CHAPTER 85

A SYSTEMS APPROACH
TO PETROLEUM PORT SITE SELECTION

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ABSTRACT

Petroleum port site selection is examined in the broad context of the total transportation system from production to consumption area. Basic systems engineering approaches are applied to the problem to formulate a mathematical model which permits all transportation system variables, including capital and operating costs, to be put in quantitative form. An example of the computer solution is given, along with a discussion of the principal calculations involved. Unit transportation cost is selected as the measure of effectiveness of candidate systems. The port site associated with the system yielding the lowest unit transportation cost for the entire range of throughputs is selected.

INTRODUCTION

Oil and many other natural resources are found in areas of the world far from the centers of consumption. Many alternate routes exist between the points of production and consumption; however, only one route, with the optimum mix of vehicles, permits the lowest cost transportation of the commodity.

The great tankers of today often cannot use the sheltered ports frequented by general cargo vessels, and must be moored on an exposed coast where depth and maneuvering room are adequate. Thus oil port site selection no longer represents a choice between a few natural harbors, but rather is a matter of identifying an optimum transportation system and adapting a point on the coast to permit ship loading or discharging. The basic question confronting an engineer-economist responsible for port site selection is how to locate that site, or family of sites, through which petroleum can be transported at the lowest cost.

The systems approach enforces orderly thought and is adaptable to any level of study effort, ranging from a cursory review, to the precise economic comparison of several fully designed systems. Of particular significance is that the systems approach requires that the engineer recognize and examine the entire petroleum transportation system of which the port site is only one part.

This paper examines in successive steps: (1) the basic systems engineering approach, (2) the elements of petroleum transportation systems, (3) systems engineering applied to petroleum port site selection, and (4) a mathematical model for choosing one port site from among several candidates.

1330

BASIC SYSTEMS ENGINEERING APPROACH

A commercial need, such as moving crude oil from a producing field to a refinery and then to the consumer, results in the conception of a system which will satisfy the need both technically and economically. This system may be defined in terms of specific objectives which must be met and also specific constraints which must be observed. Both the objectives and the constraints can be distilled into what can be termed system requirements which become the inputs to various alternate schemes.

Following the determination of system requirements, alternate approaches are developed to satisfy the requirements. In other words how to attain the stated objectives while respecting the limitations of the constraints.

Next a trade-off study, or economic comparison, is conducted to choose the most promising approaches from among all of those proposed. A simple mathematical model is used which accounts for system cost and performance. In some cases only one approach is technically feasible while in other cases many approaches, with nearly equal merit, may be identified. Each scheme which shows technical and economic promise is carried through a preliminary design phase so that all of its parameters may be put in quantitative form. This reqires that both capital costs and operating costs be defined by the system design.

The evaluation of these candidate systems is made on the basis of a measure of effectiveness. This measure of effectiveness is the independent variable of an economic function, or mathematical model, which permits all other system parameters to be expressed as dependent variables. It is essential that this type of study recognize and account for all performance and cost effects of a system design alternative. On this basis the most effective of the candidate systems is selected, resulting in a choice which may be defended both economically and technically.

THE ELEMENTS OF PETROLEUM TRANSPORTATION

The systems engineering approach requires consideration of all parts of the total transportation system which change with different harbor sites and requires understanding of both the technical and economic aspects of various modes of petroleum transportation and their interrelationships.
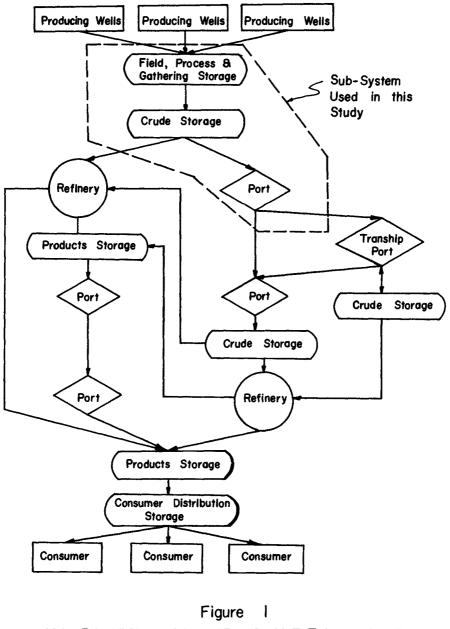
TRANSPORTATION MODES

Generally, petroleum is moved from the producing field to the consumer by a series of transportation modes. These modes are selected on the basis of economy and are normally pipelines on land and large tankers at sea. Since pipelines provide a continuous flow and ships operate as batch carriers, it is necessary to provide a surge, or storage, capability between these two modes to achieve maximum economy in the system. The size of this storage facility, or tank farm, is determined by the number of products handled, by the method of product segregation, and the regularity with which tankers arrive and depart.

A second important difference between these two widely used modes of crude oil transport is that with an increase in throughput, tankers can be added on an individual basis as required, but that a pipeline of specific diameter and wall thickness must be installed initially.

Each transportation mode and its intervening surge facility may be thought of as a series of separate, but interdependent, links which make up the total petroleum transportation system.

Figure   I

GENERALIZED   OIL   TRANSPORTATION   SYSTEM

THE GENERALIZED SYSTEM

A generalized oil transportation system is shown schematically in Figure 1, from well head to the consumption point, indicating transportation modes and interfaces. The interfaces are either points where one form of transport is exchanged for another or where there is an interruption in flow. Ports, storage tanks and refineries are all interfaces. A port is an example of a change in transportation mode, while field gathering storage is an interruption in the flow along a pipeline.

Crude is pumped from well head to field gathering storage, where gas may be separated from the crude or different crudes mixed together before being transported further. The crude then moves on to an intermediate storage facility before being pumped to a port for shipment by tanker or being piped to a refinery for processing. If oil tankers are used, the oil is unloaded at the port of destination to a tank farm before being pumped to a refinery. With the advent of the very large tankers, which are limited to a few very deep ports, the use of the trans-shipment port has become more prevalent. At a trans-shipment port the oil is off-loaded from the large tanker into smaller tankers and the excess pumped to storage; or if no smaller tankers are present, all the oil is pumped to storage to await their arrival. Alternatively, some of this crude can continue its journey to a refinery by pipeline or other forms of transport. From the refinery the product goes into product storage from which it is distributed, by any of the trans- portation modes, to the various consumption points.

Figure 1 can thus be used to identify the oil transportation system for any given situation. In a transportation system in which oil tankers are used, the choice of different routes is based mainly on consideration of possible port sites and on possible land transportation routes. Sea routes have also to be considered but they are much more flexible than land routes. If it is required to select a particular facility within a transportation system, such as a port site, it is probably not necessary to analyze the entire transportation system, but only part, or sub-system. The sub-system study described as an example in this paper is indicated on Figure 1.

SYSTEMS ENGINEERING APPLIED TO PETROLEUM
PORT SITE SELECTION

The fundamental problem to be solved is how best to move oil from the area of production to the area of consumption. The systems approach provides a logical step by step process whereby the most efficient and economical method of oil transportation can be found. The port which is chosen after such a study may not require the least initial investment or be the least expensive to operate of the candidate port sites, but the transportation system of which it is a part will provide the most economical method of oil transportation from producer to consumer. Figure 2 is a flow diagram showing the steps by which a systems study of this type is carried out.

OBJECTIVES AND CONSTRAINTS

The oil port, like all other parts of the system, must be designed to meet the objectives of the entire system. These objectives normally include a definition of (a) the origin and destination of the petroleum, (b) initial and ultimate throughputs of the system, (c) anticipated rates of system growth, (d) the time scale for construction and start up, and (e) the useful life of the system.

Various types of constraints must also be recognized at the outset of
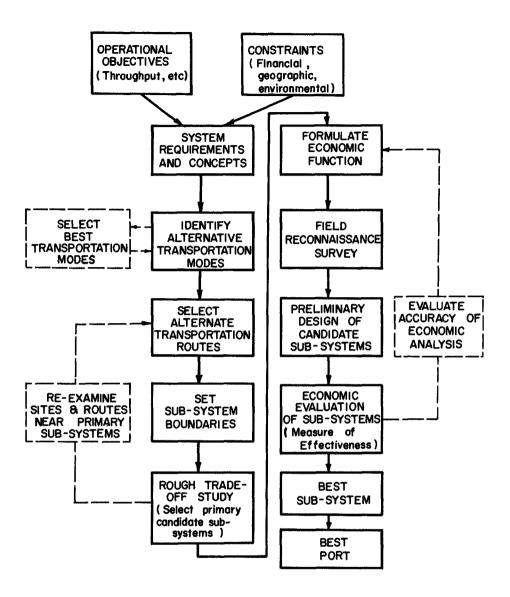
Figure   2

FLOW   DIAGRAM   FOR   SYSTEMS
APPROACH   TO   HARBOR   SITE   SELECTION

the study. These constraints may be thought of in the broader context of the system "environment". The environment can be broken down into technical, economic, and social environments. The technical environment covers existing oil transportation systems and their technical obsolescence, the present state of technology as it applies to oil transportation, and expected or possible developments in oil transportation. This would, for example, include a study of very large tankers in the 200,000 to 1,000,000 DWT range and methods of mooring, loading and unloading their oil.

The economic environment is concerned with costs of existing and pro-jected systems, unit costs of material and labor, and changing customers and markets. Since the transportation system chosen must operate for a number of years, it must be designed with the flexibility to accomodate possible changes in throughput and consumption areas.

Within the social environment are considered the possible effects of changing political climates on the operation of the system, and the advan-tages of operating in one country rather than another.

SYSTEM REQUIREMENTS

Under the heading of system requirements all objectives and constraints are distilled into a compatible performance criteria for each part of the system. In this step the scope of the total system is established and the general type of route from origin to destination is identified.

ALTERNATIVE TRANSPORTATION MODES

There will be a number of transportation modes (i.e. tankers, pipelines, railcars, etc.) which may be used to move the oil. These modes are now considered and alternative combinations which satisfy the system requirements are chosen. In this case, one of these modes will be a form of ocean trans-port requiring a port. The alternative modes are then assessed by making a rough cut trade-off study based on the applicability of the transportation mode to the terrain and its use cost. In the case used in this paper, the modes are pipelines and ocean going tankers.

TRANSPORTATION ROUTES

There are theoretically an infinite number of different routes between the production and consumption areas. Practically, however, only those routes which appear technically feasible are chosen. This choice will normally be made by experienced people using available topographic maps and hydrographic charts. Each port site may be served by several sea routes and also by several pipelines routes. Every different combination, even though passing through the same port site, represents a separate transportation route.

SUB-SYSTEMS

For the purpose of port site selection it may only be necessary to consider part of the total transportation system. It is probable that geographic or national boundaries have placed several constraints on the candidate systems and that all systems pass some common (or nodal) point such as a strait, pass, canal, or cape which may, for study purposes, be regarded as the terminal point of a sub-transportation system. If such sub-systems are in fact independent of the total transportation system they may be used for the optimization study and as a consequence permit a substanital reduc-tion in field investigation, preliminary design, and economic analysis efforts

Figure 3 shows the transportation sub-system discussed in this paper, and which is shown schematically in Figure 1. The sub-system used as a basis for this optimization study has as its upstream nodal point the field gathering facilities. Proceeding downstream, the sub-system contains the following
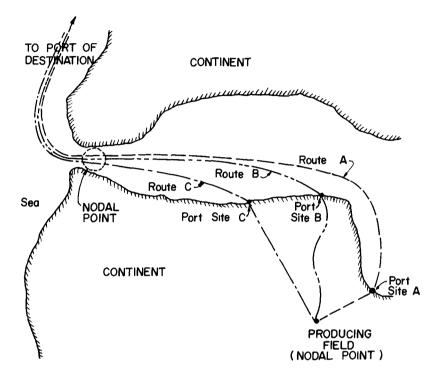

Figure 3

ALTERNATE   PETROLEUM   TRANSPORTATION   ROUTES

links: (1) pipeline, (2) tank farm at the marine terminal, (3) high capacity ship loading lines, (4) the harbor and ship loading berths, and (5) a sea voyage to the downstream nodal point. This nodal point is designated as the nearest point to the candidate harbor sites which all ships pass.
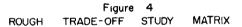
The accuracy required in setting the boundaries, or nodal points, of the sub-systems depends on the accuracy required of the study. In the case of oil port site selection, the transportation route is analyzed both upstream and downstream from the port site until those points are identified which are common to all sub-systems and such that the consideration of any candidate port site has no effect on those portions of the transportation system outside the sub-system boundaries.

ROUGH TRADE-OFF STUDY

Once the candidate sub-systems have been identified a rough trade-off study can be used to eliminate those which are grossly non-competitive. Sub-systems considered in this paper are compared in Figure 4. Each sub-system has been assigned five cost variables which represent the links in the sub-system including: (a) pipeline (b) tank farm, (c) harbor, (d) sea voyage, and (e) unusual operating costs. The last item is used to convert any unique annual costs not common to all sub-systems into a capital cost.

PRELIMINARY   EVALUATION   OF   CANDIDATE   SUB-SYSTEMS
(CAPITAL COST BASIS IN   MILLIONS OF DOLLARS)
(FOR   ANTICIPATED   MEDIAN   THROUGHPUT)

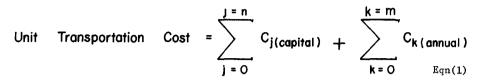| SUB-SYSTEM	PIPELINE	TANK FARM	HARBOR	SEA VOYAGE	UNUSUAL OPERATING COSTS	SUB-SYSTEM COST	SELECTED PRIMARY CANDIDATES
A	50	9	6	2	—	67	Yes
B	120	10	6	2	1	139	No
C	150	8	7	2	2	169	No
D	55	10	7	3	—	75	Yes
E	70	9	5	3	1	88	Yes
ETC							ETC

Figure   4
ROUGH   TRADE-OFF   STUDY   MATRIX

This simple comparison of the candidate sub-systems shows that due to high pipeline costs for systems B and C neither could be competitive with A, D, and E even though the assigned costs are only approximate. Those sub-systems with the lowest costs are selected as primary candidates for more detailed economic comparison.

THE ECONOMIC FUNCTION

At this point in the study it is desirable to formulate the economic function which will be used in a more precise trade-off study for the comparison of the primary candidate sub-systems. This method of selection requires a mathematical model, though it may be quite simple, which reflects the influence of two types of quantifiable parameters -- one related to system performance, and the other related to system cost. The accuracy of the study rests in the degree to which all parameters are quantifiable, although it is occasionally necessary to use quasi-quantifiable inputs.

The purpose of this procedure is to set forth systematically the parameters which affect the rational selection of a port site under the present, and foreseeable, conditions of system operation. A key part of the trade-off study is the selection of a Measure of Effectiveness (MOE) of all the system design alternatives. The Unit Transportation Cost (UTC), expressed in say dollars per ton, is a measure of effectiveness which permits all other

variables in a petroleum transportation system, or sub-system, to be express-
ed as dependent variables in a single economic function. It is essential
that this type of study recognize and account for all performance and cost
effects of a design alternative.

    The economic function

$$\text{Unit Transportation Cost} = \sum_{j=0}^{j=n} C_{j(capital)} + \sum_{k=0}^{k=m} C_{k(annual)} \qquad \text{Eqn(1)}$$

contains (n) capital cost terms (C_j) and (m) annual cost terms (C_k), each
representing a quantifiable feature of a candidate sub-system. This economic
function should be established before undertaking the design of the candidate
sub-systems since it identifies the significant cost parameters. The economic
importance of each term should be determined early in the study so that the
field investigation and design effort can be devoted to the items which have
the greatest impact on the UTC.

Accuracy of the Economic Function

    At this stage in the study it is also possible to examine each term of
the economic function and make a preliminary estimate of the accuracy with
which each can be evaluated. From this the potential range of inaccuracy,
or error, of the UTC can be established and in turn the required accuracy
of all terms of the economic function can be set.

Comparitive vs Absolute Economic Studies

    It should also be decided whether the UTC is to represent the absolute
costs of a sub-system or whether its purpose is only to compare similar
systems. If absolute UTC's are desired all cost items of each system must
be represented by a cost term in the economic function. If comparative UTC's
are required, as is the case if port site selection is the only objective,
all equal cost terms common to each candidate sub-system may be omitted from
the economic function. The omission of these common terms will reduce the
amount of effort required to complete the study.

    It should be noted that Equation (1) represents a steady-state condi-
tion for a given increment of system expansion. Its formulation should not
be confused with a dynamic analysis which examines the state of the trans-
portation system at uniform increments of time or at each event.

FIELD RECONNAISSANCE SURVEY

    A field reconnaissance survey is normally necessary before beginning
the preliminary sub-system design phase, particularly when the candidate
routes and sites are located in an unfamiliar part of the world. The first
step is to conduct a rough trade-off study as shown in Figure 4, so that
only the several most promising sub-systems are retained for further inves-
tigation. The second step is to formulate the economic function to identify
all significant cost items associated with the sub-systems being compared.
The field reconnaissance survey can then be planned to concentrate on those
features of the candidate sub-systems which represent the items of greatest
cost and about which the least is known.

Typical reconnaissance surveys involve continuous seismic profiling at harbor sites to determine marine soil conditions, estimates of quantities of littoral drift, scattered borings in the tank farm area to appraise foundation conditions, and low level flying of the pipeline routes to determine elevations and assess the types of material to be excavated in pipeline burial. Data is also collected on local costs and availability of material and labor, duties, taxes, etc.

DESIGN OF PRIMARY CANDIDATE SUB-SYSTEMS

Each candidate sub-system, with its attendant port site, must be carried through a preliminary design phase in sufficient detail to permit all major cost items to be quantified.

Criteria

The first step in the preliminary design phase consists of establishing specific engineering criteria for both design and operation. This is contrasted to the general system performance criteria formulated at the beginning of the study.

ENGINEERING DESIGN CRITERIA

Candidate sub-systems were selected on the basis of rough order-of-magnitude estimates of the physical size of the harbor and tank farm area needed to accomodate the ultimate throughput of the system. As a supplement to this selection criteria it is necessary to establish further engineering criteria so that alternate preliminary designs can be prepared for each port site. Typical items for which criteria will be required are average ship size, maximum ship size, water depths, ship turning radii, typical pier configuration, typical breakwater cross-sections, storage tank sizes, and ship loading rates. Since several types of loading facilities (i.e. fixed piers, sea berths and mono-moorings) may be considered for each candidate site, it is necessary to establish comparable sets of criteria for each.

OPERATIONAL CRITERIA

Each alternate route and port site must be studies to determine what environmental characteristics will affect its performance uniquely. Overland and sea transportation routes will be affected by temperature extremes and storms. Port sites are particularly sensitive to wind and wave conditions which delay docking or require ships to leave a berth during loading or unloading operations. For each type of harbor development considered, separate criteria must be established for maximum permissible wave height and wind velocity. In comparing the effects of weather conditions on alternate port sites, a quantifiable parameter is that of port closure.

A ship turnaround time must be established which is compatible with demurrage-free time in port and with ship loading rates. Deballasting time and loading equipment capacity must also be selected to be compatible with ship turnaround.

Harbor Design

Crude oil and petroleum products are normally loaded or discharged across a fixed pier or through hoses to the ship in a sea mooring. Fixed piers may either be in a moderately exposed location or in a horbor sheltered by a breakwater. Sea berths are of either the spread mooring type where the ship rides to the center of a set of fixed lines, or the mono-mooring type where the ship "weather vanes" behind a single point bow attachment. All of these types of

berth designs have different operational requirements and thus will show
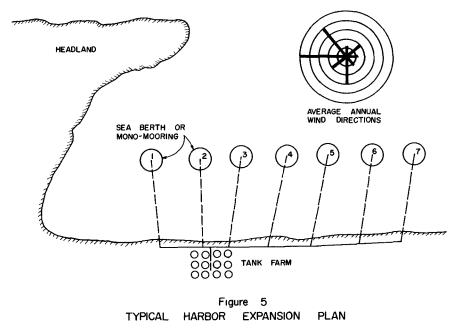economic differences at each candidate port site.

     In general it can be said that a pier and breakwater design will show a
high initial UTC since the first cost of a breakwater is great in relation to
the throughput of the port. This assumes that the ultimate harbor area is
enclosed initially. As the throughput increases with system expansion to the
UTC will drop due to both the greater volume of petroleum shipped and also
the minimal weather delays affecting a shelter harbor.

     The sea berth and mono-mooring harbors will be closed by storms more
often than a sheltered harbor, however their UTC's may be lower due to their
installation cost. Also, sea berths and mono-moorings can be installed as
needed in the course of system expansion instead of requiring a high early
investment as in the case of a harbor sheltered by a breakwater. A small
craft harbor to accomodate tugs and line running launches is needed in any
event.

     Port closure criteria assigned to these three types of harbor installa-
tion will normally take the following form:

Type of Harbor	Max. Wave	Max. Wind
Piers with Breakwater	15 feet	40 knots
Sea Berths	5 feet	20 knots
Mono-moorings	5 feet	30 knots

     Thus piers sheltered behind a breakwater can be expected to operate
under more severe conditions. The sea berth, on the other hand, is hampered

Figure 5
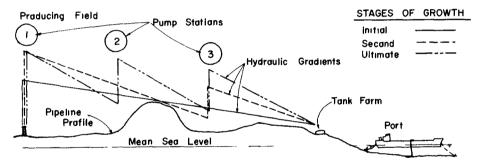TYPICAL   HARBOR   EXPANSION   PLAN

by small waves due to the inability of line running launches to work in heavy seas and high winds; beam winds particularly may force the ship to leave the berth. The mono-mooring is also hampered by small waves since it must be served by line running launches but it can remain in the berth longer in high winds due to its ability to "weather vane" behind the mooring buoy.

Figure 5 shows a typical harbor expansion plan for sea berths or mono-moorings. If we assume that this port site is exposed to local fetches and thus the wind and wave directions are approximately identical, it can be seen that substantial protection is afforded berth No.1 by protruding headland and that protection decreases along the coast through berth No.7. This then means that berth No.1 will be closed least because wind or waves exceeded the operational limit and that berth No.7 will be closed the most.

Pipeline Design

A pipeline is a part of a petroleum transportation system which represents a high initial investment and which is relatively inflexible once installed. The sub-system used for the study described in this paper includes a pipeline which delivers crude oil to the port. Thus pipeline design is an integral part of the system design.

Pipeline size is normally determined by the anticipated ultimate throughput of the system. Figure 6 shows a typical ground surface profile and hy-

Figure 6
SCHEMATIC OVERLAND PIPELINE PROFILE

draulic gradients at several increments of system expansion. The initial system consists of the pipeline, Pump Station No.1 at the producing field, and a tank farm at the marine terminal. The hydraulic gradient decreases uniformly from Pump Station No. 1 at the producing field to the tank farm. Normally, the hydraulic gradient is kept above the ground surface thus maintaining a positive pressure in the line at all points.

The second stage of growth requires that Pump Station No.3 be installed and that additional horsepower be installed at Station No.1. The hydraulic gradient steepens between stations due to velocity head losses. Ultimate expansion is shown in the third state with the addition of Pump Station No.2 and increasing horsepower in Station No.3.

INCREMENTAL EXPANSION OF SYSTEM

Oil transportation systems are seldom constructed to handle their ulti-
mate capacity initially but rather to be expanded in several increments. The
engineering design of each candidate system must be based on incremental
expansion of the system, recognizing that failing reserves or marketing con-
siderations could curtail expansion at any intermediate stage.

An oil harbor can be enlarged by adding more berths, a tank farm by
adding more storage tanks, and pipeline capacity by adding more pump stations.
On the other hand, some parts of the system must be built initially to accom-
modate the ultimate throughput of the system. Typical of such parts would be
pipeline diameter and wall thickness.

All engineering design for study purposes should be carried out on the
basis of incremental expansion. Engineering quantities can then be associated
with a given throughput of the system.

Tank Farm and Loading Lines

Designs in detail similar to those carried out for the harbor and pipe-
line portion of the sub-system must also be completed for the tank farms and
loading lines. Factors which must be considered are land cost, number of
different crudes to be handled, tanker loading rates, pumping requirements,
and the availability of labor and local utilities.

Review of the Economic Function

Sub-system design may reveal significant features which were not
properly represented in the economic function. Upon completion of the design
phase, the mathematical model should be reviewed to be certain that all items
are adequately described. This can be readily accomplished by completing the
material quantity take off for each increment of sub-system expansion since
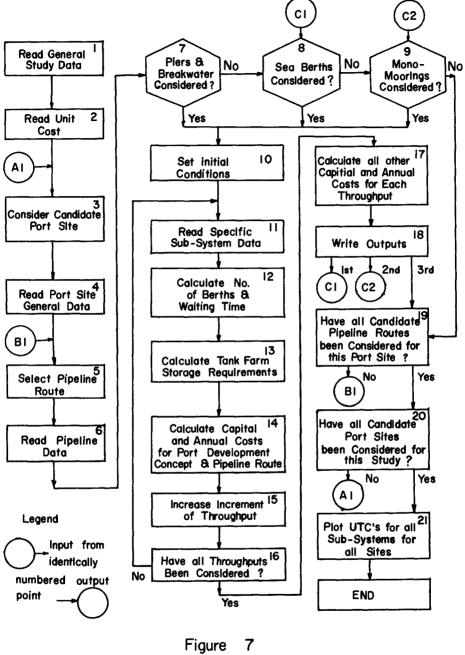each quantity must be represented by a term in the economic function.

A MATHEMATICAL MODEL FOR CHOOSING
BETWEEN ALTERNATE PORT SITES

The economic function of Equation (1) is the mathematical model which is
used to select the "best" sub-system and its attendant port site. While it
is not mandatory that the economic function be programmed for a digital com-
puter, investigation of incremental growth and design alternates makes its
use quite desirable in all but the most elementary cases. This paper assumes
that the iterative capabilities of a digital computer will be employed in the
illustrative example which follows.

ORGANIZATION OF ANALYSIS

Figure 7 shows a descriptive computer flow diagram which is designed to
analyze the type of sub-system discussed in this paper (i.e. pipeline, tank
farm, loading lines, and harbor). It requires as inputs the general data
applicable to all systems, quantity data for each sub-system on an incremen-
tal basis, unit cost data for both capital and annual costs, and the initial
and ultimate system throughputs.

The program then computes the unit transportation cost for each desig-
nated increment (usually 1/10 or 1/20 of range between initial and ultimate)
of throughput for each candidate sub-system. The output may be either printed
or plotted as graphs.

Read General Study Data — 1

Read Unit Cost — 2

AI

Consider Candidate Port Site — 3

Read Port Site General Data — 4

BI

Select Pipeline Route — 5

Read Pipeline Data — 6

CI

Piers & Breakwater Considered? — 7   No

C2

Sea Berths Considered? — 8   No

Mono-Moorings Considered? — 9   No

Yes   Yes   Yes

Set initial Conditions — 10

Calculate all other Capital and Annual Costs for Each Throughput — 17

Read Specific Sub-System Data — 11

Write Outputs — 18

Ist   2nd   3rd

CI   C2

Calculate No. of Berths & Waiting Time — 12

Have all Candidate Pipeline Routes been Considered for this Port Site? — 19

Calculate Tank Farm Storage Requirements — 13

No   Yes

BI

Calculate Capital and Annual Costs for Port Development Concept & Pipeline Route — 14

Have all Candidate Port Sites been Considered for this Study? — 20

No   Yes

AI

Increase Increment of Throughput — 15

Have all Throughputs Been Considered? — 16

No

Yes

Plot UTC's for all Sub-Systems for all Sites — 21

END

Legend

Input from identically numbered output point

Figure 7

DESCRIPTIVE COMPUTER FLOW DIAGRAM

The following sections describe the principal features of the pro-
grammed mathematical model and the basis of important computations.

GENERAL INPUTS

Step 1 in the program is to establish general study data which will
typically consist of the following items:

1. Throughput range to be considered.   7. Escallation costs.

2. Throughput increment for analysis.   8. Duties & taxes.

3. Crude oil specific gravity.   9. Indirect costs.

4. Ship turnaround time.   10. Load factor of system.

5. Storage tank size.   11. Contingency allowance.

6. Financial costs.   12. Study currency.

Any other items which will remain constant for all sub-systems may be in-
cluded in general study data.

Step 2 consists of listing the basic unit cost items which are required
to establish both capital and annual costs of all sub-systems. Such items as
dredging cost per cubic yard, and pier maintenance cost per year are included
in this section. Assignment of unit costs can be simplified by relating all
cost units of the same general type of material to a single basic unit. An
example would be that of breakwater armor stone cost based on core rock cost
times a multiplier. All unit costs are established to represent actual on-
site prices.

PORT SITE

Step 3 requires that a port site be chosen that is associated with one
of the candidate primary sub-systems for which quantity information has been
supplied as data.

The general port site data of Step 4 concerns input items such as cost
of land at the port site, cost of access, cost of utilities, and other simi-
lar items peculiar to the geographical location of the candidate site.

It is possible that several tank farm sites may be considered at each
port site. It is probable however that an independent hand calculation will
permit a single tank farm site to be selected for a given port without expand-
ing the sub-system analysis. One of the most significant data items associ-
ated with the storage tanks will be earth-moving and foundation preparation.

PIPELINE

To each port site will come several pipeline routes. Step 5 requires
that one of these candidate pipeline routes be selected while Step 6 reads
the quantity items such as pipeline length, miles of ditching in rock, and
pumping horsepower at existing stations or by the addition of new stations
along the line.

SPECIFIC HARBOR DEVELOPMENT CONCEPTS

At this point in the analysis a single port site on the coast is under
consideration, as is one of several pipelines leading from the producing
field to the port. At each port site several harbor development concepts
have been carried through the preliminary design phase. For this study three

harbor development schemes are considered for each candidate site, fixed
piers with breakwater, sea berths, and mono-moorings. Due however to avail-
able area or peculiar bathymetric conditions, some sites may not be adaptable
to all three designs.

       If the piers and breakwater scheme of Step 7 is to be considered, the
throughput is initialized in Step 10 and then specific sub-system data is
read in Step 11. Specific data consists of weather delay days or hours
which result in port closure (this varies with natural protection at the site
as noted in Figure 5 and with the operational limits of the mooring equipment
included in the scheme), length and size of loading lines, pumping horsepower,
and items such as dredging or removal of wrecks.

Calculate Number of Berths

       The number of berths in a port must be such that the throughput can be
loaded into tankers in the most economical manner. This calculation depends
primarily on tanker size, loading rate, throughput, and weather delay.
Observations at several ports have indicated that ship arrivals and queuing
can be accurately described by a Poisson distribution (References 3,4, and 5).
Two methods may be used to determine what queuing delay is acceptable.

  (1) The first method is to assume a maximum congestion figure of
      say, 5%. This means that 5% of the time there are tankers
      waiting for a berth. This figure is based on experience with
      tankers, however, it is rather unsatisfactory as it makes no
      allowance for variation in demurrage and berth costs.

  (2) The alternative, and better, method is to make a benefit-cost
      analysis by comparing demurrage costs with the capital and
      annual costs of a new berth. Figure 8 shows the results of
      such an analysis. Here The Berth Unit Transportation Cost
      (BUTC, which is the unit cost of moving oil from the tank
      farm into the tanker) is plotted against throughput. For each
      number of berths there is optimum throughput giving a minimum
      BUTC shown by the vertical dotted line in Figure 8. If the
      throughput is less than this optimum value, the BUTC rises since
      the berths are not being used at their optimum occupancy. If
      the throughput is greater, the BUTC again rises due to demurrage
      costs on waiting tankers, until the curve intersects the down-
      ward curve of the next higher number of berths. At this point
      the BUTC falls again and for this throughput a new berth should
      be added to the port. As the number of berths increases the
      BUTC for the optimum throughput decreases due to an increase in
      berth occupancy for the same delay time.

TANK STORAGE CAPACITY

       The necessary volume of tank storage capacity in Step 13 is deter-
mined by the uncertainty of tanker arrivals and of discontinuities in pipe-
line delivery. The Poisson distribution calculation in Step 12 gives the
probability of a given number of tankers arriving on a single day and the
probability of consecutive days this number will arrive. If no tankers
arrive for a number of days, then oil from the pipeline must be stored. If a
large number of tankers arrive for several days, for example just after a
storm, then there must be sufficient oil in storage to load these tankers
even if flow through the pipeline has ceased. For a single crude it is usual
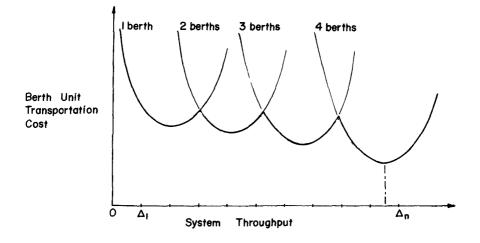to allow three-and-a-half days of storage for pipeline stoppages. The extreme

Figure 8

BERTH UNIT TRANSPORTATION COST AGAINST SYSTEM THROUGHPUT

storage requirement which is normally chosen is such that on one or two days a year the storage capacity is inadequate.

After determination of the storage capacity and selection of a tank size, the tank farm area is computed. The tank size and height and slope of dikes is general input data read in Step 1. The program also computes the amount of earth moving required to construct the dikes.
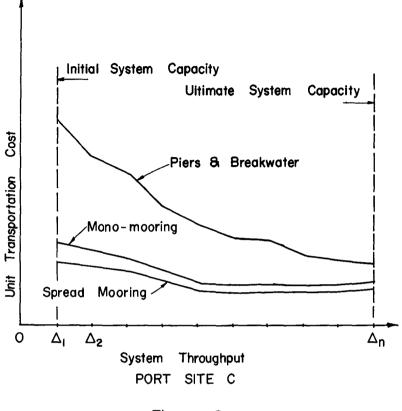
CAPITAL AND ANNUAL COSTS

After the number of berths and tank farm size has been determined in Steps 12 and 13, the program then returns to the input quantities associated with that particular increment of growth. Capital and annual costs are computed on the basis of the unit cost input data for the individual sub-system under consideration. These costs are then stored and the next increment of throughput is considered.
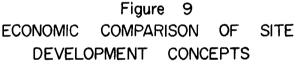
The program completes the analysis of each combination of pipeline and port development concept in Steps 17 through 23.

SELECTION OF PORT SITE

After the computation of unit transportation costs for each increment of throughput, curves are plotted for each sub-system associated with a particular candidate port site. Figure 9 shows curves which typically result from the analysis of three alternate harbor concepts associated with a single candidate pipeline route. Since these curves are plotted from the UTC's computed only at the designed increments of throughput, they may be smoothed by decreasing the increment and thereby plotting a greater number of points.

The high initial UTC associated with the piers and breakwater design can be attributed largely to the high first cost of the breakwater. As throughput

PORT SITE C

Figure 9
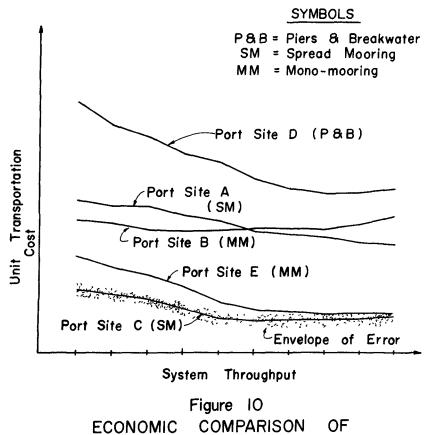ECONOMIC COMPARISON OF SITE
DEVELOPMENT CONCEPTS

increases, the UTC decreases reflecting the fewer weather delays and higher loading rates at fixed piers. Mono-moorings and spread moorings on the other hand show a lower initial UTC due to the fact that the only first cost associated with this type of port, other than the berth equipment, is the small craft harbor. The UTC for these two types of designs remains nearly constant, or increases slightly, with increased throughput. The increased UTC results from longer loading lines to distant berths coupled with larger line sizes and increased loading pump horsepower. The shapes of these curves, however, reflect the local design, construction, and operational pecularities of the candidate port site.

Following the selection of a "best" development concept for each port

site, a composite or summary graph may be plotted as shown in Figure 10. This
graph shows only the lowest UTC sub-system for each port site considered. The
lowest UTC curve represents the selected site or sites and the associated
harbor development concept.

SYMBOLS

P & B = Piers & Breakwater
SM   = Spread Mooring
MM   = Mono-mooring

Port Site D (P & B)

Port Site A
        (SM)

Port Site B (MM)

Port Site E (MM)

Port Site C (SM)

Envelope of Error

Unit Transportation Cost

System   Throughput

Figure 10

ECONOMIC   COMPARISON   OF
ALTERNATE   PORT   SITES

ACCURACY OF ANALYSIS

Early in the study the required accuracy of the economic analysis was
established. That accuracy can be represented as an absolute or percentage
error for each UTC. If that plus or minus error is plotted as an envelope on
the lowest curve in Figure 10, it may enclose one or more other curves above
it. All curves which fall within this envelope must be considered to represent
"best" sub-systems. In Figure 10 the Port Site E employing mono-moorings must
be considered to be equal to the Port Site C at higher throughputs. At this

time economic, political, or social factors not expressed in the economic function may determine the port site. In the absence of such factors, an analysis of the type described in this paper, but performed on the basis of more thorough definition of all variables may permit a rational decision to be reached.

When the difference in unit transportation costs times the maximum annual throughput represents a capital cost less than the normal difference in construction bids, further refinement of the analysis is academic.

Occasionally two port sites, or alternate development concepts at one site, will change relative position as throughput is increased. This is shown in Figure 10 for Port Sites A and B. In such a case additional economic factors must be considered to arrive at a rational decision.

CONCLUSIONS

(1) The systems approach to petroleum port site selection requires the engineer to recognize that port site selection is not an independent problem, but is intimately related to adjacent parts of a total transportation system.

(2) The systems approach represents a method of accounting for all variables which affect the economics of shipping through a particular port site and results in economically defensible decisions.

(3) By the systems approach it is possible to determine the accuracy with which unit transportation cost is computed by means of the economic function so that excessive accuracy is not unjustifiably presumed.

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