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A SYSTEMS ANALYTIC APPROACH

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Preface

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1. The Role of the Systems Analysis in the Iowa Coal Project

It seems reasonable to view the implementation of any public goal such as the development of Iowa's coal reserves as a three-step process. The first step is to evaluate the merit of the goal and thus answer the fundamental question of whether or not its implementation constitutes a worthwhile use of public funds. If and when the worth of the goal has been affirmed, attention should turn to the question of how to best attain the goal. Assuming that it is determined that a large-scale research and development project is the best way to implement the goal, further investigation is necessary to determine how the project's budget should be allocated among possible subprojects which may be proposed to investigate particular aspects of the problem area. Then, and only then, the third step of the three-step process can be implemented. This step involves carrying out the actual research and development.

In the framework of the Iowa coal project, a feasibility study has been funded to investigate the first step of the process. The systems analysis is concerned with the second stage of the process. All of the other projects are concerned with the third stage of the process.

To reiterate, then, the systems analysis is concerned with answering the following questions:

(1) Given that the goal of developing Iowa's coal reserves constitutes a worthwhile use of public funds, is a research and development project the best way to go about implementing this goal? It should be pointed out here that the answer to this question is not immediately apparent since the state government can influence the behavior of private

industry through such means as taxes, subsidies, or standards.

(2) If the answer to question (1) is "yes," which subprojects should be funded?

Answering these questions involves a detailed knowledge of all the variables affecting the Iowa coal industry from the time mineral rights are acquired for mining until the coal is burned. The relationships among these variables are discussed in what will hopefully be an intuitively appealing manner in the text of this report and in a more rigorous, precise way in Appendix I. Estimating the magnitude of these relationships will be the subject of a later report.

2. Factors Affecting the Development of Iowa Coal

In this section, the many variables which affect Iowa's coal industry will be identified, and their interrelationships will be discussed. The discussion will center around the development of five basic components of the coal industry.

The first component is that of production. This includes mining, discovering new reserves, acquiring mining rights to reserves, and questions of land and water quality associated primarily with surface coal mining. The beneficiation component which follows describes the process by which the quality of mined coal, particularly in terms of sulfur content, may be improved. The third component, transportation, is concerned with shipping coal from the mines to the beneficiation sites and demand centers and from the beneficiation plants to the demand centers. The research and development component allows for the discovery of new processes or improvement of existing processes in the preceding three components. Finally, the demand component describes some of the important relationships affecting the final consumption of coal.

In addition to the five components described above, a public decision-making sector is included to allow for the formulation of laws, taxes, and subsidies that can affect the behavior of decision makers in any of the above components. The concerns of the public sector are assumed to be in such areas as energy demand, air quality, and land reclamation.

2.1 Production

2.1.1 Mining. In the production component, the rate at which coal is mined depends on several factors. Two obvious ones are the rate at which variable and fixed inputs are employed in the mining process. Variable inputs are such items as labor and fuel to run equipment; fixed inputs are such items as draglines and other major pieces of equipment. Perhaps not so obviously, past uses of the fixed and variable inputs used for mining coal also affect the level of production. This is accomplished through what is commonly referred to as "learning-by-doing"; that is, production processes become more efficient as more experience is gained through using them. Research and development expenditures may also make a mining process more efficient. Finally, of course, the level of production depends on the amount of known reserves.

2.1.2 Discovering New Reserves. Sooner or later, expanding the rate of mining will involve increasing the known coal reserves through exploration. The key feature that should be emphasized here is uncertainty. There is no direct relationship that suggests spending more money for exploration will necessarily increase the level of reserves. Instead, the best that can be said is that such expenditures will increase the probability of discovering new reserves. This is not a trivial point; a cost is attached to risk by private firms comprising the industry.

It is also necessary to allow exploration processes (drilling, remote sensing, etc.) to become more efficient by learning more about them through past use of the processes or through research and development.

2.1.3 Acquiring Mining Rights to Reserves. Once reserves are discovered, rights to them must be acquired by mining companies before any mining can take place. There are basically three ways in which coal mining rights can be obtained:

(1) The land under which there is coal can be purchased outright.

(2) A mining lease may be entered into with the landowner which usually involves a payment of some fixed amount per ton mined to the landowner, subject to a minimum annual payment.

(3) The subsurface alone can be purchased. Since surface mining by its nature destroys the surface, this option is felt to be suitable for underground mining only.

2.1.4 Land Use. Attention here is primarily focused on the reclamation of surface-mined land. Both the number of acres reclaimed and the quality of the reclaimed land in terms of such measures as land productivity and slope need to be considered. The number of acres reclaimed and the land quality levels will be determined by the amount of fixed inputs (bulldozers, etc.) and variable inputs (labor, fuel, etc.) devoted to reclamation. In addition, knowledge gained through past reclamation efforts and research and development expenditures will have an affect on the reclamation process.

In addition to land quality measures, the conceptual model also includes measures of water quality. Typical water quality measures would be the pH and suspended solids of the water at a mine site. The level of the water quality measures are assumed to depend on the overburden characteristics of the mine site (amount of acid shale, etc.), the number of acres left unreclaimed, and how long these acres are left unreclaimed.

Allowance is made for either governmental standards or mining lease requirements which may regulate the final use of unreclaimed land or the water quality at the mine sites.

2.1.5 Profits. The assumption is made that decision makers in the production component have as their goal maximizing profits while minimizing the associated risks involved. Their profits are obviously the amount of money taken in (revenue) minus costs. The two principal sources of revenue are the sale of coal and the sale of reclaimed land which the mining companies own. Costs are purchasing land for mining, leasing reserves, buying subsurface rights, purchasing fixed and variable inputs for exploration, mining and land reclamation, and institutional costs. Institutional costs are those costs necessary to meet mining law requirements for such items as reclamation bonds, mining permits, public liability insurance, and contributions to reclamation funds.

It is important to notice that the government can impose taxes or subsidies on prevailing market prices for any of the outputs or inputs which determine profits and thus alter the behavior of decision makers in the production component. For example, adding a subsidy to the price of Iowa coal would, all other things being equal, raise profits in the production component and make mining Iowa coal a more attractive proposition.

2.2 Beneficiation

The beneficiation component is concerned with improving the quality of mined coal, principally by reducing its sulfur content. For each beneficiation process used, the amount of fixed and variable inputs, along with the amount and quality of input coal to the process, will to a large extent determine both the quantity and quality of coal produced as well as the amounts of various byproducts such as sulfur. In the case of beneficiation, a typical fixed input would be the beneficiation plant itself, and typical variable inputs would be labor and various chemicals. It is also necessary to allow processing of coal from outside of Iowa in Iowa's beneficiation plants. Other factors influencing the output level of the beneficiation processes are knowledge gained through past experience in operating the processes, along with research and development.

As with the production component, the objective of decision makers in the beneficiation component is presumed to be profit maximization, taking into account the associated levels of risk. The source of revenue to the beneficiation component is the sale of processed coal. The costs are those for fixed and variable inputs and for input coal from both within and outside of Iowa.

2.3 Transportation

In the transportation component, shipments by several methods (rail, truck, etc.) are allowed from each mine site to each beneficiation site, from each mine site to each demand center, and from each beneficiation site to each demand center. Only shipments of coal are considered, even though it is recognized that the possibility of transporting byproducts such as ash and sulfur also exists. It should also be noted that on some routes, particularly those from beneficiation sites to demand centers, shipment of both Iowa and non-Iowa coal are possible.

The amount of coal that can be transported over any particular route depends on the amounts of fixed inputs (roadways, track, railroad rolling stock, etc.) and variable inputs (labor, fuel, etc.) purchased. The amount shipped is also obviously limited by the coal available from Iowa and non-Iowa mines and Iowa beneficiation centers. Furthermore, the transportation methods in use can become more efficient through knowledge gained by experience in using the transportation methods and through research and development.

A slightly different type of objective function has been specified for the transportation component. More specifically, not only the profits from shipping coal but also the potential profits from shipping other commodities (grains, etc.) are important determinants of the transportation decision makers' behavior. To put it a different way, even if shipping coal is profitable in the sense that revenue exceeds costs, it may still be the case that no coal will be shipped if shipping grain is more profitable.

2.4 Research and Development

The research and development component has as its goal the maximization of benefits to the first three components within the limits of the budget allocated to them. There are two basic decisions that must be made with respect to allocating the research and development budget. The first is the question of where the money will be spent, i.e., a choice must be made between mining, exploration, reclamation, beneficiation, and transportation. The second question concerns how the money will be allocated to processes within each component once the total amount allocated to each component has been determined.

In the systems model, two choices are allowed with respect to money allocated to processes within each component. One possibility is to allocate money to pure research to discover new processes or methods of operation. The other is to spend money to increase the productivity and dependability of existing processes. These options will now be discussed in more detail using the beneficiation component as an example.

For illustrative purposes, assume that there are two beneficiation processes available: mechanical beneficiation and coal gasification. Furthermore, assume that it is felt that spending a certain amount of money on beneficiation research will, with a high probability, come up with a new process, say, chemical beneficiation. On the other hand, spending the same money on mechanical beneficiation will improve the productivity and dependability of a process that is already commercially accepted. Finally, spending the money on gasification will possibly improve the process to the extent that it will become commercially adopted on a widespread level.

Some of the relevant questions that arise in making the decision of how to allocate money for this illustrative example are:

(1) What degree of improvement can be achieved in mechanical beneficiation? Are there limits on the process that tend to exclude it as a relevant alternative in the future?

(2) What would be the impact of introducing gasification on a wide scale? How much improvement in the gasification process is needed for it to compete effectively with mechanical beneficiation?

(3) Will developing existing processes provide a satisfactory solution to our beneficiation needs without developing new processes such as chemical beneficiation? How much will it cost to develop chemical beneficiation into a commercially competitive process once the idea is fully conceived?

2.5 Final Consumption

Final consumers of coal (primarily electricity generation plants and some industries) are assumed to have as their objective minimizing the cost of satisfying some predetermined level of coal consumption. This demand for coal in Iowa may be satisfied by either Iowa or non-Iowa coal, depending on both the prices and dependability of coal from the two sources. Since the predetermined level of coal consumption is specified in heating units rather than by weight, another factor entering into the decision of which coal source to use will be the heating value per weight unit of the different coals.

Heating value per unit sulfur content is also an increasingly important measure of a particular coal's usefulness in view of governmental standards aimed at regulating air quality. Imposing sulfur-level standards will, all other things being equal, increase the demand and prices for low-sulfur coal, either directly from mines or as a product of beneficiation. However, it is also important to make allowances for the fact that as prices for low-sulfur coal rises, investing in post-combustion sulfur removal becomes more attractive.

As the systems model is now specified, many market forces which influence the level of coal consumption are not specified. These will be discussed here. Two of the most important determinants of consumption levels of coal are the price of alternative energy sources and the price of coal.

The price of alternative energy sources can conceivably play a critical role in the development of Iowa's coal resources. For example, one might suspect that mining Iowa coal will become more and more attractive if the price of coal continues to rise. This is only true if, among other things, coal at a higher price can still compete with alternative energy sources such as nuclear power plants. Otherwise, the level of coal demanded would decrease as consumers substituted alternative energy sources for coal, and the Iowa coal industry would not be in such a favorable position as the coal price increase would initially indicate.

The price of coal also affects the demand for coal in a more direct way. That is, as the price of coal gets higher, consumers can be expected to reduce their consumption of coal regardless of the price of other energy sources. The extent to which consumers adjust their coal consumption in the face of price increases is difficult to estimate. However, as part of the systems analysis, an investigation is currently underway to determine consumer reaction to price changes in electricity. Since much of Iowa's coal use is for the production of electricity, some inferences may then be made about the impact of these electricity price increases (which are in part due to coal price increases) on the demand for coal.

2.6 The Public Sector

The public objective function is a means by which legislative entrance into the decision-making processes of any component of the model is allowed. The concerns of the public are specified as: the level of coal consumption, the price of coal to consumers, land reclamation, water quality at mine sites, air quality at demand centers, and the income distribution that comes about through the acquisition of mining rights in the production component.

Actions by the public via the legislature to achieve their goals may take the following forms:

(1) influencing the prices of outputs or inputs in any component through taxes or subsidies;

(2) imposing standards on land reclamation, water quality, or the sulfur level of coal that is burned; or

(3) allocating money for research and development.

Two of the principal factors affecting the decisions of the public are their expectations of the benefits that might arise by spending public money in areas other than that of the coal industry and the basic behavior patterns of decision makers in the five components of the system.

It is once again stressed that allocating money for research and development is only one of three possible ways to influence private industry. As a somewhat farfetched example, the three million dollar, three-year appropriation for the Iowa coal project could have alternatively provided a one dollar per ton payment for a one-million-ton-per-year Iowa coal industry over the specified three-year period. Which action would have had a greater impact on the industry is not immediately obvious without some further careful analysis.

2.7 Flow Diagram

The Iowa coal system as discussed here is represented in flow chart form in Figure 1.

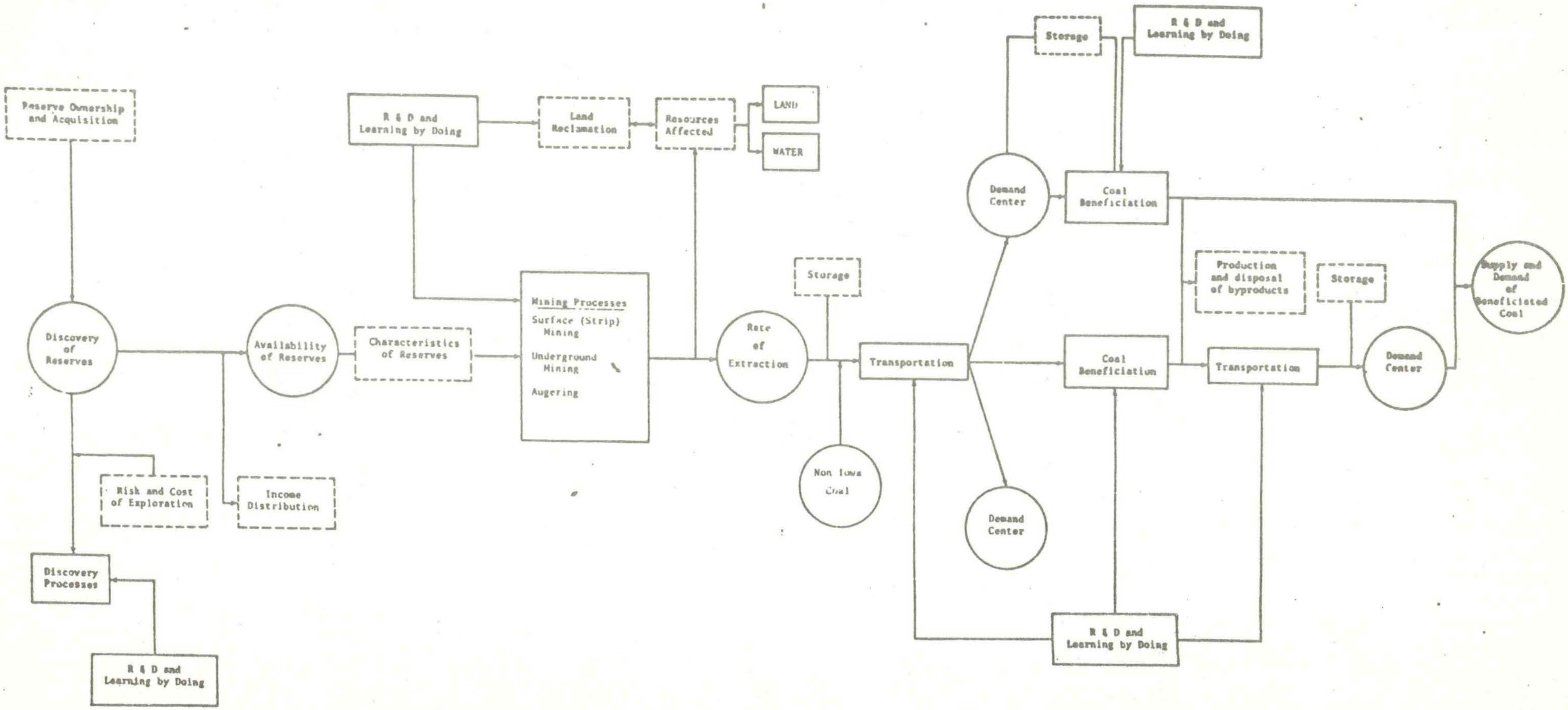

Figure 1. The physical flow of the Iowa Coal System.

3. Application to EMRRI Coal Research Program

Appendix II presents a listing of twenty subprojects which are currently being funded as parts of the Iowa coal project. A detailed evaluation of each at this time is hampered by a lack of quantitative estimates of the relationships between the many variables affecting the Iowa coal industry. However, the knowledge gained by more clearly understanding the identity and interrelationship between these variables can in itself be of value to the coal project administration. Therefore, a general discussion of sixteen of these twenty subprojects will be undertaken here with the purpose of suggesting some assumptions that are implicit in the funding of each subproject. Projects 1, 7, 15, and 16 (see numbers in Appendix II) will not be analyzed directly since their impact seems only identifiable through the outputs of the other sixteen projects.

Thirteen of the sixteen projects to be discussed relate solely to the production component of the systems model. Two of the remaining projects relate only to the beneficiation component. Project 5 relates to both the beneficiation and demand components. Apart from certain limited investigations of Project 20, none of the projects relates directly to transportation,[1] and only a portion of one project looks at the demand component.

In this discussion, subprojects are evaluated only in the context of their potential contribution to the goal of effectively spending Iowa funds to develop Iowa coal. However, the impact of some subprojects on other coal producing regions or on individual fields of learning may be quite valuable. For example, a beneficiation improvement may result in the capability to produce less expensive low-sulfur coal for the benefit of all consumers, including Iowans, even if no coal is mined in Iowa.

Of the thirteen production subprojects, numbers 4, 8, 12, and 13 are concerned with exploration. Project 12 involves actual determination of reserves in a specific area and in the opinion of the authors is among the "safest" of all the projects insofar as it rests on relatively few assumptions that may or may not prove true. The other three exploration projects are concerned with discovering new methods for coal exploration rather than discovering coal directly. This distinction is not trivial because these three projects apparently rest on the additional assumption that there is sufficient coal in Iowa to support a viable industry. The reason Iowa coal has not been better explored to date is at least partly due to a lack of sophisticated exploration methods. Since this is a state-funded project, these three subprojects further assume that discovering Iowa coal requires special techniques which are not likely to be developed by more general federal projects.

Projects 6, 9, 10, and 14 are all concerned with identifying the characteristics, rather than the quantity, of Iowa coal and again seem "safe" in that they rest on very few assumptions.

All of the remaining projects (with the exception of the feasibility study) hinge on two assumptions:

(1) there is sufficient recoverable coal of suitable quality in Iowa to support a mining industry, and

(2) economic conditions are favorable for mining Iowa coal, or at the very least, economic conditions can reasonably be expected to change so that mining Iowa coal will be profitable.

Projects 3, 17, 18, and 19 rest on the further assumption that not only do Iowa's reserves exist in sufficient types and quantities to justify mining, but they also are strippable. The omission of deep-mining investigations may turn out to be a serious void if it should be determined that either Iowa has mostly nonstrippable coal or if land reclamation requirements or other circumstances make strip mining a much less attractive economic proposition than it has been in the past.

The role of the feasibility and systems parts of Project 20 has been discussed previously. As for the legal analysis part of this subproject, it will again only be relevant and worth pursuing if sufficient minable coal exists and if the economic climate for mining coal in Iowa is favorable.

Projects 2 and 11 are quite obviously related to the beneficiation component. The results of these studies are critical to the production component (mining and ecological studies) since in the likely event that stringent air quality standards are imposed, there may be virtually no market for run-of-mine Iowa coal, due to its high sulfur content. There are some additional critical assumptions underlying these specific two projects:

(1) Beneficiation is preferable to flue-gas desulfurization as a means of making Iowa coal conform to EPA standards.

(2) Beneficiation processes developed under federal or other projects are not suitable for Iowa.

(3) Processes such as gasification will not make beneficiation breakthroughs obsolete before they can be commercially put into practice.

Project 5 relates to both the beneficiation and the demand components.

The assumption is made that flue-gas desulfurization is competitive with beneficiation and that the new beneficiation methods investigated will not be superceded by such processes as gasification before they are commercially adoptable.

The discussion of this section is summarized in Figure 2. The coal project research is visualized as a three-stage process with the various subprojects fitting in as inputs to the stages. Each stage has a question or set of questions that must be answered affirmatively before research in later stages can be meaningfully undertaken. The arrows between questions in each stage and between stages indicate that the question or stage to which the arrow points is dependent on an affirmative response to the question or group of questions (stage) from which the arrow originates.

If one accepts the conceptualization depicted in Figure 2, two revisions of the coal project's orientation seem in order. First, a study of the transportation system in Iowa must be undertaken.[1] Such a study should have among its objectives to determine the amount of coal that can economically be transported with Iowa's existing transportation resources, and what investments would be necessary to expand this capacity. Secondly, a shift in emphasis away from mining and reclamation and towards an accurate determination of the extent of Iowa's coal resources seems warranted. An accurate picture of Iowa's coal resources would greatly reduce the uncertainty private mining companies face in deciding whether or not to invest in mining Iowa coal. Furthermore, since a recent Bureau of Mines publication[2] has estimated Iowa's demonstrated reserve base of strippable coal to be close to zero, some work needs to be done on exploration if for no other reason than to justify expenditures on developing strip mining and reclamation techniques.

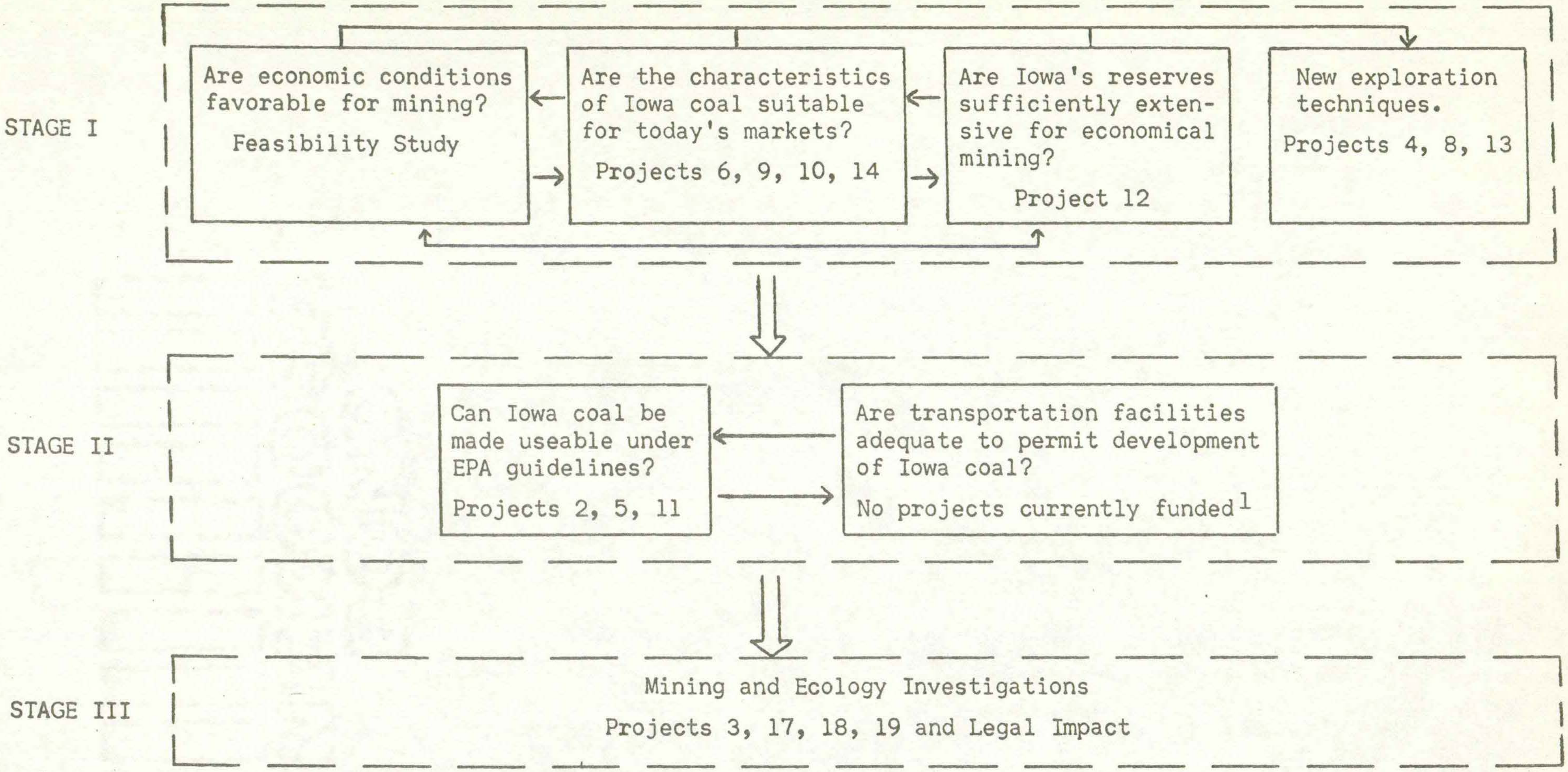

Figure 2. Interdependencies of Subprojects.

FOOTNOTES

1. Since the initial writing of this report, a study of the transportation situation of Iowa coal has been undertaken.
2. U.S. Bureau of Mines. Demonstrated Coal Reserve Base of the United States, by Sulfur Category, on January 1, 1974. May 1975.

APPENDIX I

In this appendix, the Iowa coal system is presented in mathematical terms. Since a descriptive discussion of the system was presented in the text, an effort has been made to keep this appendix as concise as possible.

The system as conceptualized here has production as its first component. This includes mining, discovering new reserves, acquiring mining rights to reserves, and questions of land and water quality associated primarily with surface coal mining. The beneficiation component which follows describes the processes by which the quality of mined coal, particularly in terms of sulfur content, may be improved. The third component, transportation, is concerned with shipping coal from the mines to the beneficiation sites and demand centers and from the beneficiating plants to the final consumption centers. The research and development component allows for the discovering of new processes or improvement of existing processes in the preceding three components through research and development. Finally, the demand component describes some of the important relationships affecting the final consumption of coal.

Each of the above five components has a specific objective function associated with it. In addition, a "public" objective function has been specified to allow for legislative entrance into any of the components of the system to achieve public objectives in such areas as air quality and land reclamation.

The flows of coal of different quality levels between each component are described in the "Identities" section.

The Production Component

Mining

Let $u_{m,j,k,\ell,p,t}$ represent the rate of coal mining, $\underline{x}^M_{p,m,t}$ represent a vector of variable inputs used in mining, $\underline{F}^M_{p,m,t}$ represent a vector of fixed inputs available for mining, $\underline{f}^M_{p,m,t}$ be a vector of rates of investment in the components of $\underline{F}^M_{p,m,t}$, and $d^M_{p,t}$ be the rate of development expenditures on mining process p. We may specify a production function for a given reserve level ($R_{m,j,k,\ell,t}$) as follows:

$$\text{(P.1)}\quad u_{m,j,k,\ell,p,t} = u(\underline{x}^M_{p,m,t}, \underline{F}^M_{p,m,t}, \sum_{t=0}^{t-1}\sum_{m} \underline{x}^M_{p,m,t}, \sum_{t=0}^{t-1}\sum_{m} \underline{f}^M_{p,m,t}, d^M_{p,t}; R_{m,j,k,\ell,t})$$

The subscript m denotes a particular mining area in Iowa. The subscript j denotes the sulfur content of the coal as it is mined. For concreteness, let j = 0, 1, ..., 8, where j=0 represents 0 percent sulfur, j=1 represents 1 percent sulfur, etc. For purposes of determining income distribution, the subscript k is used to denote the various classes of mineral rights owners. The subscript ℓ is used to distinguish various types of reserves in terms of overburden thickness and seam thickness. There are P^M_t mining processes available at time t. The subscript p refers to a particular one of these processes. For notational convenience, let Ω^M represent the expression "$\underline{x}^M_{p,m,t}, \underline{f}^M_{p,m,t}; R_{m,j,k,\ell,t}$." Then, we have:

$$\text{(P.2)}\quad E(u_{m,j,k,\ell,p,t} \mid \Omega^M) = E(u_{m,j,k,\ell,p,t-1} \mid \Omega^M) + \epsilon^M(\sum_m \underline{x}^M_{p,m,t-1}, \sum_m \underline{f}^M_{p,m,t-1}, d^M_{p,t})$$

$$\text{(P.3)}\quad V(u_{m,j,k,\ell,p,t} \mid \Omega^M) = V(u_{m,j,k,\ell,p,t-1} \mid \Omega^M) + v^M(\sum_m \underline{x}^M_{p,m,t-1}, \sum_m \underline{f}^M_{p,m,t-1}, d^M_{p,t})$$

where E and V represent the expected value and variance operators, and ϵ and v are functions whose partials are explained below. We have the usual partials:

$$\frac{\partial u}{\partial \underline{x}^M}, \quad \frac{\partial u}{\partial \underline{F}^M}, \quad \frac{\partial u}{\partial R} \geq 0 .$$

Learning-by-doing is presumed to have the following effects:

$$\frac{\partial \epsilon^M}{\partial \sum_t \sum_m \underline{x}^M}, \quad \frac{\partial \epsilon^M}{\partial \sum_t \sum_m \underline{F}^M} \geq 0 \; ; \quad \frac{\partial v^M}{\partial \sum_t \sum_m \underline{x}^M}, \quad \frac{\partial v^M}{\partial \sum_t \sum_m \underline{F}^M} \leq 0$$

Finally, the development expenditures have these effects:

$$\frac{\partial \epsilon^M}{\partial d^M_{p,t}} > 0; \quad \frac{\partial v^M}{\partial d^M_{p,t}} \leq 0$$

The stock of fixed inputs available for mining use in time t is determined by:

$$\text{(P.4)} \quad \underline{F}^M_{p,m,t+1} = \underline{F}^M_{p,m,t} + F^M\Big(\underline{F}^M_{p,m,t}, \sum_j \sum_k \sum_\ell u_{m,j,k,\ell,p,t}, \underline{f}^M_{p,m,t}\Big)$$

$$\frac{\partial F^M}{\partial \underline{F}^M} \leq 0, \quad \frac{\partial F^M}{\partial \sum\sum\sum u} \leq 0, \quad \frac{\partial F^M}{\partial \underline{f}^M} > 0$$

Discovering New Reserves

Letting $r^D_{m,j,k,\ell,t}$ be the rate at which new reserves are discovered, the stock of known reserves is determined by:

$$\text{(P.5)} \quad R_{m,j,k,\ell,t} = R_{m,j,k,\ell,t-1} + r^D_{m,j,k,\ell,t} - \sum_p u_{m,j,k,\ell,p,t}$$

Let $\theta^i_{m,j,k,\ell,t}$ be the probability that decision makers attach to the event of $r^D_{m,j,k,\ell,t}$ taking on the ith value with $\sum_{i=1}^{\infty} \theta^i_{m,j,k,\ell,t} = 1$. Also, let $p = 1, \ldots, P^D_t$ be the discovery methods available in time t, $\underline{x}^D_{m,p,t}$ be a vector of variable inputs employed in discovery, and $\underline{F}^D_{m,p,t}$

be a vector of fixed inputs available for discovery with $\underline{F}^D_{m,p,t}$ determined by

$$\underline{F}^D_{m,p,t+1} = \underline{F}^D_{m,p,t} + F^D(\underline{F}^D_{m,p,t}, \underline{f}^D_{m,p,t}, r^D_{m,j,k,\ell,t}) \quad \frac{\partial F^D}{\partial \underline{F}^D} \leq 0, \tag{P.6}$$

$$\frac{\partial F^D}{\partial \underline{f}^D} > 0, \quad \frac{\partial F^D}{\partial r^D} < 0$$

where $\underline{f}^D_{m,p,t}$ is a vector of rates of investment in the components of $\underline{F}^D_{m,p,t}$.

It then seems reasonable to presume that the θ distribution has the form:

$$\theta^i_{m,j,k,\ell t}(\underline{x}^D_{m,p,t}, \underline{F}^D_{m,p,t}, \sum_{t=0}^{t-1}\sum_{m} \underline{x}^D_{m,p,t}, \sum_{t=0}^{t-1}\sum_{m} \underline{f}^D_{m,p,t}, d^D_{p,t}) \tag{P.7}$$

where we assume that increased values of $\underline{x}^D$ and $\underline{f}^D$ shift the θ distribution towards higher values of r^D. We further assume that higher values of $\sum_t \sum_m \underline{x}^D$ and $\sum_t \sum_m \underline{f}^D$ shift the θ distribution towards higher values of r^D through a learning-by-doing effect and that increasing $d^D_{p,t}$, the rate of development expenditures devoted to discovery process p, will also shift the θ distribution towards higher values of r^D.

Letting $r^D_{i,m,j,k,\ell,t}$ be the ith value of $r^D_{m,j,k,\ell,t}$, we may now take the expected value of (P.5) to obtain

$$\begin{aligned} E(R_{m,j,k,\ell,t}) &= R_{m,j,k,\ell,t-1} \\ &+ \sum_{i=1}^{\infty} [\theta^i(\underline{x}^D_{m,p,t}, \underline{F}^D_{m,p,t}, \sum_{t=0}^{t-1}\sum_{m} \underline{x}^D_{m,p,t}, \sum_{t=0}^{t-1}\sum_{m} \underline{f}^D_{m,p,t}, d^D_{p,t}) \cdot r^D_{i,m,j,k,\ell,t}] \end{aligned} \tag{P.8}$$

Previous assumptions about the θ distribution support the conclusion that increases in any of the five arguments of θ will increase $E(R_{m,j,k,\ell,t})$.

Acquiring Mining Rights to Reserves

Once discovered, reserves may be added to the stock of reserves to which the mining companies are legally entitled to mine ($R^A_{m,j,k,\ell,t}$) through purchases of subsurface rights ($r^P_{m,j,k,\ell,t}$), land purchases ($a^P_{m,k,t}$), or leasing arrangements ($r^L_{m,j,k,\ell,t}$). Thus,

$$(\text{P.9}) \quad R^A_{m,j,k,\ell,t} = R^A_{m,j,k,\ell,t-1} + r^P_{m,j,k,\ell,t} + g(a^P_{m,k,t}) + r^L_{m,j,k,\ell,t} - \sum_p u_{m,j,k,\ell,p,t}$$

where the function g relates land purchases to the types and amount of reserves per acre purchased.

We also need the following constraint:

$$(\text{P.10}) \quad r^P_{m,j,k,\ell,t} + g(a^P_{m,k,t}) + r^L_{m,j,k,\ell,t} \leq R_{m,j,k,\ell,t} - R^A_{m,j,k,\ell,t-1}$$

The assumption is made that $r^P_{m,j,k,\ell,t} = 0$ whenever ℓ denotes surface minable reserves, due to the legal impediments involved in surface mining under this type of reserve acquisition.

Land Use

We will make the assumption that questions of land use are relevant only for land affected by surface mining methods.

Let $p = 1, \ldots, P^E_t$ denote the reclamation methods available for use in period t. Also, assume that there are $i = 1, \ldots, N$ final uses for reclaimed land (agriculture, recreation, etc.), and let $a_{i,m,p,t}$ be the rate at which land at mine site m is reclaimed to use i by method p in time period t.

If we also let $a^M_{m,t}$ be the rate at which land is disturbed by mining in mining area m in time t, then the number of acres in need of reclamation in time t at area m ($A_{m,t}$) can be expressed as:

$$\text{(P.11)} \quad A_{m,t} = A_{m,t-1} + a^M_{m,t} - \sum_p \sum_i a_{i,m,p,t}$$

Legal constraints or, in the case of mining leases, lease agreements may place constraints on the rate at which land is reclaimed to any particular use:

$$\text{(P.12)} \quad \sum_p a_{i,m,p,t} \geq a^*_i \geq 0$$

The rate at which variable inputs are employed in reclamation ($\underline{x}^E_{m,p,t}$), the amount of fixed inputs available for reclamation ($\underline{F}^E_{m,p,t}$), the rate of investment in fixed inputs ($\underline{f}^E_{m,p,t}$), and the rate of development expenditures on reclamation methods ($d^E_{p,t}$) determine both the amount of land reclaimed to each of the final uses and the level of certain quality parameters (soil productivity, slope of land, etc) associated with each final use. Letting $\lambda^L_{h,i,m,p,t}$ be the hth quality parameter for $a_{i,m,p,t}$ ($h=1,\ldots,H_i$), we have

$$\text{(P.13)} \quad a_{i,m,p,t} = A(\underline{x}^E_{m,p,t}, \underline{F}^E_{m,p,t}, \sum_{t=0}^{t-1} \sum_m \underline{x}^E_{m,p,t}, \sum_{t=0}^{t-1} \sum_m \underline{f}^E_{m,p,t}, d^E_{p,t}; E_m)$$

$$\text{(P.14)} \quad \lambda^L_{h,i,m,p,t} = \lambda^L(\underline{x}^E_{m,p,t}, \underline{F}^E_{m,p,t}, \sum_{t=0}^{t-1} \sum_m \underline{x}^E_{m,p,t}, \sum_{t=0}^{t-1} \sum_m \underline{f}^E_{m,p,t}, d^E_{p,t}; E_m)$$

E_m is an index of the suitability of land at mine site m for reclamation. It is assumed that E_m and each λ^L are constructed in such a way that higher values are more desirable. In view of this, the assumption is made that the first partials of A and λ^L with respect to $\underline{x}^E_{m,p,t}$, $\underline{F}^E_{m,p,t}$, and E_m are nonnegative. The following legal or lease constraints may also be imposed:

(P.15) $$\lambda^L_{h,i,m,p,t} \geq \lambda^{L*}_{h,i,m,p,t}$$

Learning-by-doing and development expenditures ($d^E_{p,t}$) enter the model in the following way:

Denoting the expression "$\underline{x}^E_{m,p,t},\underline{F}^E_{m,p,t};E_m$+ by Ω^E for notational simplicity,

(P.16) $$E(a_{i,m,p,t}|\Omega^E) = E(a_{i,m,p,t-1}|\Omega^E) + \epsilon^E(\sum_p \underline{x}^E_{m,p,t-1}, \sum_p \underline{f}^E_{m,p,t-1}, d^E_{p,t})$$

(P.17) $$E(\lambda^L_{h,i,m,p,t}|\Omega^E) = E(\lambda^L_{h,i,m,p,t-1}|\Omega^E) + \epsilon^E_h(\sum_p \underline{x}^E_{m,p,t-1}, \sum_p \underline{f}^E_{m,p,t-1}, d^E_{p,t})$$

(P.18) $$V(a_{i,m,p,t}|\Omega^E) = V(a_{i,m,p,t-1}|\Omega^E) + v^E(\sum_p \underline{x}^E_{m,p,t-1}, \sum_p \underline{f}^E_{m,p,t-1}, d^E_{p,t})$$

(P.19) $$V(\lambda^L_{h,i,m,p,t}|\Omega^E) = V(\lambda^L_{h,i,m,p,t-1}|\Omega^E) + v^E_h(\sum_p \underline{x}^E_{m,p,t-1}, \sum_p \underline{f}^E_{m,p,t-1}, d^E_{p,t})$$

The first partials of ϵ^E and ϵ^E_h are assumed nonnegative with respect to each of their arguments. The first partials of v^E and v^E_h are assumed nonpositive with respect to each of their arguments.

$\underline{F}^E_{m,p,t}$ is determined by

(P.20) $$\underline{F}^E_{m,p,t+1} = \underline{F}^E_{m,p,t} + F^E(\underline{F}^E_{m,p,t}, a_{i,m,p,t}, \lambda^L_{h,i,m,p,t}, \underline{f}^E_{m,p,t})$$

$$\frac{\partial F^E}{\partial \underline{F}^E} \leq 0 , \quad \frac{\partial F^E}{\partial a} \leq 0 , \quad \frac{\partial F^E}{\partial \lambda^L} \leq 0 , \quad \frac{\partial F^E}{\partial \underline{f}^E} > 0$$

In passing, it might be noted that $\partial F^E/\partial \lambda^L \leq 0$ because increasing the quality parameters for a given rate of reclamation to a given land use requires increased use of fixed (and variable) inputs.

Water Quality

Only influences on water quality directly due to mining, e.g., erosion and acid drainage, and not influences associated only with final land use, e.g., fertilizer runoff from land reclaimed to agricultural uses, are considered in the model. Furthermore, it is assumed that these effects on water quality directly due to mining cease upon reclaiming land to any of the N final uses. Then, the c = 1, ..., C water quality parameters at site m in period t ($\lambda^W_{c,m,t}$) are functions of overburden characteristics (ϕ_m) and the number of mined acres left unreclaimed in each time period:

$$\text{(P.21)} \qquad \lambda^W_{c,m,t_o+w} = \lambda^W_c[A_{m,t_o}, A_{m,t_o+1}, \ldots, A_{m,t_o+w}; \phi_m] \qquad c = 1, \ldots, C$$

where t_o is the time period in which mining is initiated in site m.

Assuming the $\lambda^W_{c,m,t}$'s are specified so that higher values are more desirable than lower values and that the ϕ_m index is specified so that higher values mean less potential danger to water quality, we have

$$\text{(P.22)} \qquad \frac{\partial \lambda^W_c}{\partial A_{m,t_o}}, \ldots, \frac{\partial \lambda^W_c}{\partial A_{m,t_o+w}} \leq 0 , \quad \frac{\partial \lambda^W_c}{\partial \phi_m} \geq 0$$

Typical water quality parameters might be pH and suspended solids. Legal constraints or lease agreements on water quality enter as follows:

$$\text{(P.23)} \qquad \lambda^W_{c,m,t} \geq \lambda^{W*}_{c,m,t}$$

Objective Function

The objective is to maximize the expected value of some function of profits (π^M):

$$(\text{P.24})\qquad E\left(u^M(\pi^M)\right) \quad \text{where} \quad \frac{\partial u^M}{\partial \pi^M} \geq 0 \quad \text{and} \quad \frac{\partial^2 u^M}{\partial \pi^{M^2}} \leq 0$$

i.e., risk-aversion is assumed, and π^M is defined as:

$$\begin{aligned}
(\text{P.25})\qquad \pi^M = {} & \sum_m \sum_j \sum_k \sum_\ell \sum_p \sum_t (\gamma_1^M + \alpha_1^M)_{m,j,t}\, u_{m,j,k,\ell,p,t} + {} \\
& \sum_i \sum_m \sum_p \sum_t (\gamma_2^M + \alpha_2^M)_{i,m,t}\, a_{i,m,p,t} - \sum_m \sum_k \sum_t (\gamma_3^M + \alpha_3^M)_{m,k,t}\, a^P_{m,k,t} - {} \\
& \sum_m \sum_j \sum_k \sum_\ell \sum_t (\gamma_4^M + \alpha_4^M)_{m,j,k,\ell,t}\, r^P_{m,j,k,\ell,t} - \sum_m \sum_j \sum_k \sum_\ell \sum_t (\gamma_5^M + \alpha_5^M)_{m,j,k,\ell,t}\, r^L_{m,j,k,\ell,t} - {} \\
& \sum_m \sum_p \sum_t (\underline{\gamma}_6^M + \underline{\alpha}_6^M)_{m,p,t}\, \underline{x}^D_{m,p,t} - \sum_m \sum_p \sum_t (\underline{\gamma}_7^M + \underline{\alpha}_7^M)_{m,p,t}\, \underline{f}^D_{m,p,t} - {} \\
& \sum_p \sum_m \sum_t (\underline{\gamma}_8^M + \underline{\alpha}_8^M)_{m,p,t}\, \underline{x}^M_{p,m,t} - \sum_p \sum_m \sum_t (\underline{\gamma}_9^M + \underline{\alpha}_9^M)_{m,p,t}\, \underline{f}^M_{m,p,t} - {} \\
& \sum_m \sum_p \sum_t (\underline{\gamma}_{10}^M + \underline{\alpha}_{10}^M)_{m,p,t}\, \underline{x}^E_{p,m,t} - \sum_p \sum_m \sum_t (\underline{\gamma}_{11}^M + \underline{\alpha}_{11}^M)_{m,p,t}\, \underline{f}^E_{m,p,t} - {} \\
& \sum_m \sum_\ell \sum_t I_{m,\ell,t}(u_{m,j,k,\ell,p,t})
\end{aligned}$$

where each γ represents a discounted market price for its corresponding variable (mined coal, reclaimed land, etc.), and each α is a tax or subsidy added to the market price. γ's and α's which are underscored represent vectors, and $I_{m,\ell,t}$ is an institutional cost factor resulting from additional expenses required to meet legal restrictions on mining (permits, bonds, etc.). It is assumed that the level of $I_{m,\ell,t}$ will depend on the rate at which mining occurs.

The Beneficiation Component

Let $p = 1, \ldots, P_t^B$ denote the beneficiation processes available for use in time t. For each process, let $\underline{b}_{p,n,t}$ be a vector of rates of output production at beneficiation site n. The first nine elements of $\underline{b}_{p,n,t}$ refer to coal of the nine quality levels specified in the production component, i.e., the first element of $\underline{b}_{p,n,t}$ is the rate of production of coal with 0 percent sulfur content, etc. The remaining elements of $\underline{b}$ represent rates of production of byproducts such as sulfur and ash.

Let $\underline{x}^B_{p,n,t}$ be a vector of variable inputs other than coal used in beneficiation. Let $c^I_{j,n,p,t}$ and $c^O_{j,n,p,t}$ be the rates at which coal from Iowa and coal from other areas, respectively, are used in beneficiation. The j subscripts here refer to sulfur qualities and are defined exactly as they were in the production component. Finally, let $\underline{F}^B_{p,n,t}$ be a vector of fixed inputs available for use and $\underline{f}^B_{p,n,t}$ be a vector of rates of investment in the components of $\underline{F}^B_{p,n,t}$.

Letting $b^i_{p,n,t}$ represent the ith element of $\underline{b}_{p,n,t}$, we assume the following joint production functions:

$$(\text{B.1}) \quad b^i_{p,n,t} = b^i(\underline{x}^B_{p,n,t}, \underline{F}^B_{p,n,t}, c^I_{o,n,p,t}, \ldots, c^I_{8,n,p,t}, c^O_{o,n,p,t}, \ldots,$$

$$c^O_{8,n,p,t}, \sum_{t=0}^{t-1} \sum_n \underline{x}^B_{p,n,t}, \sum_{t=0}^{t-1} \sum_n \underline{f}^B_{p,n,t}, d^B_{p,t})$$

For notational convenience, let Ω^B denote the expression:

$$"\underline{x}^B_{p,n,t}, \underline{F}^B_{p,n,t}, c^I_{o,p,n,t}, \ldots, c^I_{8,p,n,t}, c^O_{o,p,n,t}, \ldots, c^O_{8,p,n,t}"$$

Then, we have

$$(B.2)\qquad E(b^i_{p,n,t}|\Omega^B) = E(b^i_{p,n,t-1}|\Omega^B) + h^i(\sum_n \underline{x}^B_{p,n,t-1}, \sum_n \underline{f}^B_{p,n,t-1}, d^B_{p,t})$$

$$(B.3)\qquad V(b^i_{p,n,t}|\Omega^B) = V(b^i_{p,n,t-1}|\Omega^B) + v^i(\sum_n \underline{x}^B_{p,n,t-1}, \sum_n \underline{f}^B_{p,n,t-1}, d^B_{p,t})$$

where $d^B_{p,t}$ is the rate of development expenditures on beneficiation process p.

Since some components of $\underline{b}_{p,n,t}$ are "desirable" and some are "undesirable," a general specification of the signs of the first partial derivative of the functions in (B.1), (B.2), and (B.3) is not possible.

$\underline{F}^B_{p,n,t}$ is determined by:

$$(B.4)\qquad \underline{F}^B_{p,n,t+1} = \underline{F}^B_{p,n,t} + F^B(\underline{b}_{p,n,t}, \underline{F}^B_{p,n,t}, \underline{f}^B_{p,n,t})$$

$$\frac{\partial F^B}{\partial \underline{b}} \le 0\ ,\qquad \frac{\partial F^B}{\partial \underline{F}^B} \le 0\ ,\qquad \frac{\partial F^B}{\partial \underline{f}^B} > 0$$

Objective Function

The objective is to maximize the expected value of some function of profits (π^B):

$$(B.5)\qquad E\left(u^B(\pi^B)\right) \quad \text{where} \quad \frac{\partial u^B}{\partial \pi^B} \ge 0 \quad \text{and} \quad \frac{\partial^2 u^B}{\partial \pi B^2} \le 0$$

i.e., risk-aversion is assumed, and π^B is defined as:

$$(B.6)\qquad \pi^B = \sum_p \sum_n \sum_t (\underline{\gamma}^B_1 + \underline{\alpha}^B_1)_{p,n,t}\, \underline{b}_{p,n,t} - \sum_p \sum_n \sum_t (\underline{\gamma}^B_2 + \underline{\alpha}^B_2)_{p,n,t}\, \underline{x}^B_{p,n,t}$$

$$- \sum_p \sum_n \sum_t (\underline{\gamma}^B_3 + \underline{\alpha}^B_3)_{p,n,t}\, \underline{f}^B_{p,n,t} - \sum_p \sum_n \sum_t \sum_j (\gamma^B_4 + \alpha^B_4)_{j,n,p,t}\, c^I_{j,n,p,t}$$

$$- \sum_j \sum_n \sum_p \sum_t (\gamma^B_5 + \alpha^B_5)_{j,n,p,t}\, c^O_{j,n,p,t}$$

where

$\underline{\gamma}_1^B$ is a vector of discounted market prices for $\underline{b}_{p,n,t}$. Some elements of $\underline{\gamma}_1^B$ may be negative for "undesirable" byproducts requiring disposal,

$\underline{\gamma}_2^B$, $\underline{\gamma}_3^B$ are the discounted market prices for fixed and variable inputs,

$\underline{\alpha}_i^B$, i = 1, ..., 5 are taxes or subsidies added to market prices, and

γ_4^B and γ_5^B are the discounted market prices for unbeneficiated coal from Iowa and other states, respectively.

The Transportation Component

Let $s_{j,y,z,p,t}$ be the rate at which coal is shipped. The subscript $j = 0, 1, \ldots, 8$ denotes sulfur content as defined in the production component. The subscripts y,z represent a particular transportation rule from origin y to destination z. Allowable routes are mine site to beneficiation site, mine site to demand center, and beneficiation site to demand center. The $p = 1, \ldots, P^S_t$ subscript refers to available transportation methods (rail, track, etc.) in time t. For simplicity, shipping coal byproducts (ash, etc.) is not considered explicitly.

Let $\underline{x}^S_{y,z,p,t}$ be a vector of variable inputs used for route y,z, $\underline{F}^S_{y,z,p,t}$ be a vector of fixed inputs available for use for route y,z, $\underline{f}^S_{y,z,p,t}$ be a vector of rates of investment in the components of $\underline{F}^S_{y,z,p,t}$, and $d^S_{p,t}$ be the rate of development expenditures on transportation method p. Also, let $c^I_{j,y,z,p,t}$ and $c^O_{j,y,z,p,t}$ be the amounts of Iowa and non-Iowa coal available for shipping on route y,z. Then, we have

$$(S.1) \quad s_{j,y,z,p,t} = s(\underline{x}^S_{y,z,p,t}, \underline{F}^S_{y,z,p,t}, c^I_{j,y,z,p,t}, c^O_{j,y,z,p,t}, \sum_{t=0}^{t-1} \sum_y \sum_z \underline{x}^S_{y,z,p,t}, \sum_{t=0}^{t-1} \sum_y \sum_z \underline{f}^S_{y,z,p,t}, d^S_{p,t})$$

For notation convenience, let Ω^S represent the expression:

$$"\underline{x}^S_{y,z,p,t},\ \underline{F}^S_{y,z,p,t},\ c^I_{j,y,z,p,t},\ c^O_{j,y,z,p,t}"$$

Then, we have

$$(S.2) \quad E(s_{j,y,z,p,t}|\Omega^S) = E(s_{j,y,z,p,t-1}|\Omega^S) + h^S(\sum_y \sum_z \underline{x}^S_{y,z,p,t-1}, \sum_y \sum_z \underline{f}^S_{y,z,p,t-1}, d^S_{p,t})$$

$$(S.3)\quad V(s_{j,y,z,p,t}|\Omega^S) = V(s_{j,y,z,p,t-1}|\Omega^S) + v^S\Big(\sum_y \sum_z \underline{x}^S_{y,z,p,t-1}, \sum_y \sum_z \underline{f}^S_{y,z,p,t-1}, d^S_{p,t}\Big)$$

We have the usual partials:

$$\frac{\partial s}{\partial \underline{x}^S}, \quad \frac{\partial s}{\partial \underline{F}^S}, \quad \frac{\partial s}{\partial c^I}, \quad \frac{\partial s}{\partial c^O} \geq 0$$

We account for the effects of learning-by-doing and development expenditures by specifying that all first partials of h^S are nonnegative and all first partials of v^S are nonpositive.

$\underline{F}^S_{y,z,p,t}$ is determined by

$$(S.4)\qquad \underline{F}^S_{y,z,p,t+1} = \underline{F}^S_{y,z,p,t} + F^S(\underline{F}^S_{y,z,p,t}, \underline{s}_{y,z,p,t}, \underline{f}^S_{y,z,p,t})$$

where $\underline{f}^S_{y,z,p,t}$ is a vector of rates of investment in the elements of $\underline{F}^S_{y,z,p,t}$ and

$$\frac{\partial F^S}{\partial \underline{F}^S} \leq 0\ , \quad \frac{\partial F^S}{\partial \underline{s}} \leq 0\ , \quad \frac{\partial F^S}{\partial \underline{f}^S} \geq 0$$

Objective Function

The objective is to maximize the expected value of some function of profits from shipping coal (π^{SC}) and the profits of shipping alternative products (π^{SA}) such as grain. It is important that π^{SA} be considered since transportation resources, unlike mining and beneficiating resources, can be conveniently used for products other than coal. Thus, we wish to maximize

$$(S.5)\qquad E\left(u^S(\pi^{SA}, \pi^{SC})\right)$$

where both first partials of u^S are nonnegative and the two direct second partials are nonpositive, i.e., risk-aversion is assumed. Further assume that π^{SC} is defined by

$$\text{(S.6)} \qquad \pi^{SC} = \sum_j \sum_y \sum_z \sum_p \sum_t (\underline{\gamma}_1^S + \underline{\alpha}_1^S)_{y,z,p,t}\, s_{j,y,z,p,t} - \sum_y \sum_z \sum_p \sum_t (\underline{\gamma}_2^S + \underline{\alpha}_2^S)_{y,z,p,t}\, \underline{x}^S_{y,z,p,t} - \sum_y \sum_z \sum_p \sum_t (\underline{\gamma}_3^S + \underline{\alpha}_3^S)_{y,z,p,t}\, \underline{f}^S_{y,z,p,t}$$

where

$\underline{\gamma}_1^S$ is a vector of discounted market revenues for shipping coal,

$\underline{\gamma}_2^S$ and $\underline{\gamma}_3^S$ are vectors of discounted market prices for variable and fixed inputs, and

$\underline{\alpha}_1^S$, $\underline{\alpha}_2^S$, $\underline{\alpha}_3^S$ are vectors of discounted taxes or subsidies.

It should be noted in passing that costs for $c^I_{j,y,z,p,t}$ and $c^O_{j,y,z,p,t}$ do not appear in (S.6) because the transportation component does not purchase the coal they ship. Instead, they sell the service of transporting coal which they do not actually own.

The Research and Development Component

We assume that the R & D agency has a fixed amount of money it can spend in period t, G_t. The agency can allocate this money on research or development in any of the components as they see fit:

$$(R.1) \quad g_t^M + g_t^D + g_t^E + g_t^B + g_t^S + \Sigma d_{p,t}^M + \Sigma d_{p,t}^D + \Sigma d_{p,t}^E + \Sigma d_{p,t}^B + \Sigma d_{p,t}^S \le G_t$$

where g_t represents the rate of research money allocation, $d_{p,t}$ represents the rate of development money allocation on process p, and M,D,E,B,S represents mining, discovery, land use, beneficiation, and transportation.

Research Expenditures

Expenditures for research generate new processes, i.e., they increase of at least one of P_t^M, P_t^D, P_t^E, P_t^B, or P_t^S. To demonstrate the mechanism by which research expenditures affect the number of process, we will show the particular case of the impact of g_t^M on P_t^M. Exact analogous arguments can be made for discovery, land use, beneficiation, and transportation.

Letting $\delta_t^M \ge 0$ be the rate at which new mining processes are discovered in time t, we have

$$(R.2) \qquad P_t^M = P_{t-1}^M + \delta_t^M$$

We assume that decision makers in the research agency assign discrete probabilities to each value of δ_t^M. Let the believed probability that δ_t^M will take on its ith value be Φ_t^i with $\sum_{i=1}^{\infty} \Phi_t^i = 1$.

The decision makers' beliefs concerning the Φ distribution are influenced by g_t^M. Thus, we can more generally represent Φ_t^i as $\Phi_t^i(g_t^M)$ and assume that higher values of g_t^M lead to Φ distributions that are more heavily weighted towards higher values of δ_t^M. We can now take the expected value of (R.2). Letting $\delta_{i,t}^M$ be the ith value of δ_t^M, we have

$$(R.3) \qquad E(P_t^M) = P_{t-1}^M + E(\delta_t^M) = P_{t-1}^M + \sum_{i=1}^{\infty} [\Phi_t^i(g_t^M) \cdot \delta_{i,t}^M]$$

Our previous assumption concerning the relationship between Φ and g_t^M leads to the desired result that:

$$\frac{\partial E(P_t^M)}{\partial g_t^M} \geq 0$$

There is no reason to assume for R & D decision makers that $\Phi(\delta_t^M = 0 \mid g_t^M = 0) = 1$. In other words, they may feel that processes will be discovered in other areas and will become available to them with no research expenditures.

Development

Development expenditures improve existing processes by increasing their productivity for a given input combination or decreasing the variability of the process. Hence, $d_{p,t}$ and P_t are unrelated for all superscripts.

Equations (P.3), (P.4), (P.8), (P.20)-(P.23), (B.2), (B.3), (S.3), and (S.4) precisely define the role of development expenditures in the model.

Objective Function

The objective is to maximize the expected value of some function of the number of processes available to each component and the productivity and variability of these processes:

$$\text{(R.4)}\quad \text{Max } E\Big[u^R\Big(P^M_t, P^D_t, P^E_t, P^B_t, P^S_t, E(u_{m,j,k,\ell,p,t}), V(u_{m,j,k,\ell,p,t}),$$

$$E(\theta^i_{m,j,k,\ell,t}), E(a_{i,m,p,t}), V(a_{i,m,p,t}), E(\lambda^L_{h,i,m,p,t}), V(\lambda^L_{h,i,m,p,t}),$$

$$E(b^i_{p,n,t}), V(b^i_{p,n,t}), E(s_{j,y,z,p,t}), V(s_{j,y,z,p,t})\Big)\Big]$$

where the first partials with respect to all P's and expected values are nonnegative and with respect to all variances are nonpositive.

The Demand Component

We assume that consumers desire to minimize the cost (C) of obtaining a predetermined amount of coal. This can be expressed as:

$$\text{(D.1)} \qquad \text{Minimize } C = (\gamma^I + \alpha^I)_{j,d,t}\, q^I_{j,d,t} + (\gamma^O + \alpha^O)_{j,d,t} q^O_{j,d,t} + \psi_{d,t}$$

subject to

$$\text{(D.2)} \qquad \sum_j H^I_j \cdot q^I_{j,d,t} + \sum_j H^O_j \cdot q^O_{j,d,t} = H^*_{d,t}$$

Here, $q^I_{j,d,t}$ and $q^O_{j,d,t}$ represent the rates of consumption of Iowa and non-Iowa coal. The j subscript refers to the nine quality levels referred to in the demand component, the d subscript refers to a particular demand center, and t refers to time. γ^I and γ^O are the market prices for Iowa and non-Iowa coal, and α^I and α^O are taxes or subsidies added to these prices. H^I_j and H^O_j are the heating values of coal of quality level j from Iowa and outside of Iowa. $H^*_{d,t}$ is the demand for energy from coal expressed in heat units. $\psi_{d,t}$ is the level of private expenditures on post-combustion sulfur removal.

The model accounts for differences in reliability of coal from Iowa and non-Iowa sources by the following equations:

$$\text{(D.3)} \qquad q^I_{j,d,t} = \bar{q}^I_{j,d,t} + \epsilon^I_{j,d,t}; \quad q^O_{j,d,t} = \bar{q}^O_{j,d,t} + \epsilon^O_{j,d,t}$$

where $\epsilon^I_{j,d,t}$ and $\epsilon^O_{j,d,t}$ are random deviations from the mean values of $q^I_{j,d,t}$ and $q^O_{j,d,t}$, respectively.

Restrictions on the quality of coal that may be burned are imposed as follows:

$$(D.4)\qquad \sum_j \left[\frac{z_j^I \cdot H_j^I \cdot q_{j,d,t}^I + z_j^O \cdot H_j^O \cdot q_{j,d,t}^O}{H_{d,t}^*} \right] \le z_{d,t}^* + G(\psi_{d,t} + \alpha_{d,t}^G)$$

Here, z_j^I and z_j^O are the weights of sulfur per heating unit of Iowa and non-Iowa coal of quality level j, $z_{d,t}^*$ is a legislated maximum for the weight of sulfur per heating unit, and $\alpha_{d,t}^G$ is a subsidy for post-combustion sulfur removal. We assume that the first partials of G are nonnegative with respect to both ψ and α^G.

Equation (D.4) is structured in such a way as to allow blending of coals of different sulfur levels and the possibility of burning coal of poorer quality than the regulations allow by investing in post-combustion sulfur removal.

The Public Objective Function

The public, through the legislature, is concerned with maximizing a function of the following type:

$$\text{(L.1)} \quad \text{Maximize } u^L(H^*_{d,t}, \gamma^I_{j,d,t}, \gamma^O_{j,d,t}, a_{i,m,p,t}, \lambda^L_{h,i,m,p,t}, \lambda^W_{c,m,t}, q^I_{j,d,t} + q^O_{j,d,t}, \beta_k, \beta_A)$$

$q^I_{j,d,t} + q^O_{j,d,t}$ enters as an argument insofar as the public is concerned with the impact on air quality of burning coal of various qualities as well as the relative risk of obtaining coal from alternative sources. The public's concern for income distribution is reflected by β_k, the income accruing to the kth class of mineral rights owners. Specifically,

$$\text{(L.2)} \quad \beta_k = \sum_m \sum_t (\gamma^M_3)_{m,k,t}\, a^P_{m,k,t} + \sum_m \sum_j \sum_\ell \sum_t (\gamma^M_4)_{m,j,k,\ell,t}\, r^P_{m,j,k,\ell,t} + \sum_m \sum_j \sum_\ell \sum_t (\gamma^M_5)_{m,j,k,\ell,t}\, r^L_{m,j,k,\ell,t}$$

Note that β_A is a measure of the usefulness of public money for purposes other than influencing the coal sector of the economy, (i.e. it is an opportunity cost measure for funds allocated to the coal sector).

The public may attempt to achieve their objectives in one of three basic ways.

(a) influence the price structure in the system by manipulating the levels of the α's or of I, or

(b) impose standards of the form (P.12), (P.15), (P.26), or (D.3), or

(c) allocate money to the research and development component through (R.1).

The effectiveness of public intervention in any of the components will be determined by the first-order conditions for the optimization problem specified in each component.

Identities

Let $S^M_{j,m,t}$ be the amount of mined coal of quality level j in storage at mine site m in time t. Then,

$$(I.1)\quad S^M_{j,m,t} = S^M_{j,m,t-1} + \sum_k \sum_\ell \sum_p u_{m,j,k,\ell,p,t} - \sum_n \sum_p s_{j,m,n,p,t} - \sum_d \sum_p s_{j,m,d,p,t}$$

Similarly, let $S^B_{j,n,t}$ be the amount of beneficiated coal of quality level j in storage at beneficiation site n. Then,

$$(I.2)\quad S^B_{j,n,t} = S^B_{j,m,t-1} + \sum_p b^{i=j}_{p,n,t} - \sum_p \sum_d s_{j,n,d,p,t}$$

We can say the following about quantities demanded:

$$(I.3)\quad q^I_{j,d,t} + q^O_{j,d,t} = \sum_m \sum_p s_{j,m,d,p,t} + \sum_n \sum_p s_{j,n,d,p,t} + c^O_{j,d,t}$$

where $c^O_{j,d,t}$ is the amount of coal shipped directly from other states to demand center d. It does not follow that $q^O_{j,d,t} = c^O_{j,d,t}$ since non-Iowa coal could have been beneficiated at Iowa sites and then shipped to demand site d. Only the following can be said about $q^I_{j,d,t}$:

$$(I.4)\quad \sum_m \sum_p s_{j,m,d,p,t} \le q^I_{j,d,t} \le \sum_m \sum_p s_{j,m,d,p,t} + \sum_n \sum_p s_{j,n,d,p,t}$$

The amount of Iowa coal beneficiated is limited by shipments from Iowa mines to the beneficiation centers:

$$(I.5)\quad \sum_p c^I_{j,n,p,t} \le \sum_m \sum_p s_{j,m,n,p,t}$$

Finally, the total amount of Iowa coal available for transportation must be related to the amount of coal mined in Iowa:

$$\text{(I.6)} \qquad \sum_{z}\sum_{p} c^{I}_{j,m,z,p,t} \leq S^{M}_{j,m,t-1} + \sum_{p}\sum_{l}\sum_{k} u_{m,j,k,l,p,t}$$

Note that $\sum_{z}\sum_{p} c^{I}_{j,m,z,p,t} = \sum_{n}\sum_{p} s_{j,m,n,p,t} + \sum_{d}\sum_{p} s_{j,m,d,p,t}$

Appendix II: EMRRI COAL RESEARCH PROGRAM

The following are brief descriptions of approved projects:

1. COAL PROJECT ADMINISTRATION AND PLANNING (D. J. Zaffarano & R. W. Shearer)

   Manage the Coal Division of the Energy and Mineral Resources Research Institute (EMRRI).

2. MECHANICAL BENEFICIATION OF IOWA COAL (R. W. Fisher)

   Investigate physical methods including crushing, washing, and separation processes to reduce the sulfur and ash in Iowa coal. This particular portion of the project will concern bench scale studies and design of a demonstration plant, but it is expected that the project will be continued through the demonstration plant operation.

3. ECOLOGICAL STUDIES FOR COAL PROJECT (D. C. Glenn-Lewin)

   General survey of ecological conditions of coal bearing areas of Iowa, development of guidelines for environmental impact statements, and preparation of laboratory facilities for specific site studies.

4. LOCATION OF COAL BY REMOTE SENSING (B. K. Lunde)

   Project definition study to establish, by literature search, consultation, and analysis, which remote sensing methods would best merit detailed experimental investigation for applicability to Iowa Coal location, and to recommend sites suitable for testing them.

5. PREPARATION OF ASH-FREE LOW SULFUR FUEL FROM IOWA COAL (P. Chiotti & F. A. Schmidt)

   Undertake bench-scale investigations of the desulfurization of flue gas by fused salts and of the desulfurization of coal by hydrochlorination, chlorination, and related processes.

6. PETROGRAPHY OF IOWA COALS (D. L. Biggs)

   Describe, sample, determine sample constituents petrographically and compare samples for each of the ten operating Iowa coal mines.

7. UNIVERSITY YEAR FOR ACTION (UYA)—TUITION SUPPORT (Roy Park)

   Tuition support for UYA students.

8. THE FEASIBILITY OF DEVELOPING A PORTABLE SURFACE-LOCATED INSTRUMENT TO PROBE FOR COAL DEPOSITS BY MEANS OF ELECTROMAGNETIC OR ACOUSTIC WAVES (R. E. Post)

   This project aims at determining the feasibility of using surface-located electromagnetic or acoustic probing techniques to sense the presence of coal deposits located within 100 feet of the earth's surface, based on properties of waves reflected from the deposits. Initial studies will be based on computer simulations.

9. ANALYTICAL CHARACTERIZATION OF COAL (V. A. Fassel)

Provide routine analytical support for coal research projects including proximate and ultimate analyses and sulfur and trace element monitoring of the effectiveness of chemical and mechanical processes for coal beneficiation.

10. PULSED NMR STUDIES OF THE CHEMICAL CONSTITUTION OF COAL (B. C. Gerstein)

Establish a method for differentiating carbon and hydrogen in coal between aromatic and non-aromatic fractions in the solid state.

11. CHEMICAL PROCESSES FOR DESULFURIZATION OF IOWA COAL (T. D. Wheelock & A. H. Pulsifer)

Screen existing methods (including, but not limited to, oxidation and hydrodesulfurization) for reducing sulfur content in coal, and to develop at least one industrial process technically and economically feasible for reducing sulfur content in Iowa coal to useable levels.

12. DETERMINATION OF THE SIZE, SHAPE, EXTENT, CONTINUITY OF COAL DEPOSITS IN THE VICINITY OF MADRID, IOWA (John Lemish)

Determination of size, shape, extent, and continuity of coal deposits in the vicinity of Madrid, Iowa, through analysis of approximately 500 existing drill hole logs, and develop statistical models based on these determinations to permit more efficient future survey designs.

13. SEARCHING, PROSPECTING AND IN SITU ANALYSIS RELATED TO IOWA COAL DEPOSITS (D. M. Roberts & R. G. Struss)

Investigation of advanced methods of detecting and mapping Iowa coal deposits. The initial phase (3 months) of this project will be limited to literature search, visitations, and consultations relative to possibly more efficient and economical methods of drilling test holes and logging them.

14. MICROSTRUCTURAL CHARACTERIZATION OF IOWA COAL (R. T. Greer)

Characterize the occurrence of pyrites, as to size, morphology, and distribution in Iowa coal and further characterize the ultrafine structure of coal constituents. Recommendations for methods of seam identification are also sought.

15. UNIVERSITY YEAR FOR ACTION (UYA)—EXPENSE SUPPORT (Roy Park)

Support work performed by ACTION-UYA students in conjunction with the Iowa Coal Project.

16. FIELD DEMONSTRATION PROJECT COORDINATION (Lyle V.A. Sendlein)

Demonstration projects to be conducted in the field represent an important aspect of the Coal Project mission. The field project(s) will investigate many aspects of the surface mining and processing of Iowa coal in representative settings.

17. COAL MINING RECLAMATION - AGRONOMY (S.J. Henning & John Pesek)

Determine the physical, chemical and biological properties of representative stratigraphic materials found over Iowa coal relative to water quality and plant growth. Determine the stratification of the reclaimed overburden required to achieve a specified land use and conduct field tests of such reclaimed land to determine crop production and related effects.

18. INTEGRATION OF MINING AND LAND RECLAMATION OPERATIONS FOR RETURNING LAND TO ECONOMIC PRODUCTIVITY (C.E. Anderson)

Develop an economic mining procedure to achieve desired land-use including considerations of minimizing materials handling, overburden replacement methods and equipment, and minimizing lost time of land-use.

19. COAL MINING - EQUIPMENT (T.E. Hazen)

For purchase of equipment incident to the Coal proposal entitled "Integration of Mining and Land Reclamation Operations for Returning Land to Economic Productivity."

20. LEGAL AND SYSTEMS ANALYSES; ECONOMIC ANALYSIS (N. Harl, M. Boehlje, & G. Rausser)

Legal and systems analyses of mining and reclamation operations; overall economic analysis.