the following considerations should be examined carefully :

1) Economics
2) Service Reliability and Customer Satisfaction
3) Static and Dynamic Voltage Level (Voltage drop and Flicker)
4) Phase Balancing
5) Ampacity
6) Protection
7) Standardization
8) Ease of Construction
9) Ease of Maintenance
10) Ease of Expansion

Data Obtained from Developer

Prior to the start of engineering, the plat developer must provide the designer with as much information as possible regarding the new development. In addition to the legal documents and construction schedules, the developer should provide:

1)Set of following drawings:

- Water main
- Sewer main with profile
- Road and storm drainage
- Gas main if gas is available and gas company is not using the same trench.
- Typical road section
- Temporary erosion plans
- Topography

2)Information regarding any other natural (big rocks, creeks,etc) or constructed (fire hydrants, traffic lights) obstacles present in the development area.

3)Information about special requirements for commercial loads (wells or sewer lift station, community center, etc) specially if they require three-phase service.

4) Information about lots which do not require service (lots used for drainage, or lots that will derive service from already existing adjacent supply).

5) Information concerning possible future expansion in different phases.

6) Street lighting requirements. If already designed by others, the developer has to provide approved site plan with light locations.

7) All possible information with regard to residential load such as:

- Number of lots
- Anticipated home size
- Anticipated type of heating
- Construction standards (Comfort Plus, 1986 WA.ST.Energy Code).
- Expected presence and anticipated size of the heat pumps
- Expected panel size (100 , 200 & 400A)

Transformer Design

Applicable standards, codes and guidelines:

Transformers used in the secondary distribution system are padmounted, single phase transformers.[107,108,109]. Transformer sizing for residential load depending on the number of total electric customers is determined based on [107].
Terminology and definitions are based on Guidelines for Use in Developing a Specific Underground Distribution System Design Standard (IEEE Committee Report 1978)[23].

Rules:

a) Transformer placement:

1)Transformer should be placed on the front (street) lot corner that is not used for sewer stubout.

2)Transformer should be placed within the 10 feet frontage utility easement.

2a)If prespecified, transformer can be placed at the boundary line between two lots within front 10 feet utility easement.

3)If the primary or feeder route is already proposed, transformers should be placed on the same side of the street.

4)It is desirable to keep all transformers on the same side of the street.

5)If the gas company is not utilizing same trench with electric utility and the gas pipe route is already proposed, transformers should be placed on the opposite side of the street.

6)If possible a transformer should be placed on the side of the street without sidewalk.

7)Whenever possible, a transformer should be placed on the side of the curved street which has longer radius (outer side of the curve).

8)Road corner lots should be avoided for the transformer site.

9)Narrow frontage lots (less than 30 feet) should be avoided for transformer placement (end of the cul-de-sac).

10)All prespecified natural (solid rocks) or constructed (fire hydrants) obstacles should be avoided.

11)Keeping the above rules in mind, a cluster of defined number of lots that should be served by one transformer must be identified, and transformer should be placed in the cluster center.

12)Cul-de-sac is a well defined cluster of the lots and can be used as the starting point for transformer placement.

12.a)In the case of cul-de-sac, transformer will be placed at the neck rather than at the turn around.

13)If the primary design is already accomplished, alternative starting point for transformer placement can be a cluster near the primary source point.

14)The transformer placement is a step-by-step process and usually needs a backtracking readjustment if at the end only few lots are to be served from one transformer.

b) Transformer sizing:

15)After the process of transformer placement and the "lots-to-transformer" assignment has been done, the size of the transformer is determined based on anticipated heating. The table used for transformer sizing is given in [107]. This table takes into account load diversity as well as portion of the nonelectric space heating customers.

Secondary Runs Design

Applicable standards, codes and guidelines

Residential loads within the plat are supplied from a distribution transformer by single-phase, three-wire underground cables (secondary runs). Conductors used for plat underground distribution system are 600V 1/0, 4/0 (AWG) and 350 kcmil polyethylene direct buried aluminum cables.

Rules:

a) Route determination:

1)Secondary runs should utilize trench located on the front (street side) of the 10' utility easement.

2)If the trench route is already designed for primary, secondary runs should utilize them.

3)If the number of secondary runs from transformer in one direction on the same side of the street is three or less, each lot should have an individual secondary.

4)If the "handhole based solution" is not chosen to be preferable, lots on the opposite side of the street will be served with one crossing for every two lots, still utilizing individual runs.

5)If not specified differently by the designer, each conductor in the crossing should have a separate conduits.

6)If the number of the lots on the opposite side of the street is odd, last three lots should be served from the handhole placed in the corner between first and second lot. Run for the farthest lot should be put in the trench with respect to rule 1.

7)If the handhole must be used due to the need for serving more than eight lots from one transformer, use this handhole for satisfying rule 6.

8)In the case of cul-de-sac, the lots on the opposite side of the transformer should be served by crossing over rather than going around cul-de-sac.

9)If the number of the lots to be served after crossing cul-de-sac is higher than two, a handhole should be used.

10)If the heat pump is anticipated on the particular lot, this lot should be served by individual secondary run from transformer rather than sharing common handhole with others.

b) Secondary conductor sizing:

11)The conductor between a transformer and a handhole should be 350 kcmil size.

12)Lots adjacent to the transformer and handhole should be served by 1/0 conductor.

13)All others conductors, if the run is shorter than 200', should be 4/0 size.

14)Secondary runs longer than 200' should be served by 350 kcmil conductors.

15)To reduce a short circuit current available at the point of delivery in the case of 1/0 conductor, the minimal conductor lengths should be 40 feet.

16)If the conductor used is 4/0, the minimal length should be 80 feet.

17)If the conductor is 350 kcmil, the minimal length should be 120 feet

18)The conductor sizing for the heat pump must be checked for the tolerable voltage drop during the motor startup.

19)If the tolerable voltage drop cannot be satisfied even with the 350 kcmil conductor, the size of the serving transformer must be increased.

Underground Primary Distribution Design

Applicable standards, codes and guidelines:

Transformers on the plat are supplied by a nominal 12470 V (15 kV) underground primary distribution system [107,108,109]. Conductors used are 1/0 (AWG) solid aluminum with concentric neutral cable and polyethylene insulation. Primary distribution cables are mostly direct-buried or in some cases CIC type (Cable in Conduit defined in [107]). General requirements and procedures concerning primary as well as secondary facilities in joint occupancy trenches are covered in [108]. Terminology and definitions are based on Guidelines for Use in Developing a Specific Underground Distribution System Design Standard (IEEE Committee Report 1977) [23].

Rules:

a) Number of phases determination:

1)If there is a three phase load on the plat, primary distribution should be three phase.

2)If the total anticipated load is greater then 35 A (at 15 kV) more then one phase should be used.

2a)If there is a need for more than one phase, use three instead two phases even in the case where total load is less than 70 A. (Two phase solution should be exception rather than a rule).

3)Use a three-phase primary even if the total load is less than 35 A, if the extension of the plat or significant growth in the neighboring areas can be expected in the future.

4)If one or two phases solution is accepted, phase that will be used should be determined based on source substation monthly readings.

4a)If previous data are not available, phase or phases that will be used should be determined based on total already connected transformer kVA on the feeder, or actual load readings taken at that point on the circuit.

b) Source points identification:

5)The existing feeder connecting points that are closest to the new plat boundaries should be identified as a possible source point.

5a)Radial primary generally should be avoided, which means that more than one possible source points will need to be identified.

6)Among the possible multiple source points, those that are on the opposite side of the plat should be used.

7)If the feeder routes are going through the plat, "entrance" and "exit" of the feeder should be used as source points.

c) Primary routes determination:

8)Primary routes are utilizing a trench located on the front (street side) of the 10' utility easement.

9)If there is feeder corridor passing through the plat primary (as well as secondary), routes should utilize same trench as much as possible.

10)If the trenches for the secondaries are already designed, primary routes should utilize them as much as possible.

11)Primary routes should be kept on one side of the street as much as possible.

c1)Set of rules which apply to routes determination for multiple sources

12)In the case of one phase primary and multiple sources, the primary route should connect source points while picking up all transformers and keeping additional trenching minimal.

13)In the case of multiple phases and multiple sources depending on the plat size and shape, each phase can have different routes, or all phases can have same major route and utilize the same trench. Also phases can utilize same routes in some parts and different routes in other parts of the plat.

13a)If the shape of the plat area is mostly longitudinal with lots clustered around main road, all phases should have the same route and utilize the same trench.

13b)If the roads are branching, and around particular road there is enough load so that branching one phase lateral is not justified, then this phase should follow its own route.

13c)In the case of very long primary lateral with only one transformer connected, FAST transformer should be used as the origin for that lateral.

14)If all phases are using same trench and there exists multiple source points rule 12 should be used for defining major routes.

14a)In the case 14) transformers should be divided equally among the phases by a "leap frogging".

14b)In the case 14) and 14a) transformers that are away from the main route should be picked up by branching one phase laterals.

15)If shape of the plat is such that it can be divided into same number of "equally sized " subplats as number of phases used for supply, each subplat should be served by one phase which will use its own route through that subplat.

15a) In the case 15) within the each subplat, primary route should be determined as in the case of one phase primary (rule 12).

15b)In the case 15 primary routes for each phase should start and finish at common three phase source point rather than having individual source points for each phase.

c2)Set of rules which apply for the routes determination for single source (radial primaries)

16)In the case of single phase and single source, the end point for the primary must be determined. This end point should be near the direction of the most likely possible future expansion, and would be a source of power for future development.

16a)After the end point has been identified, the route should be determined using rule 12.

17)In the case of multiple phase and single source primary, the end point must be determined according to the rule 16).

18) In the case 17) depending on the plat size and shape, primary phases can utilize same or different routes determined using rules 13,14 or 15.

19)J-boxes or switching cabinets that will be used for cable termination and possible reconfiguration will be placed according to the same set of rules and restrictions as used for transformer and handhole placement.

d)Paralleling and looping:

20)In the case of multiple sources, part of the primary from one source should back up part of the same phase primary from another source.

21)In the case of radial multiple phase one phase can be back up for another or each phase can back up itself by paralleling conductors in the same trench. Which way will be used depends on the reliability and designer attitude toward customer satisfaction versus installation cost consideration.

22)In the case of single phase radial primary, or single phase lateral connected to the main primary route, whenever two or more transformers are to be served, conductors should be paralleled.

CIC Design:

23)In order to maintained a required cable pulling tension within the tolerable limits additional vaults may be needed. The number and approximate location for vaults can be determined using [108].

24)Vaults needed for achievement of the required pulling tension will be placed according to the rules and restriction valid for the transformer and handhole placement.

Street Lighting Design

Applicable standards, codes and guidelines:

Street lighting system at the residential plat is defined in [107,108,109]. IES (Illuminating Engineering Society) recommendations, NESC and ANSI (C136.13) codes, as well as local billing agency requirements are additional depository of rules and guidelines for the street lighting design.

Rules:

a) Street light placement:

1)Street light should be placed 3 feet in front of the street side of the 10 feet utility easement.

2)Street light should be placed in the lot corner side rather than in the middle of the lot frontage.

3)During the placement process all prespecified natural (solid rocks) or constructed obstacles (fire hydrants) should be avoided.

4)Lots with narrow frontage should be avoided.

5)Lot corners used for transformers should be avoided too.

6)If the residential street is not over 50 feet wide street lights should be placed on the side of the street where joint utility trench lies.

7)If the residential street is wider than 50 feet light should be placed along the street alternating between both sides.

8)Street light should be placed first in the intersections.

8a)In the case of T intersection light should be placed in the center of the opposite side of the incoming street.

8b)In the case of the X intersection luminary should be placed on the far right corner of more heavily traveling street (wider street).

9)In the case of cul-de-sac luminary should be placed at the neck rather than in the turn-around.

10)Additional lights should be placed evenly along the street. Distance between street light can be obtained by dividing total length of the street to be covered by lighting system with number of available lights previously defined by customer.

11)Each street light should be connected to the nearest transformer or handhole.

11a)Already placed street light can be used as supply point for the next street light if it is closer to the that luminary than any other transformer or handhole. It will represent case of multiple luminary circuit wiring.

12)Routes for the street light supply system should utilize as much as possible already existing trenches.

13)If the distance between the luminary and source is over the 10 feet fuseholder should be installed in the handhole or the street light handhole can be used.Field condition or designer preferences will determine way to go.

14)If the light has to be placed on the curved roadway with short radius luminary should be placed on the inner side of the curve.

b) Street light style, type and size selection:

15)If not otherwise defined by customer luminary should be Town & Country (Type III) or Cobrahead (Type II).

16)If not stated otherwise by customer lamp size should be 100 W.

17)Mounting heights should be 25 feet for size mentioned in 16 or will be determined from table 6 PSPL SPM 6375.2000

18)Connecting wire should be #8 or 1/0 triplex.

Appendix B

OPTIMAL SOURCE LOCATION FOR THE GIVEN LOAD ARRANGEMENT

The problem of finding an optimal transformer location within the given cluster of lots can be stated as follows:

> *For the given arrangements of the load points, find the placement site for the transformer such that the capital investment cost as well as the operational losses are minimal. In addition placement site must be chosen such that cable thermal rating and voltage regulation constraints are satisfied.*

As shown in [9] and according to the results of knowledge acquisition [19] this problem can be solved sequentially in two steps:

- by unconstrained minimization of the overall cost function that contains capital investment and operational losses part, in order to find an optimal location for the transformer
- by secondary conductor sizing, in order to take care of the thermal rating and voltage drop constraints.

This appendix will discuss only the first part of the transformer placement optimization procedure because the cable sizing problem is part of the secondary design segment of the AEPD. Furthermore, the voltage drop constraint is already partially taken care of with the appropriate size for the cluster determination.

The overall cost function **C** can be defined as:

C=trenching cost+cable laying cost+cost of cables+electric losses cost

In more details this formula can be expressed as:

$$C = c_1 \sum_{i=1}^{n} l_i + c_2 \sum_{i=1}^{n} d_i + \sum_{i=1}^{n} c_i d_i + c_3 T \sum_{i=1}^{n} R_{1i} \left(\frac{L_i}{V_i}\right)^2 d_i \qquad \text{(B.1)}$$

where:

c_1 - cost of trenching per unit length

l_i - length of the trench segment required for the i-th load point (0 if that cable utilize existing trench)

c_2 - cost of cable laying per unit length

d_i - length of the cable that connects transformer and i-th load point

c_i - cable cost per unit length for the conductor that connects transformer and i-th load point

c_3 - unit price for electric energy

R_{1i} - cable resistance per unit length for the i-th cable

L_i - load of the i-th load point

V_i - voltage at the i-th load point

T - utilization period

As a first approximation let assume that:

a) the distances between transformer and load points are straight line "crow fly" distances. This assumption also implies that each cable utilize its own trench and that the trench length for the i-th cable l_i is equal to the length of that cable d_i

b) all cables are equal which implies that $c_i = c$ for $i = 1, n$.

c) the load (L_i) and the voltage (V_i) of each load point are equal.

With those assumption (B.1) reduces on:

$$\mathbf{C} = c'_1 \sum_{i=1}^{n} d_i + c'_3 \sum_{i=1}^{n} d_i \qquad \text{(B.2)}$$

where:

$$c'_1 = c_1 + c_2 + c$$

$$c'_3 = c_3 \, T \, R_1 \left(\frac{L}{V}\right)^2$$

and

$$d_i = \sqrt{(x_t - x_i)^2 + (y_t - y_i)^2}$$

with:

x_t, y_t - coordinates of the transformer placement sites

x_i, y_i - coordinates of the i-th load point

Finally the first approximation of the overall cost function as the function of the transformer placement site coordinates is given as:

$$\mathbf{C}(x_t, y_t) = c' \sum_{i=1}^{n} \sqrt{(x_t - x_i)^2 + (y_t - y_i)^2} \qquad \text{(B.3)}$$

where:

$$c' = c'_1 + c'_3$$

Minimizing (B.3) with respect to transformer placement site coordinates:

$$\frac{\partial C(x_t,y_t)}{\partial x_t} = 0 \qquad \text{(B.4)}$$

$$\frac{\partial C(x_t,y_t)}{\partial y_t} = 0 \qquad \text{(B.5)}$$

yields the implicit formulas for finding the coordinates of the optimal site for the transformer:

$$x_t = \frac{\displaystyle\sum_{i=1}^{n} \frac{x_i}{\sqrt{(x_t - x_i)^2 + (y_t - y_i)^2}}}{\displaystyle\sum_{i=1}^{n} \frac{1}{\sqrt{(x_t - x_i)^2 + (y_t - y_i)^2}}} \qquad \text{(B.6)}$$

and

$$y_t = \frac{\displaystyle\sum_{i=1}^{n} \frac{y_i}{\sqrt{(x_t - x_i)^2 + (y_t - y_i)^2}}}{\displaystyle\sum_{i=1}^{n} \frac{1}{\sqrt{(x_t - x_i)^2 + (y_t - y_i)^2}}} \qquad \text{(B.7)}$$

Because of the implicit form of the equations (B.6) and (B.7) in regard to coordinates of the optimal placement sites x_t and y_t, the iterative procedure, given in (B.8) and (B.9), must be employed.

$$x_t(k+1) = \frac{\displaystyle\sum_{i=1}^{n} \frac{x_i}{\sqrt{(x_t(k) - x_i)^2 + (y_t(k) - y_i)^2}}}{\displaystyle\sum_{i=1}^{n} \frac{1}{\sqrt{(x_t(k) - x_i)^2 + (y_t(k) - y_i)^2}}} \tag{B.8}$$

and

$$y_t(k+1) = \frac{\displaystyle\sum_{i=1}^{n} \frac{y_i}{\sqrt{(x_t(k) - x_i)^2 + (y_t(k) - y_i)^2}}}{\displaystyle\sum_{i=1}^{n} \frac{1}{\sqrt{(x_t(k) - x_i)^2 + (y_t(k) - y_i)^2}}} \tag{B.9}$$

where

k - denotes iteration step.

To start the iterative procedure an initial point $x_t(0)$, $y_t(0)$ must be found such that the optimal placement site lies in its vicinity.

In the AEPD tool which does not employ the iterative procedure for finding the optimal placement site, that initial point can be used as the point in regard to which the nearest available placement site will be chosen as a transformer location. The determination of the initial point $x_t(0)$, $y_t(0)$ is based on the following consideration.

Equations (B.6) and (B.7) can be rewritten in the form:

$$x_t = \frac{\sum_{i=1}^{n} w_i \, x_i}{\sum_{i=1}^{n} w_i} \qquad \text{(B.10)}$$

$$y_t = \frac{\sum_{i=1}^{n} w_i \, y_i}{\sum_{i=1}^{n} w_i} \qquad \text{(B.11)}$$

where:

$w_i\,(x_t,y_t) = \dfrac{1}{\sqrt{(x_t - x_i)^2 + (y_t - y_i)^2}}$ is the wieghting factor for coordinates of the particular load point.

Equations (B.10) and (B.11) define transformer coordinates as a weighted average of the load point coordinates. The problem with using formulas (B.10) and (B.11) is that to chose the proper weight, the coordinates of the transformer locations x_t and y_t, which are to be determined, must be known in advance. As these coordinates are not known in advance the reasonable initial assumption is to weight all load point coordinates with the same value.

With that assumption the initial coordinates are given as:

$$x_t = \frac{\sum_{i=1}^{n} x_i}{n} \qquad \text{(B.12)}$$

$$y_t = \frac{\sum_{i=1}^{n} y_i}{n} \qquad \text{(B.13)}$$

which are precisely the coordinates of the cluster centroid.

In [64] these coordinates are experimentally found to be satisfactory as the initial point for the iterative algorithm that finds the optimal location for the distribution substation.

If there is information about size of the load for each particular load point, this information can be used as the weighting factor $w_i = L_i$. Applying this information the initial values for the optimal placement site coordinates can be calculated as:

$$x_t = \frac{\sum_{i=1}^{n} L_i x_i}{\sum_{i=1}^{n} L_i} \qquad \text{(B.14)}$$

$$y_t = \frac{\sum_{i=1}^{n} L_i y_i}{\sum_{i=1}^{n} L_i} \qquad \text{(B.15)}$$

If the size of the particular load point is not known but there is an established correlation between the load size and lot area, that information can be used as the weighting factor $w_i = Area_i$. Thus with this information the initial values for the optimal site coordinates are given as:

$$x_t = \frac{\sum_{i=1}^{n} Area_i \, x_i}{\sum_{i=1}^{n} Area_i} \qquad (B.16)$$

$$y_t = \frac{\sum_{i=1}^{n} Area_i \, y_i}{\sum_{i=1}^{n} Area_i} \qquad (B.17)$$

Appendix C

SECONDARY RUNS DESIGNER PROTOTYPE IMPLEMENTED IN LISP PROGRAMMING LANGUAGE

The domain knowledge for this prototype is a simple excerpt from the set of rules acquired during the knowledge acquisition (Appendix A). This prototype is based on assumption that the process of transformer placement that includes clustering and lot to transformer assignment has been done. Thus all necessary topological information for the secondary routing and sizing are available .

Data Structure

The production system working memory used with an expert system shells in this prototype is emulated as a list LOTS that contains atoms called LOT#, each of which represents a particular lot in the cluster that is served by one transformer. Relevant attributes used to decide which rules must be fired are stored in the atom's property list and consist of set of topological and relational attributes.

Control Structure

The program control structure is a data driven forward chaining production rules control structure given in the flow chart in Figure 34. By using an apply mode of the rules, state of the working memory (property lists of atoms that are elements of the list LOTS) are examined and checked if they satisfy LHS of the rules. If matching is found then the action contained in the RHS is performed (the rule is fired), usually causing some change in the other elements of the working memory which in turn cause other rules to be fired. The process continues until the final solution is reached, which in this case means until all lots are connected to the transformer and length and conductor size are determined and if they violate fault current condition. The rules are grouped together based on sharing common properties such as rules which apply to lots that are left of the transformer on the same side of the street. This rule grouping makes the pattern matching procedure more efficient and reduce the maximum number of subcondition tests that are required (reducing complexity of the linear search). The order in which rules are fired is given and printed as a trace of "reasoning" process.

Results

Program has been tested on the three simple lot transformer arrangement called CASE 1, 2, and 3. Case 1 and 2 represent the same lot arrangement with transformer placed in different positions while Case 3 comprise different lot arrangement. For each case input drawing is given (Figure 35, 37 and 39) with already placed transformer and handholes (a connecting device on the opposite side of the street). The program output is given as a printout of the log file containing trace with explanation how (based on what rule) is a particular lot connected, as well as a conductor length and size for each lot. In addition Figures 36, 38 and 40 contain a graphical interpretation of the results for the Case 1, 2, and 3 respectively. The violation of the minimal distance between the transformer and lot, for the particular size of conductor, which is required for the fault current reduction, is also reported

.

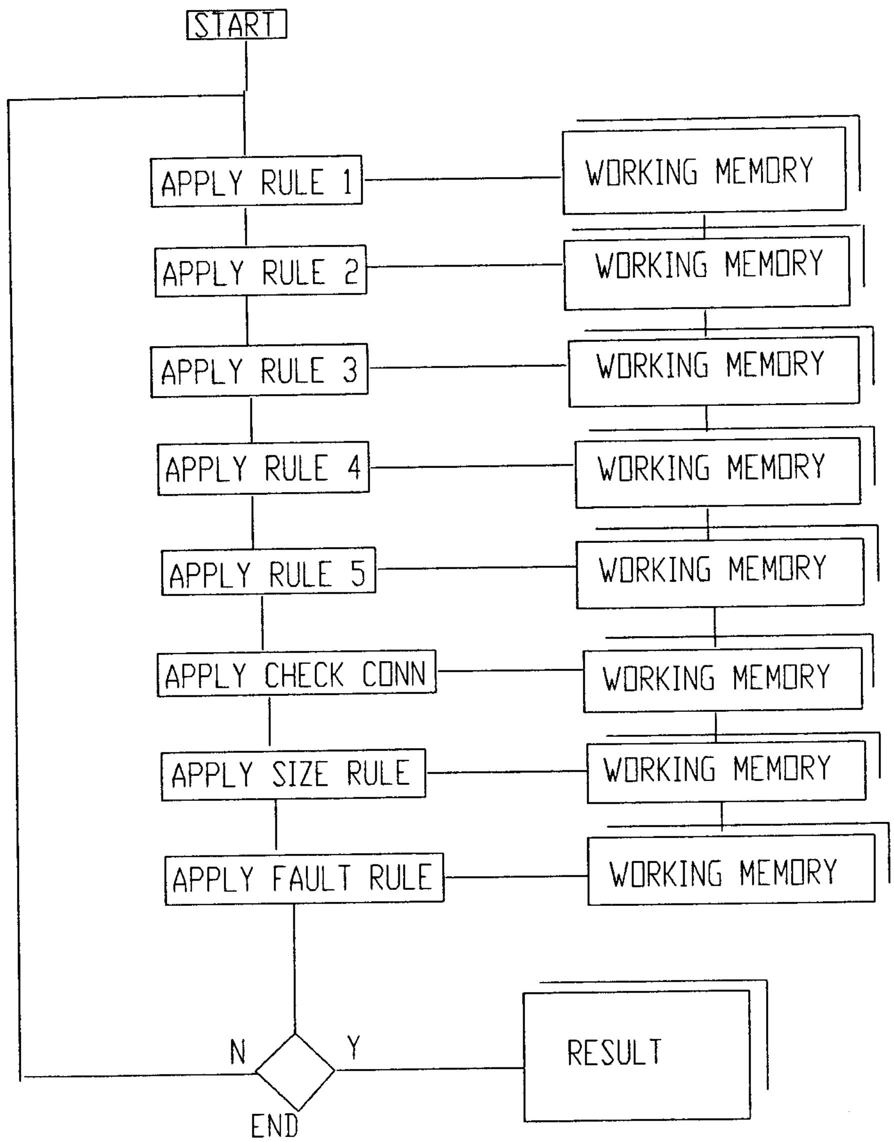

Figure 37. Appendix c: LISP Prototype Control Structure

Working Memory Element (LISP Program List)

```
;=============================================================
;=============================================================
;
;generate initial state of the working memory
;
;list LOTS contains list of atoms representing each particular lot
;
;attributes of each particular lot are stored in its property list those attributes are:
;
; ATTRIBUTES:
;
;
;    SOFS     CHAR side of the street where the lot is in regard
;                  to the transformer (S - means same, O - means
;                  opposite)
;    SOFT     CHAR position on the lot along the street in regard
;                  to the transformer (L - means left,
;                  R - means right)
;    LN       INT  id number of the left neighbor lot
;    RN       INT  id number of the right neighbor lot
;    ON       INT  id number of the opposite side of the street
;                  neighbor
;    SLC      CHAR status of the lot's left corner. If connecting
;                  device transformer or handhole is placed there
;                  Y otherwise N
;    SRC      CHAR status of the lot's right corner. If connecting
;                  device transformer or handhole is placed there
;                  Y otherwise N
;    CONN     CHAR if the lot is already connected Y otherwise N.
;    FRLE     INT  lot frontage length in feet
;    LENGTH INT    length of the secondary runs connecting lot
;                  and transformer or handhole.
;    SIZE     STRING size of the secondary run
;
(setq lots (list 'lot1 'lot2 'lot3 'lot4 'lot5 'lot6 'lot7 'lot8))
;
;define property list for lot1
;
(putprop 'lot1 1 'id)
(putprop 'lot1 's 'sofs)
(putprop 'lot1 'l 'soft)
(putprop 'lot1 0 'ln)
(putprop 'lot1 2 'rn)
(putprop 'lot1 5 'on)
(putprop 'lot1 'n 'slc)
```

```
(putprop 'lot1 'n 'src)
(putprop 'lot1 'n 'conn)
(putprop 'lot1 50 'frle)
(putprop 'lot1 0 'length)
(putprop 'lot1 0 'size)
;
;define property list for lot2
;
(putprop 'lot2 2 'id)
(putprop 'lot2 's 'sofs)
(putprop 'lot2 'l 'soft)
(putprop 'lot2 1 'ln)
(putprop 'lot2 3 'rn)
(putprop 'lot2 6 'on)
(putprop 'lot2 'n 'slc)
(putprop 'lot2 'n 'src)
(putprop 'lot2 'n 'conn)
(putprop 'lot2 40 'frle)
(putprop 'lot2 0 'length)
(putprop 'lot2 0 'size)
;
;define property list for lot3
;
(putprop 'lot3 3 'id)
(putprop 'lot3 's 'sofs)
(putprop 'lot3 'r 'soft)
(putprop 'lot3 2 'ln)
(putprop 'lot3 4 'rn)
(putprop 'lot3 7 'on)
(putprop 'lot3 'y 'slc)
(putprop 'lot3 'n 'src)
(putprop 'lot3 'n 'conn)
(putprop 'lot3 60 'frle)
(putprop 'lot3 0 'length)
(putprop 'lot3 0 'size)
;
;define property list for the lot4
;
(putprop 'lot4 4 'id)
(putprop 'lot4 's 'sofs)
(putprop 'lot4 'r 'soft)
(putprop 'lot4 3 'ln)
(putprop 'lot4 0 'rn)
(putprop 'lot4 8 'on)
(putprop 'lot4 'n 'slc)
(putprop 'lot4 'n 'src)
(putprop 'lot4 'n 'conn)
(putprop 'lot4 50 'frle)
(putprop 'lot4 0 'length)
```

```
(putprop 'lot4 0 'size)
;
;define property list for the lot5
;
(putprop 'lot5 5 'id)
(putprop 'lot5 'o 'sofs)
(putprop 'lot5 'l 'soft)
(putprop 'lot5 0 'ln)
(putprop 'lot5 6 'rn)
(putprop 'lot5 1 'on)
(putprop 'lot5 'n 'slc)
(putprop 'lot5 'y 'src)
(putprop 'lot5 'n 'conn)
(putprop 'lot5 50 'frle)
(putprop 'lot5 0 'length)
(putprop 'lot5 0 'siaze)
;
;define property list for the lot6
;
(putprop 'lot6 6 'id)
(putprop 'lot6 'o 'sofs)
(putprop 'lot6 'l 'soft)
(putprop 'lot6 5 'ln)
(putprop 'lot6 7 'rn)
(putprop 'lot6 2 'on)
(putprop 'lot6 'y 'slc)
(putprop 'lot6 'n 'src)
(putprop 'lot6 'n 'conn)
(putprop 'lot6 40 'frle)
(putprop 'lot6 0 'length)
(putprop 'lot6 0 'size)
;
;define property list for the lot7
;
(putprop 'lot7 7 'id)
(putprop 'lot7 'o 'sofs)
(putprop 'lot7 'r 'soft)
(putprop 'lot7 6 'ln)
(putprop 'lot7 8 'rn)
(putprop 'lot7 3 'on)
(putprop 'lot7 'n 'slc)
(putprop 'lot7 'y 'src)
(putprop 'lot7 'n 'conn)
(putprop 'lot7 60 'frle)
(putprop 'lot7 0 'length)
(putprop 'lot7 0 'size)
;
;define property list for the lot8
;
```

```
(putprop 'lot8 8 'id)
(putprop 'lot8 'o 'sofs)
(putprop 'lot8 'r 'soft)
(putprop 'lot8 7 'ln)
(putprop 'lot8 0 'rn)
(putprop 'lot8 4 'on)
(putprop 'lot8 'y 'slc)
(putprop 'lot8 'n 'src)
(putprop 'lot8 'n 'conn)
(putprop 'lot8 50 'frle)
(putprop 'lot8 0 'length)
(putprop 'lot8 0 'size)
;
;==========================================================
;==========================================================

(setq connected 'connected)
(putprop 'connected 'n 'conall)

(setq sized 'sized)
(putprop 'sized 'n 'sizall)
```

Secondary Runs Designer Prototype (LISP Source Program List)

```
;============================================================
;============================================================
;
;APD ()
;
;PURPOSE:   Main function (program) that emulates operation
;           of the production system in the following way:
;           Rules are applied at the element of the working
;           memory elements (WME) and fired if that element
;           satisfies set of the conditions given in the left hand
;           side of the rule. RHS of the rule than usually change
;           one or more attributes in the WME which in turn cause
;           another rule to be fired. In a such way system is
;           moving toward solution which will be reached when all
;           lots are connected and all conductors are checked.
;           Using APPLY mode of the rule each rule is
;           browsed through all WME. The rules will be applied
;           continuously in the loop until the solution is reached.
;           Program control  emulates data driven forward
;           chaining inferencing procedure.

(DEFUN APD ()
  (PROG  ()
LOOP
    (APPLY_RULE_1)
    (APPLY_RULE_2)
    (APPLY_RULE_3)
    (APPLY_RULE_4)
    (APPLY_RULE_5)
    (APPLY_CHECK_CONN)
    (APPLY_RULE_SIZE)
    (APPLY_FAULT_RULE)
    (COND
      ((EQUAL  (GET SIZED 'SIZALL) 'Y) (RETURN t))
    )
  )
)
;============================================================
;============================================================
;  RULE_1  (I)
;
;  PURPOSE: rule for connecting lot to the transformer placed in
;             one of its corners.
;
;  PARAMETERS:
;    I   INT    an integer indicating lot number as a element of the
```

```
;               ordered list LOTS
;
(DEFUN RULE_1 (I)
  (COND
    ((AND
;
;if i-th lot is on the same side of the street as transformer
;
       (EQ (GET (GETNTH I LOTS) 'SOFS) 'S)
;
;and it is not connected yet
;
       (EQ (GET (GETNTH I LOTS) 'CONN) 'N)
;
;and provision for connecting exist in its left or right corner
;
       (OR
         (EQ (GET (GETNTH I LOTS) 'SLC) 'Y)
         (EQ (GET (GETNTH I LOTS) 'SRC) 'Y)))
;
;then connect i-th lot to the transformer
;and print rule1 is fired
;
       (PUTPROP (GETNTH I LOTS) 'Y 'CONN)
       (PRIN1 'RULE_11) (TYO 32)(PRINT (GET (GETNTH I LOTS) 'ID)))
    (T (SETQ I I))
  )
)
;
;
;------------------------------------------------------------------------------------------------
;  APPLY_RULE_1 ()
;
;  PURPOSE:  to browse through the "working memory elements"  (list of lots)
;            with rule 1
;
(DEFUN APPLY_RULE_1 ()
  (PROG (I)
    (SETQ I 0)
    (DO_N_TIMES 8 (SETQ I (ADD1 I)) (RULE_1 I))
  )
)

;
;=============================================================
;=============================================================
;  RULE_2 (I)
;
;  PURPOSE: set of rules applicable for connecting lots which are
;           on the  same side of the street on the left side of the
```

```
;               transformer.
;
; PARAMETERS:
;   I  INT    an integer indicating lot number as an element of the
;               ordered list LOTS
;
(DEFUN RULE_2 (I)
  (PROG (J K L1 L2)
;
; LOCAL VARS:
;   J   INT  #id of the i-th lot right neighbor
;   K   INT  #id of the j-th lot right neighbor
;   L1  INT  length of the frontage of the j-th lot
;   L2  INT  length of the frontage of the k-th lot
;
  (COND
   ((AND
;
;set of  general conditions for lots which are left of the X-former
;on the same side of the street
;
;IF i-th lot is not connected yet
;
      (EQ (GET (GETNTH I LOTS) 'CONN) 'N)
;
;and it is on the left side of the transformer
;
      (EQ (GET (GETNTH I LOTS) 'SOFT) 'L)
;
;and it is on the same side of the street as transformer
;
      (EQ (GET (GETNTH I LOTS) 'SOFS) 'S)
;
;and transformer is not in its left or right corner
;
      (EQ (GET (GETNTH I LOTS) 'SLC) 'N)
      (EQ (GET (GETNTH I LOTS) 'SRC) 'N))
;
;THEN set J to id of its right neighbor
;      K to id of the right neighbor of the right neighbor
;      L1 to frontage length of j-th lot
;      L2 to frontage length of k-th lot
;
      (SETQ J (GET (GETNTH I LOTS) 'RN))
      (SETQ K (GET (GETNTH J LOTS) 'RN))
      (SETQ L1 (GET (GETNTH J LOTS) 'FRLE))
      (SETQ L2 (GET (GETNTH K LOTS) 'FRLE))

      (COND
```

```
;
;IF there is a transformer in left corner of the j-th lot
;THEN connect i-th lot to it and print RULE_21 fired with i-th lot id
;
        ((EQ (GET (GETNTH J LOTS) 'SLC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y  'CONN) (PRIN1 'RULE_21) (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the right corner of the j-th lot
;THEN connect i-th lot to it, store L1 in its property list as
;conductor length and print RULE_22 fired together with i-th lot id
;
        ((EQ (GET (GETNTH J LOTS) 'SRC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) L1 'LENGTH) (PRIN1 'RULE_22)
(TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the left corner of the k-th lot
;THEN connect i-th lot to it, store L1 in its property list as
;conductor length and print RULE_23 fired together with i-th lot id

        ((EQ (GET (GETNTH K LOTS) 'SLC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) L1 'LENGHT) (PRIN1 'RULE_23)
(TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is transformer in the right corner of the k-th lot
;THEN connect i-th lot to it, store L1+L2 in its property list as
;conductor length and print RULE_24 fired together with i-th lot id
;
        ((EQ (GET (GETNTH K LOTS) 'SRC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) (PLUS L1 L2) 'LENGTH)  (PRIN1
'RULE_24) (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
        (T (SETQ I I))
      )
    )
    (T (SETQ I I))
  )
  )
)
;
;
;------------------------------------------------------------------------------------------------
;  APPLY_RULE_2 ()
;
;  PURPOSE:  to browse through the "working memory elements"
;              (list of lots) with rule 2
;
(DEFUN APPLY_RULE_2 ()
  (PROG (I)
    (SETQ I 0)
    (DO_N_TIMES 8 (SETQ I (ADD1 I)) (RULE_2 I))
  )
```

```
)

;
;================================================================
;================================================================
; RULE_3 (I)
;
; PURPOSE: set of rules applicable for connecting lots which are
;          on the same side of the street on the right side of the
;          transformer
;
; PARAMETERS:
;   I  INT    an integer indicating lot number as an element of the
;             ordered list LOTS

(DEFUN RULE_3 (I)
 (PROG (J K L1 L2)
;
; LOCAL VARS:
;  J    INT  #id of the i-th lot left neighbor
;  K    INT  #id of the j-th lot left neighbor
;  L1   INT  length of the frontage of the j-th neighbor
;  L2   INT  length of the frontage of the k-th neighbor
;
 (COND
  ((AND
;
;set of the general conditions for lots which are right of the
;X-former on the same side of the street
;
;IF i-th lot is not connected yet
;
     (EQ (GET (GETNTH I LOTS) 'CONN) 'N)
;
;and it is on the right side of the transformer
;
     (EQ (GET (GETNTH I LOTS) 'SOFT) 'R)
;
;and it is on the same side of the street as transformer
;
     (EQ (GET (GETNTH I LOTS) 'SOFS) 'S)
;
;and transformer is not in its left or right corner
;
     (EQ (GET (GETNTH I LOTS) 'SLC) 'N)
     (EQ (GET (GETNTH I LOTS) 'SRC) 'N))
;
;Than set J to the #id of its left neighbor
;      K to the #id of the left neighbor of the left neighbor
```

```
;      L1 to frontage length of j-th lot
;      L2 to frontage length of k-th lot
;
       (SETQ J (GET (GETNTH I LOTS) 'LN))
       (SETQ K (GET (GETNTH J LOTS) 'LN))
       (SETQ L1 (GET (GETNTH J LOTS) 'FRLE))
       (SETQ L2 (GET (GETNTH K LOTS) 'FRLE))
       (COND
;
;IF there is a transformer in right corner of the j-th lot
;THEN connect i-th lot to it and print RULE_31 fired with i-th lot
;id
;
         ((EQ (GET (GETNTH J LOTS) 'SRC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y'CONN) (PRIN1 'RULE_31) (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the left corner of the j-th lot
;THEN connect i-th lot to it, store L1 in its property list as
;conductor length and print RULE_32 fired together with i-th lot id
;
         ((EQ (GET (GETNTH J LOTS) 'SLC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) L1 'LENGTH)(PRIN1 'RULE_32)
(TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the right corner of the k-th lot
;THEN connect i-th lot to it, store L1 in its property list as a conductor
;length and print RULE_33 fired together with i-th lot id
;
         ((EQ (GET (GETNTH K LOTS) 'SRC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) L1 'LENGTH)
      (PRIN1 'RULE_33) (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the left corner of the k-th lot
;THEN connect i-th lot to it, store L1+L2 in its property list as a conductor
;length and print RULE_34 fired together with i-th lot id
;
         ((EQ (GET (GETNTH K LOTS) 'SLC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) (PLUS L1 L2) 'LENGTH)
      (PRIN1 'RULE_34) (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
         (T (SETQ I I))
       )
    )
    (T (SETQ I I))
  )
  )
)
;
;------------------------------------------------------------------------------------------------
;  APPLY_RULE_3 ()
```

```
;
; PURPOSE:  to browse through the "working memory elements" (list of lots)
;           with rule 3
;
(DEFUN APPLY_RULE_3 ()
  (PROG (I)
    (SETQ I 0)
    (DO_N_TIMES 8 (SETQ I (ADD1 I)) (RULE_3 I))
  )
)

;
;==============================================================
;==============================================================
; RULE_4 (I)
;
; PURPOSE:  set of rules applicable for connecting lots which are on the
;           left side of the transformer on the opposite side of the street
;
; PARAMETERS:
;   I  INT    an integer indicating lot number as a element of the
;             ordered list LOTS
;
(DEFUN RULE_4 (I)
  (PROG (M J K L1 L2 L3)
;
; LOCAL VARS:
;   M   INT  #id of the lot on the opposite side of the street
;   J   INT  #id of the m-th lot right neighbor
;   K   INT  #id of the j-th lot right neighbor
;   L1  INT  m-th lot frontage length
;   L2  INT  j-th lot frontage length
;   L3  INT  k-th lot frontage length
;
  (COND
    ((AND
;
;set of the general condition for lots on the opposite side of the street
;on the left side of the transformer
;
;IF i-th lot is not connected yet
;
       (EQ (GET (GETNTH I LOTS) 'CONN) 'N)
;
;and it is on the left side of the transformer
;
       (EQ (GET (GETNTH I LOTS) 'SOFT) 'L)
;
;and it is on the opposite side of the street
```

```
;
      (EQ (GET (GETNTH I LOTS) 'SOFS) 'O)
;
;and there is provision for connection in left or right corner of the lot
;
      (OR
        (EQ (GET (GETNTH I LOTS) 'SLC) 'Y)
        (EQ (GET (GETNTH I LOTS) 'SRC) 'Y)))
;
;THEN set M to id# of the lot on the opposite side of the street
;       J to id# of the right neighbor of M
;       K to id# of the right neighbor of the right neighbor of M
;       L1 to frontage length of M
;       L2 to frontage length of J
;       L3 to frontage length of K
;

      (SETQ M (GET (GETNTH I LOTS) 'ON))
      (SETQ J (GET (GETNTH M LOTS) 'RN))
      (SETQ K (GET (GETNTH J LOTS) 'RN))
      (SETQ L1 (GET (GETNTH M LOTS) 'FRLE))
      (SETQ L2 (GET (GETNTH J LOTS) 'FRLE))
      (SETQ L3 (GET (GETNTH K LOTS) 'FRLE))

      (COND
        ((AND
;
;IF there is a transformer at the lot M and it is in the same corner as
;connecting provisions in the i-th lot
;THEN connect i-th lot to transformer, store 20 in its property list as
;a conductor length (20 stands for street crossing) and print RULE_41
;fired together with i-th lot id
;
          (OR
          (EQ (GET (GETNTH M LOTS) 'SLC) 'Y)
          (EQ (GET (GETNTH M LOTS) 'SRC) 'Y))
          (EQ (GET (GETNTH M LOTS) 'SLC) (GET (GETNTH I LOTS) 'SLC)))
          (PUTPROP (GETNTH I LOTS) 'Y 'CONN)
          (PUTPROP (GETNTH I LOTS) 20 'LENGTH)(PRIN1 'RULE_41)(TYO
32)
          (PRINT (GET (GETNTH I LOTS) 'ID)))
        ((AND
;
;IF there is a transformer at the lot M and it is not in the same corner as
;connecting provisions in the i-th lot
;THEN connect i-th lot to transformer, store L1+20 in its property list as
;a conductor length and print RULE_42 fired together with i-th lot id
;
          (OR
```

```
        (EQ (GET (GETNTH M LOTS) 'SLC) 'Y)
        (EQ (GET (GETNTH M LOTS) 'SRC) 'Y))
        (EQ (GET (GETNTH M LOTS) 'SRC) (GET (GETNTH I LOTS) 'SLC)))
        (PUTPROP (GETNTH I LOTS) 'Y 'CONN)
        (PUTPROP (GETNTH I LOTS) (PLUS L1 20) 'LENGTH) (PRIN1
'RULE_42)  (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the left corner of the j-th lot
;THEN connect i-th lot to it, store L1+20 in its property list as
;a conductor length and print RULE_43 fired together with lot i id#
;
        ((EQ (GET (GETNTH J LOTS) 'SLC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) (PLUS L1 20) 'LENGTH) (PRIN1
'RULE_43)  (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the right corner of the j-th lot
;THEN connect i-th lot to it, store L2+20 in its property list as
;a conductor length and print RULE_44 fired together with lot i id#
;
        ((EQ (GET (GETNTH J LOTS) 'SRC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) (PLUS L2 20) 'LENGTH) (PRIN1
'RULE_44) (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the left corner of the k-th lot
;THEN connect i-th lot to it, store L2+20 in its property list as
;a conductor length and print RULE_45 fired together with lot i id#
;
        ((EQ (GET (GETNTH K LOTS) 'SLC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) (PLUS L2 20) 'LENGTH) (PRIN1
'RULE_45) (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the right corner of the k-th lot
:THEN connect i-th lot to it, store L1+L2 in its property list as
;a conductor length and print RULE_46 fired together with lot i id#
;
        ((EQ (GET (GETNTH K LOTS) 'SRC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) (PLUS L1 L2 20) 'LENGTH) (PRIN1
'RULE_46) (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
        (T (SETQ I I))
      )
    )
    (T (SETQ I I))
  )
  )
)
;
;------------------------------------------------------------------------------------------
;  APPLY_RULE_4 ()
;
```

```
;  PURPOSE:  to browse through the "working memory elements" (list of lots)
;                with rule 4
;
(DEFUN APPLY_RULE_4 ()
  (PROG (I)
    (SETQ I 0)
    (DO_N_TIMES 8 (SETQ I (ADD1 I)) (RULE_4 I))
  )
)
;
;===========================================================
;===========================================================
;  RULE_5 (I)
;
;  PURPOSE:  set of rules applicable for  connecting lots which are
;                on the opposite side of the street right of the transformer
;
;  PARAMETERS:
;     I   INT    an integer indicating lot number as a element of the ordered
;                list LOTS
;
(DEFUN RULE_5 (I)
  (PROG (M J K L1 L2 L3)
;
;  LOCAL VARS:
;     M    INT  #id of the lot on the opposite side of the street
;     J   INT  #id of the m-th lot left neighbor
;     K   INT  #id of the j-th lot left neighbor
;     L1   INT   m-th lot frontage length
;     L2   INT   j-th lot frontage length
;     L3   INT   k-th lot frontage length
;
  (COND
    ((AND
;
;set of the general conditions for the lots on the opposite side of the street
;on the left side of the transformer
;
;IF i-th lot is not connected yet
;
       (EQ (GET (GETNTH I LOTS) 'CONN) 'N)
;
;and it is on the right side of the transformer
;
       (EQ (GET (GETNTH I LOTS) 'SOFT) 'R)
;
;and it is on the opposite side of the street
;
       (EQ (GET (GETNTH I LOTS) 'SOFS) 'O)
```

```
;
;and there is provision for connection in the left or right lot corner
;
        (OR
          (EQ (GET (GETNTH I LOTS) 'SLC) 'Y)
          (EQ (GET (GETNTH I LOTS) 'SRC) 'Y)))
;
;THEN set M to id# of the lot on the opposite side of the street
;       J to id# of the left neighbor of M
;       K to id# of the left neighbor of J
;       L1 to frontage length of M
;       L2 to frontage length of J
;       L3 to frontage length of K
;
        (SETQ M (GET (GETNTH I LOTS) 'ON))
        (SETQ J (GET (GETNTH M LOTS) 'LN))
        (SETQ K (GET (GETNTH J LOTS) 'LN))
        (SETQ L1 (GET (GETNTH M LOTS) 'FRLE))
        (SETQ L2 (GET (GETNTH J LOTS) 'FRLE))
        (SETQ L3 (GET (GETNTH K LOTS) 'FRLE))

        (COND
          ((AND
;
;IF there is a transformer at the lot M and it is in the same corner as
;a connecting provisions in the i-th lot
:THEN connect i-th lot to the transformer, store 20 in its property list as
;a conductor length (20 stands for street crossing) and print  RULE_51
;fired together with i-th lot id
;
             (OR
             (EQ (GET (GETNTH M LOTS) 'SLC) 'Y)
             (EQ (GET (GETNTH M LOTS) 'SRC) 'Y))
             (EQ (GET (GETNTH M LOTS) 'SLC) (GET (GETNTH I LOTS) 'SLC)))
              (PUTPROP (GETNTH I LOTS) 'Y 'CONN)
              (PUTPROP (GETNTH I LOTS) 20 'LENGTH) (PRIN1 'RULE_51) (TYO
32)
              (PRINT (GET (GETNTH I LOTS) 'ID)))
            ((AND
;
;IF there is a transformer at the lot M and it is not in the same corner as
;a connecting provisions in the i-th lot
;THEN connect i-th lot to the transformer, store L1+20 in its property list as
;a conductor length and print RULE_52 fired together with i-th lot id
;
             (OR
             (EQ (GET (GETNTH M LOTS) 'SLC) 'Y)
             (EQ (GET (GETNTH M LOTS) 'SRC) 'Y))
             (EQ (GET (GETNTH M LOTS) 'SRC) (GET (GETNTH I LOTS) 'SLC)))
```

```
        (PUTPROP (GETNTH I LOTS) 'Y 'CONN)
        (PUTPROP (GETNTH I LOTS) (PLUS L1 20) 'LENGTH) (PRIN1
'RULE_52) (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the right corner of the j-th lot
;THEN connect i-th lot to it, store L1+20 in its property list as
;a conductor length and print RULE_53 fired together with i-th lot id
;
        ((EQ (GET (GETNTH J LOTS) 'SRC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) (PLUS L1 20) 'LENGTH) (PRIN1
'RULE_53) (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the left corner of the j-th lot
;THEN connect i-th lot to it, store L2+20 in its property list as
;a conductor length and print RULE_54 fired together with i-th lot id#
;
        ((EQ (GET (GETNTH J LOTS) 'SLC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) (PLUS L2 20) 'LENGTH) (PRIN1
'RULE_54)  (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the right corner of the k-th lot
;THEN connect i-th lot to it, store L2+20 in its property list as
;a conductor length and print RULE_55 fired together with i-th lot id#
;
        ((EQ (GET (GETNTH K LOTS) 'SRC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y
 'CONN) (PUTPROP (GETNTH I LOTS) (PLUS L2 20) 'LENGTH) (PRIN1
'RULE_55) (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
;
;IF there is a transformer in the right corner of the k-th lot
;THEN connect i-th lot to it, store L1+L2+20 in its property list as
; a conductor length and print RULE_56 fired together with i-th lot id#
;
        ((EQ (GET (GETNTH K LOTS) 'SLC) 'Y) (PUTPROP (GETNTH I LOTS)
'Y 'CONN) (PUTPROP (GETNTH I LOTS) (PLUS L1 L2 20) 'LENGTH) (PRIN1
'RULE_56) (TYO 32) (PRINT (GET (GETNTH I LOTS) 'ID)))
        (T (SETQ I I))
      )
    )
    (T (SETQ I I))
  )
  )
)
;
;
;------------------------------------------------------------------------------------------
; APPLY_RULE_5 ()
;
; PURPOSE: to browse through the "working memory elements" (list of lots)
;             with rule 5
```

```
;
(DEFUN APPLY_RULE_5 ()
  (PROG (I)
    (SETQ I 0)
    (DO_N_TIMES 8 (SETQ I (ADD1 I)) (RULE_5 I))
  )
)
;
;=============================================================
;=============================================================
;  RULE_SIZE  (I)
;
;  PURPOSE:  to select appropriate conductor size based on length  conductor
;               length
;
;  PARAMETERS:
;    I   INT     an integer indicating lot number as a element of the
;                ordered list LOTS
;

(DEFUN RULE_SIZE (I)
  (PROG (J L)
;
;  LOCAL VARS:
;      J  INT  #id  of the i-th lot
;      L   INT  length of the conductor connecting lot i to transformer
;
    (SETQ J (GET (GETNTH I LOTS) 'ID))
    (SETQ L (PLUS 20 (GET (GETNTH I LOTS) 'LENGTH)))
    (COND
;
;IF the conductor length is larger than 40
;THEN chose wire size 4/0 and print together with lot id#
;
      ((LESSP 40 L) (PUTPROP (GETNTH I LOTS) 4 'SIZE)
       (PRIN1 'LOT) (PRIN1 J) (TYO 32) (PRIN1 'CONDUCTOR_LENGTH) (TYO
32) (PRIN1 L) (TYO 32) (PRIN1 'FEET) (TYO 32 ) (PRIN1 'CONDUCTOR_SIZE)
      (TYO 32) (PRINT (GET (GETNTH I LOTS) 'SIZE)))
;
;IF the conductor length is smaller than 40
;THEN chose wire size 1/0 and print it together with lot id#
;
       (T (PUTPROP (GETNTH I LOTS) 1 'SIZE)
       (PRIN1 'LOT) (PRIN1 J) (TYO 32) (PRIN1 'CONDUCTOR_LENGTH) (TYO
32) (PRIN1 L) (TYO 32) (PRIN1 'FEET) (TYO 32) (PRIN1 'CONDUCTOR_SIZE)
       (TYO 32) (PRINT (GET (GETNTH I LOTS) 'SIZE)))
    )
  )
)
```

```
;
;---------------------------------------------------------------------------------------------
; APPLY_RULE_SIZE ()
;
; PURPOSE: check if all lots are connected and if so put SIZALL in
;          the property list of the flag SIZED
;
(DEFUN APPLY_RULE_SIZE ()
 (PROG (I)
  (COND
   ((EQUAL (GET CONNECTED 'CONALL) 'Y)
    (SETQ I 0)
    (DO_N_TIMES 8 (SETQ I (ADD1 I)) (RULE_SIZE I))
    (PUTPROP SIZED 'Y 'SIZALL))
   (T (SETQ I 1))
  )
 )
)
;
;================================================================
;================================================================
; RULE_FAULT_LIMIT (I)
;
; PURPOSE: check if all lots conductors are properly sized from the point
;          of view of the fault current limits
;
; PARAMETERS:
;  I  INT   an integer indicating lot number as a element of the ordered
;           list LOTS
;
(DEFUN RULE_FAULT_LIMIT (I)
 (PROG (L S)
;
; LOCAL VARS:
;  L  INT    conductor length for the i-th lot
;  S  STRING wire size of the i-th lot conductor
;
   (SETQ L (PLUS 20 (GET (GETNTH I LOTS) 'LENGTH)))
   (SETQ S (GET (GETNTH I LOTS) 'SIZE))
    (COND
     ((AND
;
;IF length of the conductor is less than 40 and size is 1/0
;THEN print warning message together with lot id#
;
       (LESSP L 40)
       (EQUAL S 1)) (PRIN1 '**WARNING**LOT)(PRIN1 I)(TYO 32)
       (PRINT 'CONDUCTOR_LENGTH_MUST_BE_INCREASED**))
     ((AND
```

```
;
;IF length of the conductor is less than 80 and size is 4/0
;THEN print warning message together with lot id#
;
          (LESSP L 80)
          (EQUAL S 4)) (PRIN1 '**WARNING**LOT)(PRIN1 I)(TYO 32)
          (PRINT 'CONDUCTOR_LENGTH_MUST_BE_INCREASED**))
        (T (SETQ I I))
      )
    )
)
;
;
;---------------------------------------------------------------------------------------------------
;  APPLY_FAULT_RULE ()
;
;  PURPOSE:  check if all lots conductors are sized and if so go with
;               rule_fault_limit through the "working memory elements"
;
;

(DEFUN APPLY_FAULT_RULE ()
  (PROG (I)
    (COND
      ((EQ (GET SIZED 'SIZALL) 'Y)
       (SETQ I 0)
       (DO_N_TIMES 8 (SETQ I (ADD1 I)) (RULE_FAULT_LIMIT I)))
      (T (SETQ I 1))
    )
  )
)
;=============================================================
;=============================================================
;  CHECK_CONN ()
;
;  PURPOSE:  check and count how many lots are connected and
;               return that number
;
;


(DEFUN CHECK_CONN ()
   (PROG (I NO)
;
;  LOCAL VARS:
;    I   INT   an integer indicating lot number  as an element of the
;            ordered list LOTS
;    NO   INT   number of the lots connected so far
;
    (SETQ I 0)
    (SETQ NO 0)
      (DO_N_TIMES 8 (SETQ I (ADD1 I))
```

```
      (COND
        ((EQ (GET (GETNTH I LOTS) 'CONN) 'Y) (SETQ NO (ADD1 NO)))
        (T (SETQ I I))
      )
    ) (RETURN NO)
  )
)

;
;------------------------------------------------------------------------------------------
;  APPLY_CHECK_CONN ()
;
;  PURPOSE:  check if the all lots in the "working memory elements " are
;            connected and if so put CONALL in the property list of the flag
;            CONECTED
;
(DEFUN APPLY_CHECK_CONN ()
  (COND
    ((EQUAL (CHECK_CONN) 8) (PUTPROP CONNECTED 'Y 'CONALL))
    (T (PUTPROP CONNECTED 'N 'CONALL))
  )
)
;
;==============================================================
;==============================================================
```

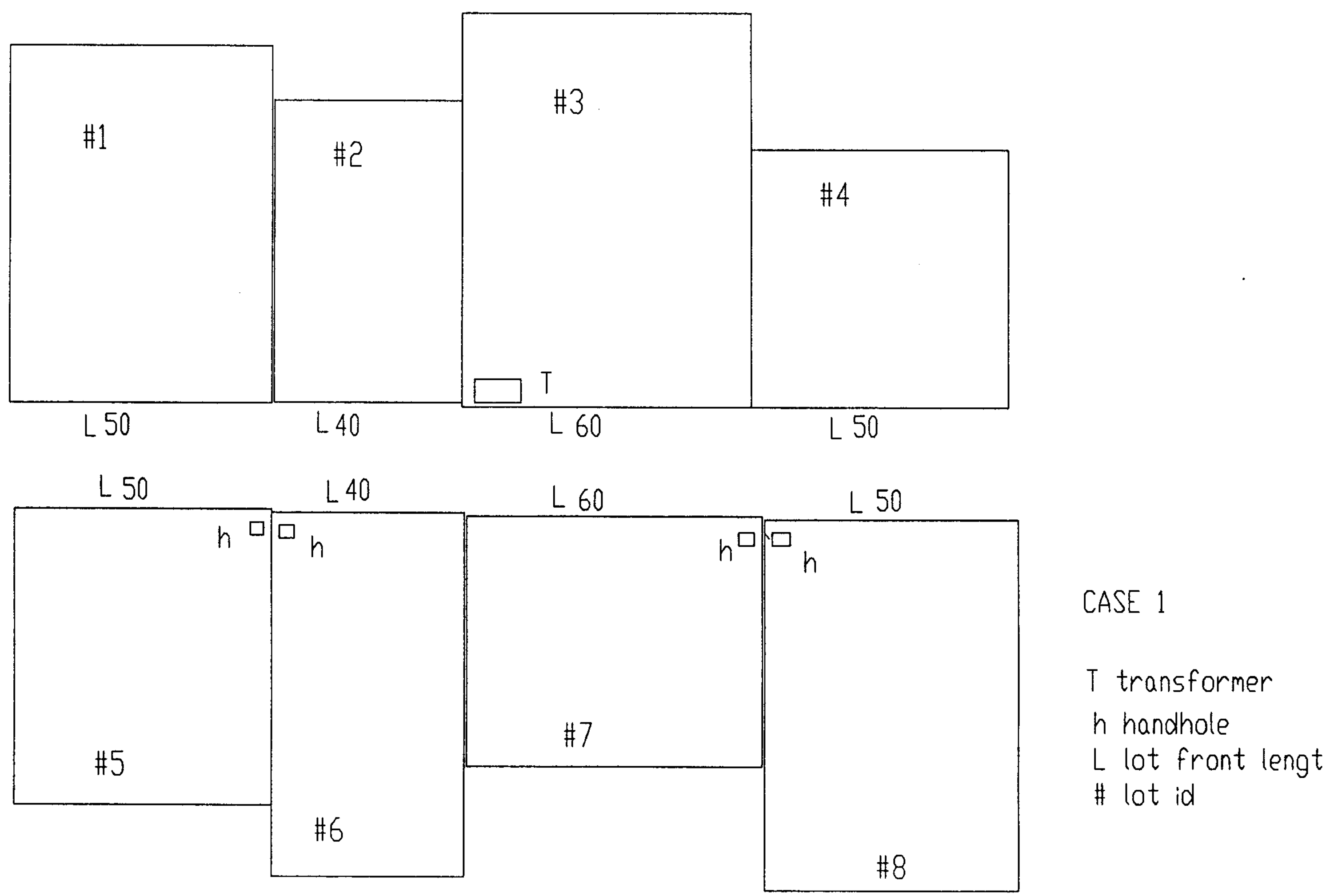

Figure 38. Appendix C: Case 1 Transformer, Handhole & Lots Arrangement

```
(A:RESULT1.LSP)

 >> (APD)

RULE_11 3
RULE_23 1
RULE_21 2
RULE_32 4
RULE_47 5
RULE_44 6
RULE_52 7
RULE_54 8

LOT1 CONDUCTOR_LENGTH 60 FEET CONDUCTOR_SIZE 4
LOT2 CONDUCTOR_LENGTH 20 FEET CONDUCTOR_SIZE 1
LOT3 CONDUCTOR_LENGTH 20 FEET CONDUCTOR_SIZE 1
LOT4 CONDUCTOR_LENGTH 80 FEET CONDUCTOR_SIZE 4
LOT5 CONDUCTOR_LENGTH 80 FEET CONDUCTOR_SIZE 4
LOT6 CONDUCTOR_LENGTH 80 FEET CONDUCTOR_SIZE 4
LOT7 CONDUCTOR_LENGTH 100 FEET CONDUCTOR_SIZE 4
LOT8 CONDUCTOR_LENGTH 100 FEET CONDUCTOR_SIZE 4

**WARNING**LOT1 CONDUCTOR_LENGTH_MUST_BE_INCREASED**
**WARNING**LOT2 CONDUCTOR_LENGTH_MUST_BE_INCREASED**
**WARNING**LOT3 CONDUCTOR_LENGTH_MUST_BE_INCREASED**

T

  >> (EXIT)
```

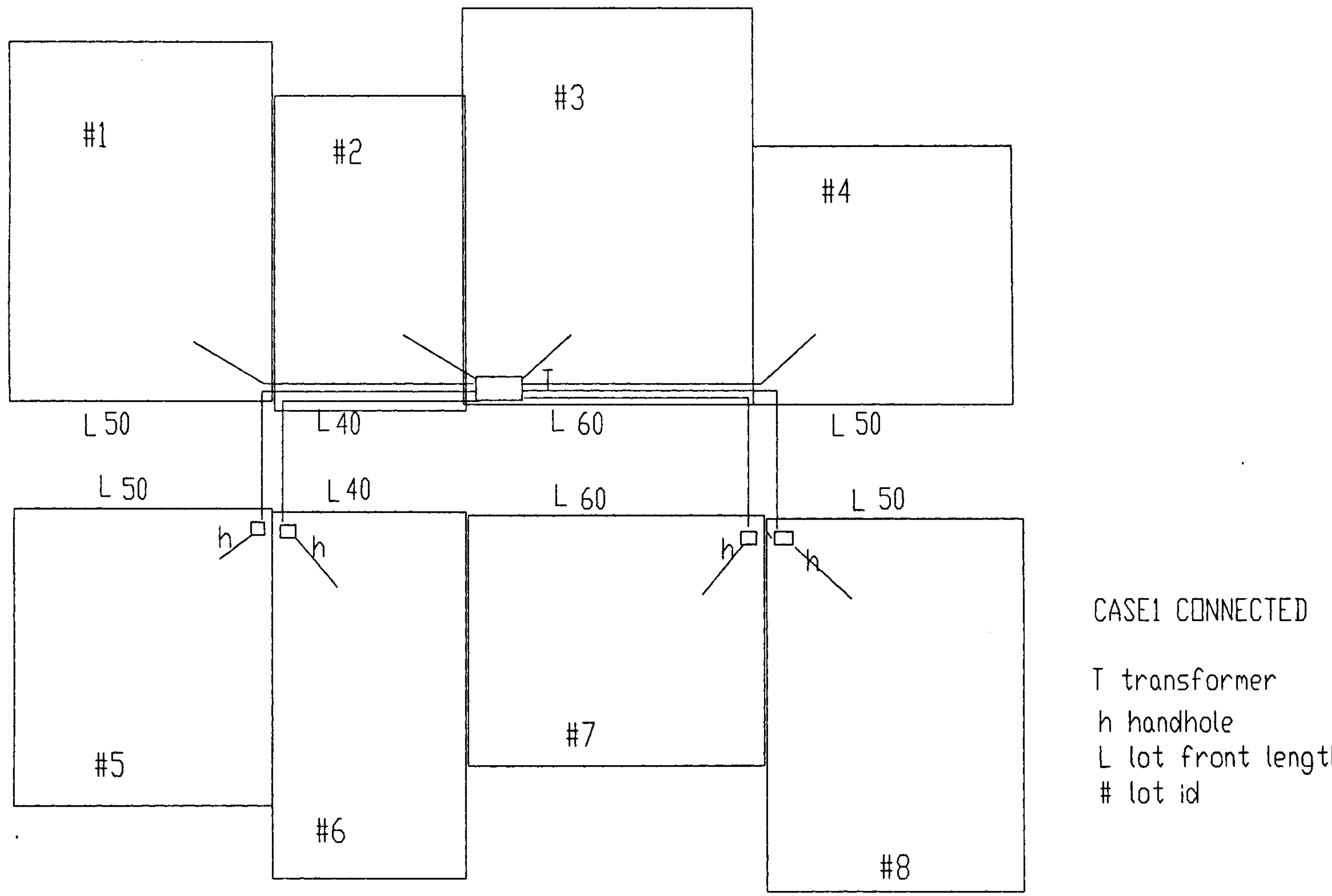

Figure 39. Appendix C: Case 1 Lots Connection

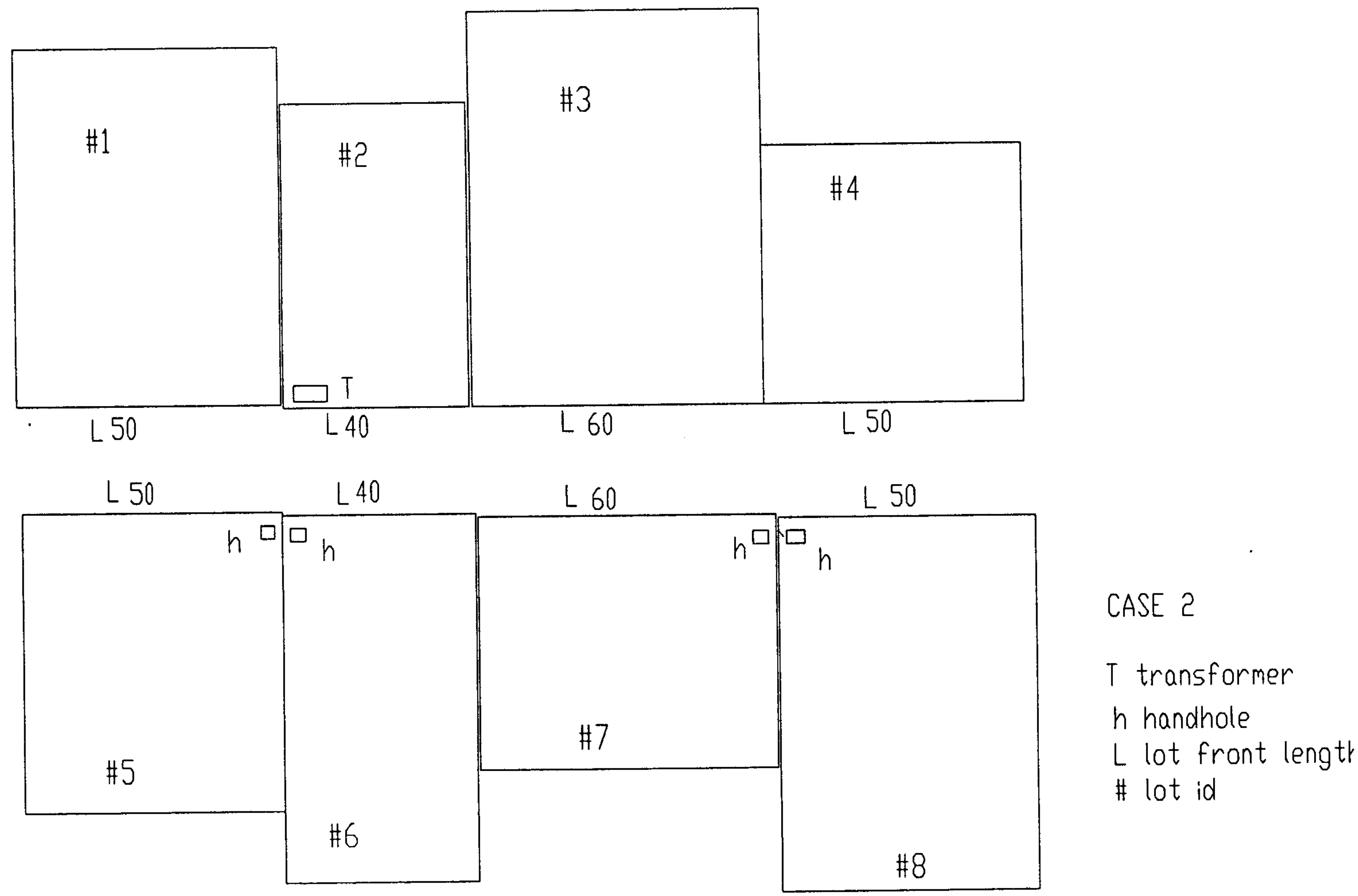

Figure 40. Appendix C: Case 2 Transformer, Handhole & Lots Arrangement

```
(A:RESULT2.LSP)

 >> (APD)

RULE_11 2
RULE_21 1
RULE_32 3
RULE_34 4
RULE_43 5
RULE_51 6
RULE_56 7
RULE_58 8

LOT1 CONDUCTOR_LENGTH 20 FEET CONDUCTOR_SIZE 1
LOT2 CONDUCTOR_LENGTH 20 FEET CONDUCTOR_SIZE 1
LOT3 CONDUCTOR_LENGTH 60 FEET CONDUCTOR_SIZE 4
LOT4 CONDUCTOR_LENGTH 120 FEET CONDUCTOR_SIZE 4
LOT5 CONDUCTOR_LENGTH 40 FEET CONDUCTOR_SIZE 1
LOT6 CONDUCTOR_LENGTH 40 FEET CONDUCTOR_SIZE 1
LOT7 CONDUCTOR_LENGTH 140 FEET CONDUCTOR_SIZE 4
LOT8 CONDUCTOR_LENGTH 140 FEET CONDUCTOR_SIZE 4

**WARNING**LOT1 CONDUCTOR_LENGTH_MUST_BE_INCREASED**
**WARNING**LOT2 CONDUCTOR_LENGTH_MUST_BE_INCREASED**
**WARNING**LOT3 CONDUCTOR_LENGTH_MUST_BE_INCREASED**

T

 >> (EXIT)
```

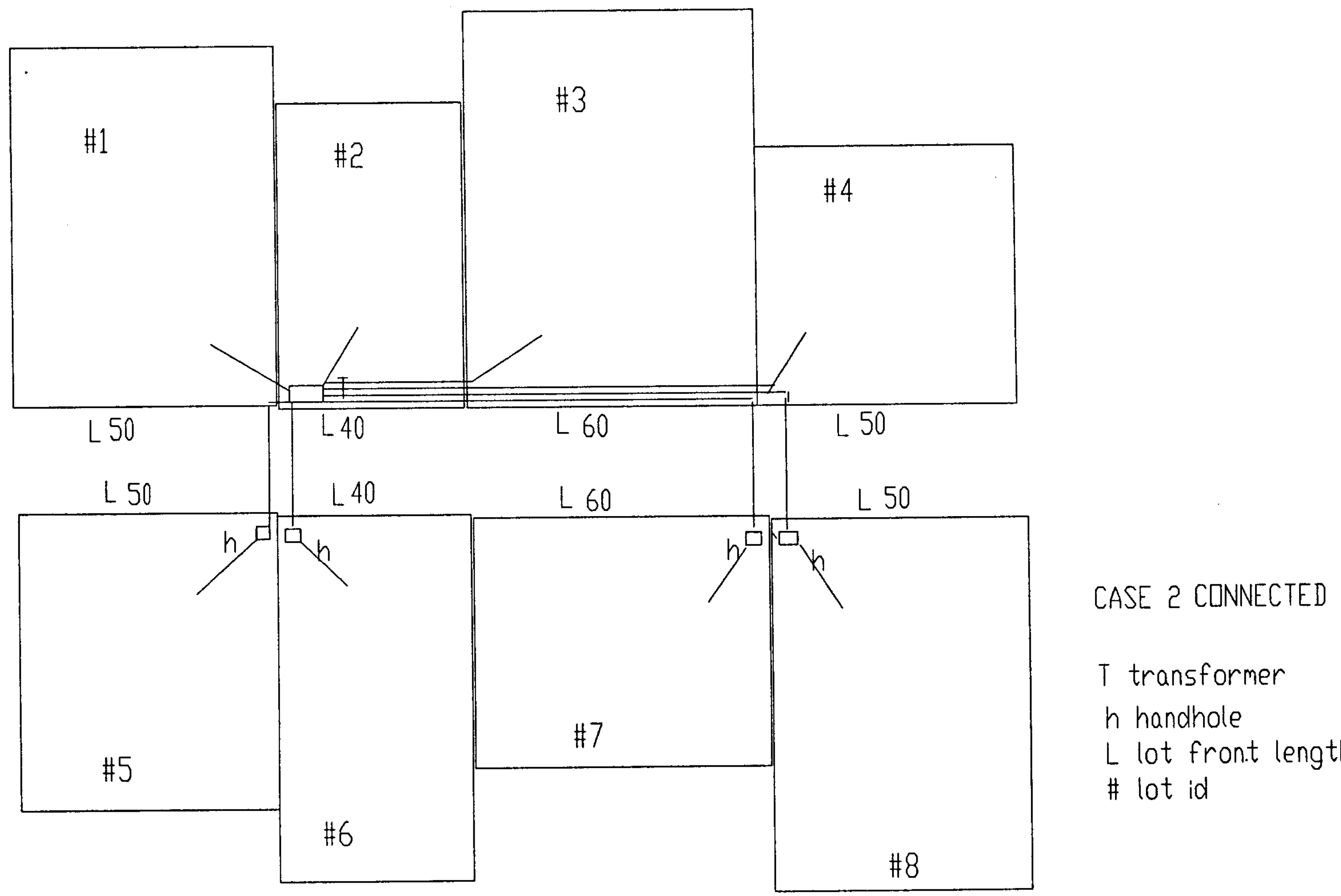

Figure 41. Appendix C: Case 2 Lots Connection

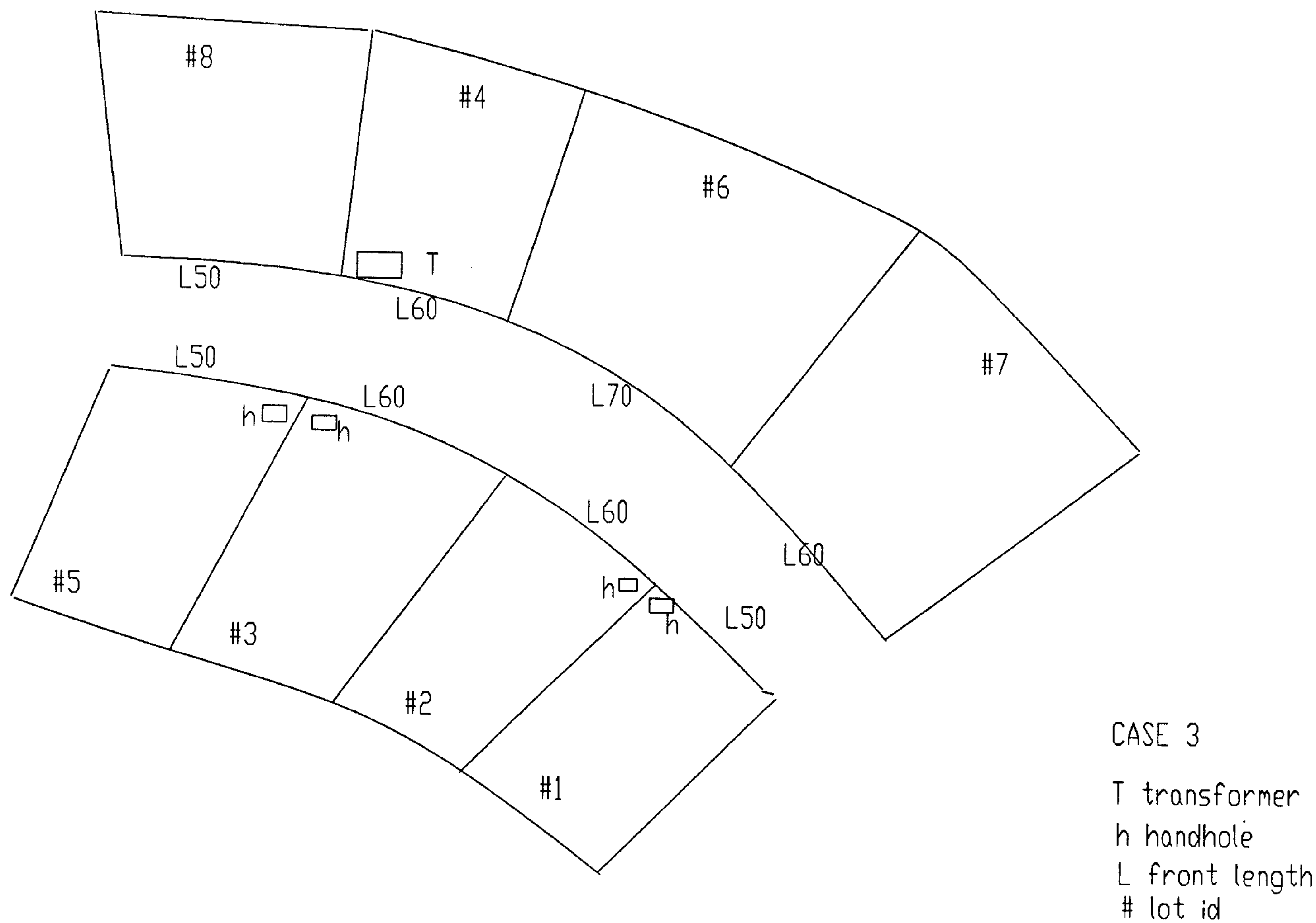

Figure 42. Appendix C: Case 3 Transformer, Handhole & Lots Arrangement

```
(A:RESULT3.LSP)

 >> (APD)

RULE_11 4
RULE_21 8
RULE_32 6
RULE_34 7
RULE_43 5
RULE_58 1
RULE_56 2
RULE_51 3

LOT1 CONDUCTOR_LENGTH 160 FEET CONDUCTOR_SIZE 4
LOT2 CONDUCTOR_LENGTH 160 FEET CONDUCTOR_SIZE 4
LOT3 CONDUCTOR_LENGTH 40 FEET CONDUCTOR_SIZE 1
LOT4 CONDUCTOR_LENGTH 20 FEET CONDUCTOR_SIZE 1
LOT5 CONDUCTOR_LENGTH 40 FEET CONDUCTOR_SIZE 1
LOT6 CONDUCTOR_LENGTH 70 FEET CONDUCTOR_SIZE 4
LOT7 CONDUCTOR_LENGTH 140 FEET CONDUCTOR_SIZE 4
LOT8 CONDUCTOR_LENGTH 20 FEET CONDUCTOR_SIZE 1

**WARNING**LOT4 CONDUCTOR_LENGTH_MUST_BE_INCREASED**
**WARNING**LOT6 CONDUCTOR_LENGTH_MUST_BE_INCREASED**
**WARNING**LOT8 CONDUCTOR_LENGTH_MUST_BE_INCREASED**

T

 >> (EXIT)
```

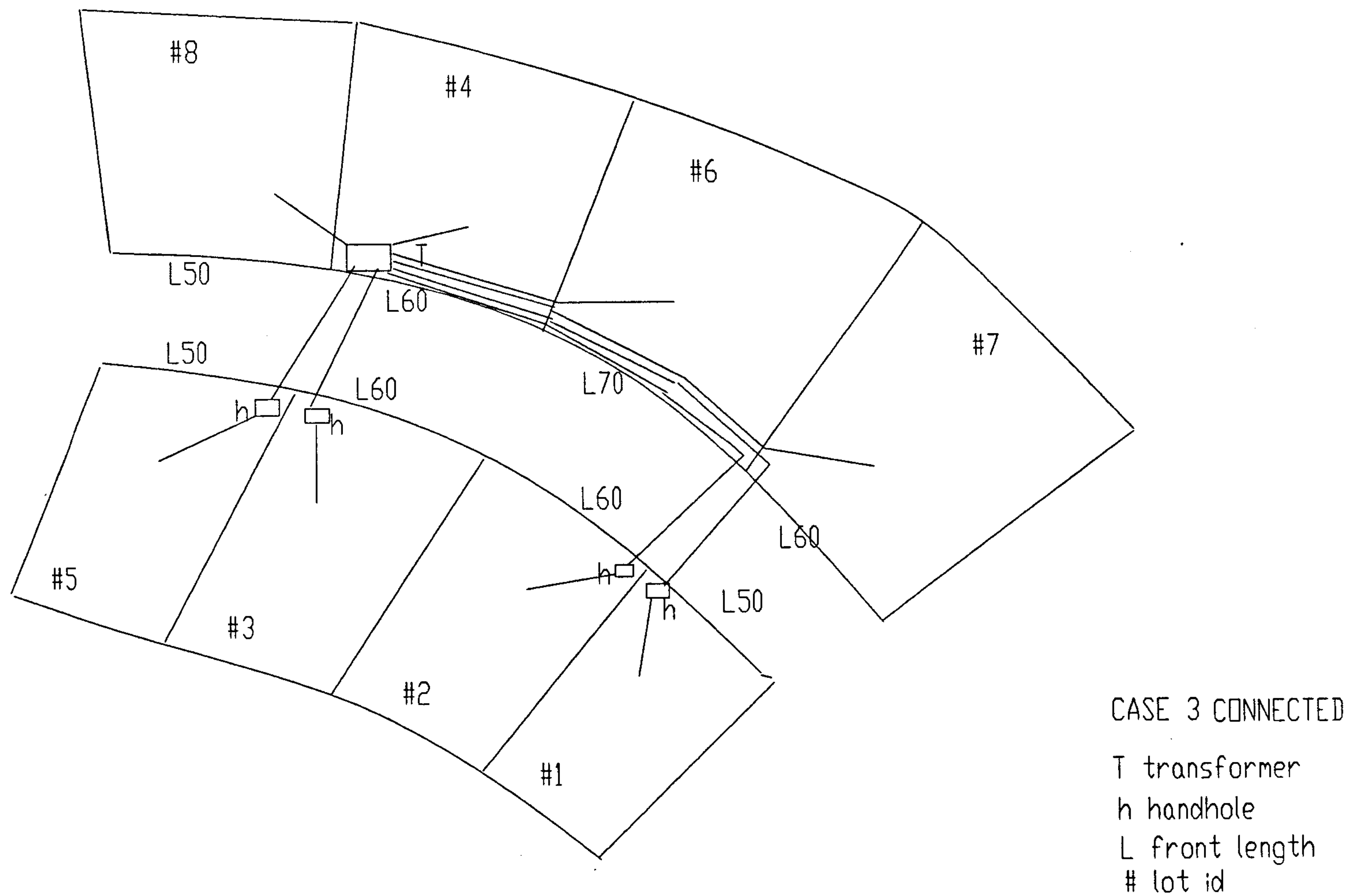

Figure 43. Appendix C: Case 3 Lots Connection

Vita

Zarko Sumic was born in Kraljevica, Yugoslavia on January the 8, 1953. He received B.S. (dipl. eng) from University of Split, Yugoslavia, and M.S. from University of Zagreb, Yugoslavia, in 1976, and 1982, respectively, all in electrical engineering. In 1984 he was British Council sponsored visiting scientist at UMIST Manchester, UK. From 1976 he is a faculty member of the University of Split, Yugoslavia where he is now on leave of absence.

In 1988 he entered the University of Washington, Seattle to pursue his Doctoral degree. During his study at the University of Washington he was recipient of the Puget Power Graduate Fellowship. Presently he is with the Puget Sound Power and Light Co., Bellevue, WA working on AI application to electrical distribution system planning and design.

His professional and research interests include computer applications to power systems, power system control, and AI applications to distribution system planning and design. From these areas he has published and presented more than 30 papers.

Mr. Sumic is a member of Yugoslav Committee CIGRE, IEEE Power Engineering Society and Eta Kappa Nu.