Main Gas Pipeline Route Selection Problems, Taking into Consideration Risk and Uncertainty Factors

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1. INTRODUCTION

At present, appreciable structural variations in the world energy situation are taking place. Petroleum, formerly considered to be the most valuable chemical-organic raw material and source of energy, is to a large extent being replaced by other energy sources such as gas, nuclear power, hydroelectric power, and coal. Natural gas is probably the next most important source after petroleum because of the availability of substantial world resources, ease of transportation, good technical-economic utilization characteristics, etc. Natural gas is also a valuable raw material for the chemical industry, and is widely used for obtaining important basic materials. These factors predetermine the rapid development of world gas output and trade. The USSR, according to the 1981-1985 five-year plan, is intending to increase its output of gas by 38-47 percent, to 600-400 billion m^3.

The harnessing of new gas resources and the construction of complexes for transportation, storage, and reprocessing of gas require large investments of capital and long time commitments. When considering such large-scale projects it is necessary to take into consideration economic, political, social, geological, and other factors involved, as well as questions of population safety, environment protection, reliability of transportation systems, etc. Thus the creation of a large gas complex is a complicated task, where an essential role is played by risk and uncertainty factors.

2. CHARACTERISTICS OF A GAS EXPORT COMPLEX

Among European countries the USSR is the only one which exports natural gas in significant quantities. However, the main gas producing regions in the USSR are in the northern, sparsely developed areas of the country, and are therefore considerable distances from the main industrial centers and potential foreign consumers. This has necessitated the construction of very long pipelines to transport the gas to consumers.

At present in the USSR liquefied natural gas (LNG) processing complexes, incorporating gas liquefaction plants, storage, and shipping facilities, are under preliminary development in the north of the European part of the USSR and on the Far Eastern coast. Both areas, however, are considerable distances from the largest gas deposits. For this reason a component part of any such complex must inevitably be the main gas transportation system. Here gas pipelines, which may be several thousand kilometers long, are the main factor determining the cost of the whole complex and its effectiveness. To a great extent this is because the pipelines have to be constructed through climatically severe, unpopulated regions, and analysis shows that the capital outlay required for such a venture may amount to 75-80 percent of the total cost of the complex.

The building of a gas pipeline is therefore a significant and often decisive element in a gas transportation complex designed to provide large-scale gas supplies. Because of this it is expedient to point out the numerous factors connected with the rational selection of gas pipeline routes, such as environmental conditions, socio-economic factors, the local population, and agreements between land-owners and administrative organizations.

When constructing a gas pipeline a guarding zone of 250-350 m from its axis is required to regulate the minimum distance from the pipeline to residential buildings, highways, farms, and other installations; with a route length of about 1000 km this amounts to 50-70 thousand hectares. Thus the main pipeline route will constitute a site of temendous size, the selection of which represents a very serious problem. The task being considered is also important practically. In the USSR the construction of 49.5 thousand km of gas pipelines for 1981-1985 is being scheduled. Fast development of pipeline transport, particularly for gases, is also characteristic of world economics as a whole. Thus, route selection problems for similar installations will become much more pronounced in the course of time (Belousov 1978).

3. FACTORS CONSIDERED IN PIPELINE ROUTE SELECTION

A gas pipeline several thousand kilometers long is a complicated and expensive technical system. Route selection depends upon natural climatic and economic-geographic conditions including the presence of topographic, geological, hydrological, natural, and artificial obstacles. We can classify the variety of natural features of the terrain along the route under the following headings: plains, deserts, swamps, permafrost, natural water barriers, and mountains. However, these headings do not include the whole range of factors which could affect construction and installation work, such as large tracts of forest, high water table, rocky soils, impassable swamps, formation of crevasses and thermokarsts in permafrost soils, deep and also planned recutting of river beds, landslides, etc. The list of headings can also be further subdivided into a series of categories that permit us to consider specific features of the terrain.

It is also necessary to take into account the quantity and size of populated areas, the effect on the route length of bypass lines, the increase in the amount of metal required to increase the pipeline wall thickness in order to safeguard the local population, and the rise in construction costs due to any demolition of dwellings and other buildings that may be necessary. It is also necessary to consider the prospective development of populated areas and cities in the next 25 years.

The quantity and quality of agricultural land have increased, so funds must be made available to cover the expenses of recultivation, reimbursement of production losses, restoration of irrigation systems, etc. Access to existing road and rail networks (to simplify the transporting of pipes, equipment, construction machinery, etc.), as well as access to existing pipelines along the route, communications, and power supply systems, all greatly reduce the amount of construction and installation work required for the building of a pipeline.

We can now specify the basic factors considered in the main gas pipeline route selection.

3.1. Presented Costs

This factor is the most common and universal estimation criterion, determined from the expression

$$C = K x + A$$

where K is the capital investment; x is the normative coefficient of capital investment efficiency (for industrial construction it is taken to be 0.12); and A is the annual maintenance cost. This basic criterion permits selection of a route from an initial to a final point which will require the minimum total capital outlay (equipment and labor) and maintenance expenses. However, it does not guarantee the selection of a truly optimal route because it can not take into account all environmental, social factors, etc., because these cannot be accurately estimated in advance (Goncharov and Oseredjko 1977).

3.2. Construction Times

This may be one of the most decisive factors in commissioning a gas pipeline. The duration of construction is partially dependent on the standards required, but can also be established by means of directive instructions. In general the preferred route alternative is that where appropriate construction organizations already exist and where seasonal transport routes are available, or where pipelines already exist, together with appropriate maintenance systems. Also, the factor of minimum change to existing construction technology, machinery, etc., is considered, as well as the availability of an adequate labor force.

3.3. Gas Pipeline Maintenance

In order to ensure reliable pipeline operation it is necessary to have access to all sections for preventive inspections, and repair work in the case of failure. Access is to some extent determined by environmental conditions in the pipeline area and by the development of the transportation system.

The reliability of maintenance mainly depends on natural climatic conditions along the route. In some cases, to ensure faultless operation of gas transportation systems in the most complicated and important sections (large areas of water or swamps, almost inaccessible mountain regions) laying two pipelines instead of one is standard practice, even though this means an increase in capital investment and can require gas supply reservation by means of underground storage in natural formations, etc.

3.4. Influence on the Environment

Construction of main gas pipelines, especially when they are three to four thousand kilometers long, has a great impact on the environment. Working on such a scale, partial forest clearance and agricultural production losses are inevitable, and are often evaluated without consideration of the long-term effects on the environment.

When laying a pipeline in highlands where there is a danger of landslides, this is not only a threat to the environment, but also affects pipeline reliability since landslides may be caused when slopes are cut to form terraces for the movement of construction machinery and for laying the pipeline. Disruptions to hydrological systems may occur; for instance, the construction of underground pipelines at insufficient depth may cause water channel deformation and drainage disruption that can adversely affect aquatic life and prevent accident-free running of the pipeline.

The environment is especially sensitive to human activities in the permafrost areas of the north. The main gas producing area of the USSR is in the north, so that the gas pipelines need to be constructed through frozen permafrost soils for considerable distances from the deposits to the LNG processing plant. To prevent disturbance of the permafrost and to ensure pipeline stability, gas cooling is used, wherein a specified temperature regime is maintained by an associated gas cooling station. However, deterioration of temperature control may occur after several years of operation, so that the influence of this on the fauna and flora of the area surrounding the pipeline must be evaluated when considering route alternatives.

Finally, factors associated with the installation process can have a major effect on the environment. For example, it is known that the noise of a gas turbine unit can have a very serious influence not only on the maintenance personnel and nearby inhabitants, but also on animals and their activities.

3.5. Connection with Regional Development Plans

The influence of gas pipeline construction on the population and economics of a region should also be taken into consideration. The building of large LNG complexes requires several thousand specialists and workers, including some from other countries, and the type of labor force required during the different construction phases may change sharply. The socio-economic influences on this influx on the populated areas close to the construction area may be important and should be carefully evaluated. When demolition of homes is necessary the problems of rehousing and selection of new residential areas arise. A subject of serious concern should be the provision of social and cultural facilities, services, etc., for the maintenance personnel and their families. The creation of such an infrastructure often involves considerable capital cost.

With balanced regard for all factors affecting the construction work and the existing socio-economic structure of the construction area, some negative consequences of construction may be compensated for by, for example, supplying gas to the area; introducing a centralized heating system for homes and agricultural installations using the waste hot water from compressor station gas turbine cooling systems; construction of new socio-cultural and life-enhancing facilities, communications systems, etc.

The influence of the gas pipeline on regional development plans often affects public opinion. The attitude of the local administrative bodies and the local population towards the approaching construction of the pipeline and the positive measures taken by these groups when making decisions on the allocation of land, permission for the various construction processes, etc., can greatly speed up the completion of the design and surveying work, as well as the construction process itself. Obviously this improves the economic viability of the project.

3.6. Construction Conditions

This factor is determined by geological, hydrological, topographic, and other conditions of the gas pipeline route selected, as well as the availability of existing infrastructure, construction bases, etc., in the region. It is necessary to consider it as an independent factor because it is important for the construction firm that also takes part in the process of route selection.

3.7. Population Safety

This is mainly ensured by keeping to the standard minimum distances from the main gas pipeline axis to populated areas, buildings, farms, highways, etc. (the guarding zone). However, this measure does not completely guarantee population safety in emergency situations. There are two ways of reducing the potential risks:

(i) by increasing the reliability of technological systems and installations;
(ii) by extending the gas pipeline guarding zone and distances from the various systems to the nearest populated areas.

It should be noted that regulations concerning violations of the guarding zone, and fire protection regulations in the USSR, are the most extensive in the world, but this affects some economic factors.

3.8. Special Permissions

Special permission requirements and limitations imposed by laws on the protection of nature, fish reserves, mineral resources, forestry, etc., and also regulations issued by sanitation and fire protection authorities, etc., are very important factors in pipeline route selection. Obviously when selecting a pipeline route it is necessary to take into consideration many factors, some of which can be expressed quantitatively, and others only in a qualitative, descriptive fashion. Initial data on the route alternatives may be available to varying degrees of accuracy. The construction of a pipeline involves vast expenditure and a design stage that may well continue for several years, yet the decision making cannot totally remove the element of risk. It is necessary to take into account the degree of reliability of gas pipeline maintenance, the conditions required for its safe functioning, its influence on the environment, etc. Thus, pipeline construction represents a good example of a multi-attribute task of decision making under conditions of risk and uncertainty.

4. AN EXAMPLE OF ROUTE SELECTION

The selection of an optimal route for the Kutaisi-Sukhumi gas pipeline, together with its branch pipelines to Poti and Batumi for gas supply to domestic and industrial consumers is considered here as a specific example. The basic factors that were taken into account, and the selection procedure, were as follows.

At the preliminary stage of the study (research, field inspections, preliminary agreements) three possible routes were selected: piedmont, median, and maritime (see Figure 1). In addition to the main gas pipeline, prospective branch pipeline routes to populated areas and other consumers were taken into consideration.

The piedmont version was the shortest route, passing through spurs of the Egriss ridge. The relief is heavily dissected with canyons carrying mountain rivers, and the elevation varies by about 700 m. Small villages are located in valleys along the route, so that demolition of homes would be inevitable. Otherwise it would be necessary to go through quite complicated mountain conditions to bypass them. Construction work would be fraught with the dangers of mud-laden torrents with karst land forms and landslides, and would be aggravated by the need to cut special "terraces" into steep slopes in order to move construction machinery and for laying the pipeline. The route is quite distant from populated zones, and the road system is not highly developed, so that pipeline surveillance and maintenance would only be possible with the help of helicopters.

The median version passes through populated zones. The relief is gentle with good geological conditions, and the road and rail systems are well developed. However, this version would require the greatest amount of building demolition and destruction of cultivated areas; it would also be necessary to build numerous crossings over artificial obstacles.

The maritime version was the shortest route, passing through the Kolkhida lowland area. The relief is fairly flat with considerable areas of alder woodland, and a well developed irrigation system. Possibly this route could have had to pass through swamps, making conditions along the route difficult, especially during rainy periods. This route would require very little building demolition or crop destruction but the situation would be quite different along the prospective branch pipelines. For the preliminary study the area to which the optimal route search was to be restricted was defined on topographic maps drawn up from aerial photographs.

5. COMPARISON OF THE THREE VERSIONS

After the three basic alternatives for the pipeline route had been considered it was possible to use correlation analysis using the criteria detailed above.

5.1. Presented Costs

The costs of construction depended upon the difficulties encountered in the laying of the gas pipeline (swamps and river crossings, terrace cutting on the mountain slopes, etc.) and its maintenance. Along with this, the costs arising from demolition of buildings (if it was impossible to go round them) were taken into consideration, as well as compensation payable if the route crossed cultivated land.

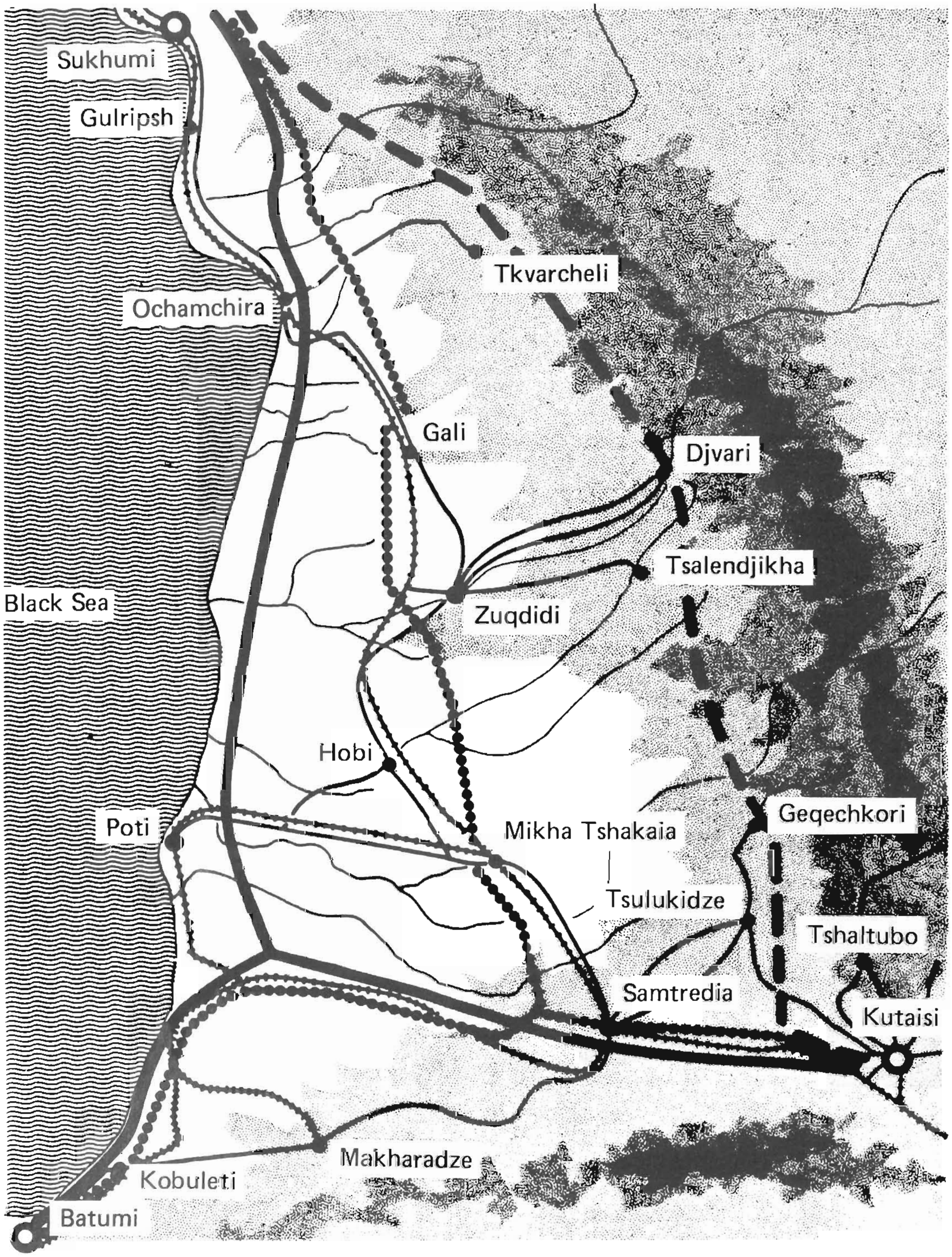

Figure 1. Scheme of the alternative routes for the Kutaisi-Sukhumi gas pipeline. Full line, maritime route; dotted line, median route; broken line, piedmont route.

These costs were determined by local administrators. According to the formula in Section 3.1 the respective costs of the three versions were as follows (in millions of roubles): maritime—8.9; median—9.5; and piedmont—10.8.

The pipeline construction process can be divided into two stages. The first stage is the construction of the main pipeline itself; the second is the laying of branch pipelines (from the main pipe to the consumers). These stages are not separated merely in time; they are also financed from different sources: the construction of branch pipelines is paid for by resources from the regional budgets. In view of this, two cost criteria must be considered separately: capital costs for the main pipeline, and those for the branch lines. Capital investment in the main route and the construction of the branch lines were, respectively (in millions of roubles): maritime route—31 and 9.5; median route—40 and 5; and piedmont route—46 and 5.

5.2. Construction Times

According to existing standards for gas pipeline construction the construction times for the different versions would not be expected to differ greatly. However, based on experience, the piedmont version would probably take much more time because of route laying difficulties. Along the maritime route construction delays might occur in marshy areas and when crossing three big rivers.

5.3. Gas Pipeline Maintenance

The most difficult route to maintain was recognized to be the piedmont version since access can only be achieved with the use of helicopters. The easiest to maintain would be the median version (good access to all sections of the pipeline), and the maritime version would be more difficult to maintain than the median one because of marshes.

Whatever the quality of the gas pipeline construction, however, the possibility of failure cannot be totally ruled out. Experience of pipeline maintenance under other terrain conditions suggests that the maritime version would be the least reliable, since a large section of the pipeline would run through an active corrosion medium (swamps). Here, as the pipeline ages, the probability of failure would increase. A similar assessment applied to the piedmont version, but for a different reason: experience of maintenance in mountain regions shows that there is a possibility of failure due to landslides and elimination of this is extremely difficult.

The most reliable is the median version where laying conditions are most favorable; it also has the best maintenance conditions which, in turn, increase its reliability.

5.4. Influence on the Environment

Based on this criterion, the maritime route is the most preferable passing through the marshy Kolkhida lowland area. The median route affects unique ancient forests and, to a greater degree than the two other versions, passes through agricultural land, citrus orchards, and tea plantations. Although the loss of this land would be temporary (for the period of construction), it would still be very undesirable.

The most undesirable route according to this criterion is the piedmont one. The cutting of terraces along mountain slopes would adversely affect the environment, and landslides could occur in consequence. Besides this, the construction of terraces would require greater amounts of land than are needed when laying pipelines on flat areas.

5.5. Connection with Regional Development Plan

The median and maritime routes would require much the same number of buildings to be demolished (69 and 61 respectively), but the piedmont version would be considerably worse (136). From the point of view of agricultural crop damage the piedmont version was again the worst (129 hectares) followed by the median version (102 hectares), and the maritime version (57 hectares). However, from the point of view of regional plans for the gas supply to potential consumers the median version was much better, so that this was the version favored by the local authorities.

5.6. Construction Conditions

According to this criterion, which is greatly dependent on the relief and other physical characteristics of the district, the median version has the best assessment. The maritime version was not so good and the piedmont version was much worse.

5.8. Population Safety

Existing standards for gas pipeline laying define necessary minimum distances from the pipeline to residential areas. Certainly, in the event of a pipeline failure, a gas leak resulting in fire risk can occur, but with the adopted working pressures and materials used in the pipeline itself, failure is very unlikely. Nevertheless, this possibility must still be considered, and here the maritime version is preferable, since it affects the smallest number of settlements, agricultural lands, and highways. The other two versions are approximately equivalent.

The analysis given above allows us to exclude the piedmont version from further consideration. The two other versions require additional analysis and comparison.

6. SELECTION PROCEDURES

Of the parties involved in the actual pipeline selection procedures, four major participants can be singled out. First, there is the customer organization, which determines the design task and performs pipeline maintenance; secondly, there is the organization that designs the pipeline; thirdly, any project has to be agreed upon with the regional authorities, which represent the interests of the local population; and, finally, the route selection is influenced by the contractor who will actually construct the pipeline.

When comparing the routes each participant in the selection process is primarily concerned with a definite subset of the given criteria. For example, the project organization draws attention to criteria C, C_1, C_2, IN, R, and S; regional authorities are concerned with criteria RP, IN, S, R, and C_2; and the customer is naturally interested in criteria C, M, R, and S. Finally, the contractor gives primary consideration to criteria T_{min} and S.

The selection procedures adopted are as follows. The project organization analyzes all possible pipeline routes. Using the initial basic outlines, the route direction in each version is then specified as that minimizing the presented costs. Then the project organization selects a version and transfers this proposal together with information about all the other versions to the customer and then to the regional authorities for approval. The contractor's representatives also take part in these discussions. In this example the project organization preferred the maritime version. When considering the various versions, the regional authorities pointed out the comparison between the far superior evaluations of the median version on criteria C_2, RP and R and the "best" evaluations of the maritime version on criteria IN and S. During the analysis the regional authorities asked the customer and the project organization to find new technical solutions to improve the evaluations of the median version on criteria S and IN in order to bring them nearer to the maritime version evaulation. As a result of investigations towards this end the project organization suggested the possibility of cutting down the guarding zone, combined with an increase in reliability effected by increasing the thickness of the pipe wall. It was found that with such an improvement the number of buildings requiring demolition would be considerably reduced and the presented costs of the median and maritime versions would become closer, despite the increase in the amount of metal required and in the cost of the pipeline. In Table 1 evaluations of the versions after incorporating this improvement are given.

With these improvements, all the participants in the selection process selected the medium version as the most acceptable, and so this version was chosen.

The example given above is typical in gas pipeline route selection. Each active participant in the procedure is at first guided by his own subset of criteria, working through from the more to the less important ones. This is characteristic of a satisfactory decision search according to Simon. We must point out that usually no single version is superior on all criteria; it is almost always necessary to look for a compromise. A typical feature of an actual comparison process is a series of attempts to revise some of the versions, in order to improve thier assessments on particular criteria.

Table 1.

			Order of preference		
Item	Criterion	Designation	Maritime	Median	Piedmont
(1)	Presented costs (million roubles)	C	8.9	9.5	10.8
(1A)	Cost of laying the main route (million roubles)	C_1	31	40	46
(1B)	Cost of laying prospective pipeline branches to consumers (million roubles, minimum)	C_2	9.5	5	5
(2)	Construction time	T_{min}	Second best	Best	Worst
(3)	Convenience of maintenance	M	Inferior	By far the best	Inferior
(4)	Reliability of maintenance	R	Best	Inferior	By far the worst
(5)	Influence on the environment	IN	Best	Inferior	By far the worst
(6)	Connection with regional development plans	RP	Second best	By far the best	Worst
(7)	Construction conditions	B	Second best	Best	By far the worst
(8)	Population safety	S	Best	Inferior	Inferior

7. GAS PIPELINE ROUTE SELECTION AND DECISION MAKING METHODS

From the point of view of decision theory the task considered in this paper constitutes a decision making problem with several parties (organizations) making decisions and evaluating various decision possibilities on a number of criteria (some criteria may be common to several versions). The number of versions considered is usually not large (2-5), but the criteria considered may be more numerous (6-12), and these are usually qualitative. It is important to realize that each gas pipeline is unique; therefore accurate quantitative data are not available, although experienced experts can give estimates for comparison purposes.

Gas pipeline route selection also represents an example of the problem of decision making involving a definite (although perhaps very insignificant) possibility of failure. The question arises as to whether it is possible to estimate the probability of failure (small or large), and the possible number of victims and amount of damage that would be caused by such a failure, etc.

Analysis of actual decision making procedures shows that such estimates are usually given in a wordy form. Naturally, these estimates are based on past experience, of breaches in normal pipeline operation as well as the conditions where such breaches occur. When selecting a route the designers and customers try to avoid such conditions, to take additional measures to increase reliability (e.g., by increasing the number of pipelines) and safety (perhaps changes in route direction) to an acceptable level by various amendments to the original plan. Usually these estimates are lengthy descriptions of various past incidents; certainly existing information will affect the estimates.

The unique character of each route and the lack of available statistics makes it impossible to obtain objective quantitative estimates. Subjective quantitative estimates given by experts are unreliable for the following reasons:

(i) experts are not used to giving parameter estimates (except for cost) in quantitative form;
(ii) it is difficult to separte the expert's past experience from his understanding of the peculiarities of the system he is investigating.

The great expenditure involved in pipeline construction makes the problem of perfection of the selection procedure very important. The question then arises of what can be achieved by utilizing the various methods of decision making to obtain a solution to the given problem and which methods are appropriate when the task peculiarities are taken into account.

Naturally, this question may be considered at two levels: that of the individual decision maker; and that of the decision making group. Because of the peculiarities of this decision making problem involving several decision makers, it is our opinion that the methods for determining the common utility of alternative decisions are often unsuitable, e.g., expected utility (Fishburn 1970), and multiattribute utility theory (MacCrimmon and Sin 1974). There are two factors that hamper the use of these methods:

(i) the difficulty in obtaining information in a quantitative form;
(ii) the small number of decision alternatives; these make the procedure of comparison less labor-consuming than measuring the utility of each of them.

With a small number of alternatives, trade-off analyses are more appropriate (Keeney and Raiffa 1976); these enable qualitative estimates of alternatives to be used, especially in comparisons of their "character". Selection of the best version is performed through binary comparisons of the various versions, in which estimates for separate criteria are compared.

Studies of such procedures have shown the possibility of intransitiveness appearing (Tversky 1969). These studies have also shown that when using binary comparisons of versions involving estimates for numerous criteria, people tend to utilize simplified heuristics, of which the following should be mentioned: (a) consideration of criteria in turn; (b) disregarding of some criteria; (c) simple calculation of the number of criteria for which one version is found to be superior to another. Although such simplified heuristics are of great value, in some cases they can lead to intransitiveness. However, with the small number of versions considered, this possibility is not great, so that cases where nontransitiveness appear can be detected and eliminated fairly easily. Data from descriptive studies show which requirements have to be met by trade-off analyses in order to avoid the distortions induced by the limits of human cognitive ability in multi-dimensional information processing.

In order to avoid undesirable heuristics it is necessary for decision makers to consider information in sections, for instance, by comparing conflicting data on only two criteria at a time (Larichev and Kozhukharov 1979). Also, if the comparison system is biased then it is desirable for the decision makers to consider using a different one. It is also desirable to hasten the comparison process by agreeing quickly on the necessity of a compromise between competing aims. Comparison procedures should include methods of checking information even where there appears to be no discrepancy.

Possible methods of improvement of the procedures for perference correlation should be investigated. The primary efforts in the elaboration of route alternatives are made by the designers, who are also the first to carry out comparisons. From the point of view of the rationality of the whole process of decision making, it is desirable for the organization designer to take into consideration the whole set of estimation criteria for the various alternatives, together with any ideas put forward by other participants. In the final analysis, the decision maker (or designer) introduces his own preferences into the comparisons even when taking into account all the criteria. However, preliminary estimation of the viewpoints of the other decision makers will help the designer to control better the development of a proposed version. Anticipating objections, a decision maker can show in advance all the negative consequences of the selection of other versions, and this improves the selection process.

8. CONCLUSION

Many problems of decision making where risk and uncertainty are involved arise in the world around us, where a possibility of major failure exists; particularly problems of natural gas output, transport, liquefaction, and storage. Any possibility of real improvement in the processes of decision making where risk and uncertainty are involved should be used. In an attempt to find such a possibility, certain methods can be applied to elaborate the decision making methods. A rational basis for such methods is a compromise between descriptive and normative approaches. Knowledge of information available and human limitations should form the basis of normative decision making methods.

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@Inbook{Oseredko_Larichev_Mechitov_1982,
  author =       "Oseredko, Y. S. and Larichev, O. I. and Mechitov, A. I.",
  title =        "Main gas pipeline route selection problems, taking
                  into consideration risk and uncertainty factors",
  booktitle =    "The Risk Analysis Controversy. An institutional
                  perspective",
  address =      "New York",
  publisher =    "Springer-Verlag",
  editor =       "Kunreuther, H. C. and Ley, E. V.",
  year =         "1982",
  pages =        "91--101",
  volume =       "",
  number =       "VII",
  series =       "Lecture Notes in Economics and Mathematical Systems",
  numpages =     "236",
}
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