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RISK ASSESSMENT AND RISK MANAGEMENT FOR NATURAL GAS DISTRIBUTION

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A DISSERTATION

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ABSTRACT

RISK ASSESSMENT AND RISK MANAGEMENT FOR NATURAL GAS DISTRIBUTION

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Paul R. Kleindorfer

Natural gas distribution is a network industry the operations of which result at times in catastrophic events of locally concentrated impact. Its traditional practice for assessing and managing technological risk has been to focus on aggregate risk measures and not on the distribution of risk burden throughout the region serviced. Methods both for assessing the regional risk distribution and for making use of it in operational and strategic decisions are proposed. A risk analysis framework is followed leading to the generation of risk maps representing risk distribution in the service region. By integrating knowledge about the pipeline network geography and technical characteristics, point risk information is estimated in closed form. The estimation of risk during natural disasters is more complicated and requires the application of Monte Carlo simulation methods. We have developed an efficient variance reduction technique to estimate regional risk when risk sources are correlated. The important decision of prioritizing pipe line segments for replacement in the presence of spatial interactions in the cost structure is addressed. An efficient optimization model is proposed based on Edmonds' optimum branching method. This method introduces a way to avoid overly simplistic assumptions of linearity in the maintenance cost structure. Finally, the use of risk maps in strategic decisions of Natural Gas Distribution companies is discussed. Guidelines are offered for two important problems, evaluating the productivity of a given safety budget, and legitimating or mitigating the distribution of risk in the service region. All these methods are easily expandable or directly applicable to the more general problem of hazardous material distribution. Together, they form a set of decision tools for technological risk analysis and management that avoids broad brush decision indicators and stresses the use of detailed decision inputs for better technological and organizational improvements.

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CHAPTER 1 : INTRODUCTION

Natural gas is a clean energy source with increasing demand in the United States and worldwide. The main uses of natural gas are for: residential heating, electricity production, industrial heating, and as a chemical feedstock. Natural gas is also expected to emerge as a significant transportation fuel. Electric Utilities account for a large part of the recent demand surge in the U.S., driven by the adoption of natural gas to promote clean air protection [Energy Information Administration, 1990]. Some experts believe that natural gas is going to become the main energy source in the next decade and that for the first half of the twenty-first century the world economy is going to be a methane economy [Ausubel, 1997]. They base their estimates on expectations of organized efforts to control the greenhouse effect.

After the deregulation of the past decade, three types of companies comprise the industry: wellhead (extraction) companies, pipeline transportation companies and local distribution companies. Pipeline transportation companies are divided in trunklines and grid companies, handling regional distribution. We focus on local distribution companies, even though methods developed here can be readily adapted to the needs of transportation companies.

Natural Gas Utilities (NGUs) purchase high pressure natural gas delivered to them by transportation pipelines and distribute it to residential and industrial customers. The basic network architecture of distribution systems consists of three parts: a primary (high pressure) network, a secondary (medium pressure) network fed by the primary network that distributes gas within the region of service, and a vast tertiary (low pressure) network delivering gas to residences via service lines. The tertiary network is very dense, "Gaz de France" (a French distribution company) has 10 meters of tertiary line for each customer it services [Paty, 1993].

Most of NGU customers require continuous service, so operational disruptions should not result in service interruption. Distribution networks are designed with a degree of redundancy that ensures reliable service. For example, if a NGU is fed by many suppliers, the primary and secondary networks are usually designed in a way that all customers can be serviced by one supplier only.

Providing reliable service is no easy feat, due to seasonal and diurnal residential demand variation. Diurnal variation is handled with line packing (inserting more gas to high pressure pipelines by raising the pressure) or by use of compressed gas holders. Seasonal demand balancing tactics include: feeding the network with propane-air mixture obtained by refineries, using LNG (Liquefied Natural Gas) or underground storage facilities, or offering interruptible service contracts to large industrial customers.

To manage the operations of a pipeline network compressors raise gas pressure to offset pressure drops due to friction or to pack the lines. Pressure reduction units couple the various grade networks and manual or remotely operated valves isolate subnetworks. In addition, meters at various points and certainly on each service line, are required for charging customers and managing the network. All these devices have their own operational performance and safety characteristics, usually presented in detail in manufacturers manuals. This work is concerned with the impact natural gas distribution systems have on Environment, Health, and Safety.

In the following sections we briefly describe the environmental impact of natural gas and natural gas distribution systems, appraise the overall safety performance of natural gas distribution in the US, give the most common causes of pipeline failures, report the major safety technologies and practices to manage pipeline risk, and outline the regulatory framework of pipeline safety in the US. Finally, a section is included guiding the reader through the chapters to follow.

Environmental Impact of Natural Gas Distribution

Natural Gas is an environmentally friendly fuel. Compared to other fossil fuels it has very good performance in terms of criteria pollutants of the lower atmosphere (NO_x , Ozone, Carbon monoxide), see for example [International Energy Association, 1982] and [National Research Council, 1991] . Natural gas is the fossil fuel with the highest hydrogen content so its combustion produces the least CO_2 , a primary greenhouse gas. On the other hand, methane the primary constituent of natural gas, may have a significant greenhouse effect if accidentally released to the atmosphere. A recent study by British Gas estimates [Rose, 1994], that the impact on the greenhouse phenomenon methane leaks from its pipeline network have is small compared to the savings in combustion emissions.

The various processes of natural gas distribution systems have some adverse effects on the environment. In general, these effects are not severe and often they do not exceed EPA thresholds. It is instructive, though, to list the number of federal and state agencies that require permits from natural gas pipeline construction and operation. The following list draws from a report of the American Gas Association (AGA) Operating Section [Environmental Matters Committee, 1987]. Some of these requirements have been enhanced by modifications of environmental laws after 1987.

Pre-Construction Requirements for High Pressure Lines : The Federal Energy Regulatory Commission (FERC) under Section 7(c) of the Natural Gas Act requires an Environmental Impact Statement prior to granting permission to major pipeline construction projects. The US Army Corps of Engineers requires permits when a pipeline passes through a stream, river, wetland, lake or other body of water. The Coastal Zone Management Office reviews pipelines passing through certain coastal zones. The US Fish and Wildlife Service determines if potential harm to endangered species is posed by onshore pipelines. Offshore pipelines are administered by the National Marine Fisheries Service. The Bureau of Land Management requires right of way permits also. Finally, the State Historic Preservation Officer needs to assess the impact on cultural resources.

Pipeline Operations : US E.P.A. requires permits prior to discharge of liquids that may harm water resources, such as the water after hydrostatic testing, spent chemicals after x-raying pipes and welds, or pesticides used to control vegetation on the right of way. There are also specific regulations for handling various hazardous wastes from compressor stations, like engine oils, oil filters, paints, and acid solutions.

Peaking Plants : Storage facilities may or may not require a pre-construction environmental impact study and a plan of mitigation measures, depending on involvement by FERC, but such studies are recommended by AGA. US E.P.A. evaluates reinjection of liquids to a well, but natural gas is exempt from regulation as a groundwater hazard, because it is considered a minimal threat. Salt water cavity storage, however, may result in contamination of the fresh water in the nearby aquifers when overfilled (see for instance [Medici,1974]) .

Maintenance Shops : Paint sludge, residues, filters or oils are some of the various types of hazardous waste out of maintenance shops. They must be disposed according to E.P.A. regulations.

Vehicle Fleets : Vehicle fleets have to be maintained so that emissions of criteria pollutants do not exceed State mandated limits. According to Clean Air Act, companies owning clean natural gas fueled vehicles may qualify for emission reduction credits. Trucks in the typical fleet of a NGU transport hazardous material and fall under the provisions of US DOTs HAZMAT rules.

Past Waste Disposal Practices : After enactment of Superfund, abandoned facilities containing hazardous material should be cleaned up. A number of abandoned manufactured gas plants have been placed in EPA's National Priority List.

The same American Gas Association report concludes that these regulations are not the outcome of a particular targeting on the natural gas industry by the federal agencies, but rather the result of comprehensive environmental laws that affect virtually all industrial operations.

Pipeline Accidents and Safety

Natural gas distribution systems fair very well with respect to safety, when contrasted with pipeline transportation of other fuels and chemicals or with hazardous material transportation using other modes (e.g. rail-lines and highways) [International Energy Agency, 1982]. Natural gas, however, constitutes a fire and explosion hazard. Natural gas pipeline failures may result in fatalities, injuries and significant monetary losses in terms of property damages and lost fuel value. The natural gas industry has aggressively pursued the development of risk reduction practices and technologies, in order for the risk of these failures to be minimized.

These safety management practices have produced significant benefits. Gas distribution damages from 1969 to 1987 were reduced by 46% while gas distribution increased by 31% in the same period [Voigt, 1987]. A study of pipeline safety in Europe, where pipeline risk management techniques are similar to US standards, shows that overall pipeline incidents (transmission and distribution) were reduced by 30% in the past decade, despite the aging on average of the European Network [Venzi,1994].

CAUSE	*Incidents*		*Property Damages*		*Deaths*	*Injuries*
Internal Corrosion	0	0%	$0	0%	0	0
External Corrosion	3	3%	$31,000	0%	1	2
Damage form Outside Forces	66	68%	$8,957,046	82%	6	24
Construction/Operating Error	5	5%	$1,027,127	9%	0	4
Accident Caused by Operator	6	6%	$90,000	1%	1	8
Other	17	18%	$845,500	8%	8	5
TOTAL	**97**	**100%**	**$10,950,673**	**100%**	**16**	**43**

Table 1.1: Office of Pipeline Safety: Distribution Pipeline Incident Summary by Cause (1/1/95 -12/31/95). Adapted from web page: http://199.103.189.216/ngdist95.htm.

Before we go on to describing these safety systems, we summarize the basic causes of distribution pipeline accidents on Table 1.1. In Table 1.2, a summary of US D.O.T. incidents from July 1984 through 1990 for transportation pipelines is presented as given in [Eiber et al., 1994]. Transportation pipeline safety statistics are relevant to high pressure distribution pipelines only, but Table 1.2 is important for this exposition, because it provides a more analytic and informative classification of failure causes than the official Table 1.1. We proceed with a brief description of the failure causes in Table 1.2.

	Incidents (% total)	Injuries (% total)	Fatalities (% total)
3rd Party Damage & Outside Force	**39.0%**	**22.1%**	**36.4%**
3rd party damage	36.4%		
Subsidence	0.3%		
Earth movement	2.3%		
Environmental Defects	**25.1%**	**8.2%**	**13.6%**
General	7.4%		
Pitting	12.8%		
Erosion	0.9%		
SCC	0.9%		
Sour Gas	0.3%		
Chemical	1.0%		
CO2	0.3%		
Microbial	0.5%		
Freezing	0.5%		
other	0.5%		
Material Construction Defects	**24.5%**	**36.9%**	**31.8%**
Construction Defects	6.0%		
Material Defects	9.8%		
Mechanical	6.4%		
Components Fabrication	1.0%		
Operational Error Other Causes	**11.4%**	**32.8%**	**18.2%**
Operator Error	2.7%		
Fire	8.5%		
Sabotage	0.2%		
Unknown	1.3%		
TOTAL	621	122	44

Table 1.2: Summary of US D.O.T. incidents on Natural Gas Transmission Pipelines (July 1984 - 1990)

Third party damage refers to incidents caused by crews digging near or into the pipeline inducing loss of gas containment to a safe pipeline. A blow to a pipeline can cause punctures, ruptures, or breaks depending on its size, material and condition. The result will be massive release of natural gas to the open air, accompanied possibly by a jet fire. The effects of a blow can be immediate or delayed, causing a corrosion nucleus or a decrease in pipe thickness.

Soil subsidence and earth movement are important considerations for transportation pipelines. For distribution pipelines (particularly cast iron mains) soil movement at a smaller scale resulting to loss of pipe support is enough to cause a break. The frequency of pipeline loss of support varies by type of soil [Iocca, et al., 1987].

The definition Eiber et al. give for “Environmental Defects” includes all types of corrosion a pipeline may endure. It is important to note that not all types of corrosion depend on the environment a pipe segment is placed into. “Sour Gas” corrosion (affecting the interior surface of the pipe) is caused by the acidic composition of certain types of natural gas. Denying permission of sour gas through a company’s pipelines is a matter of quality control. SCC (Stress Corrosion Cracking) has to do with reduction in pipe material due to the stress cycle it is subjected to. It is affected by how often a pipeline goes from maximum to zero pressure and by compressor technology. All corrosion types depend on pipe material.

Year	No. of Incidents	Fatalities	Injuries	Damage in million
84	203	12	57	$4
85	205	22	96	$9
86	142	29	104	$11
87	164	11	115	$12
88	201	23	114	$12
89	177	20	91	$9
90	109	6	52	$8
91	162	14	77	$8
92	103	7	65	$7
93	121	16	84	$15
94	141	21	91	$53
95	97	16	43	$11
96	60	9	20	$5
Total	1,885	206	1,009	$164
Average	118	13	69	$12

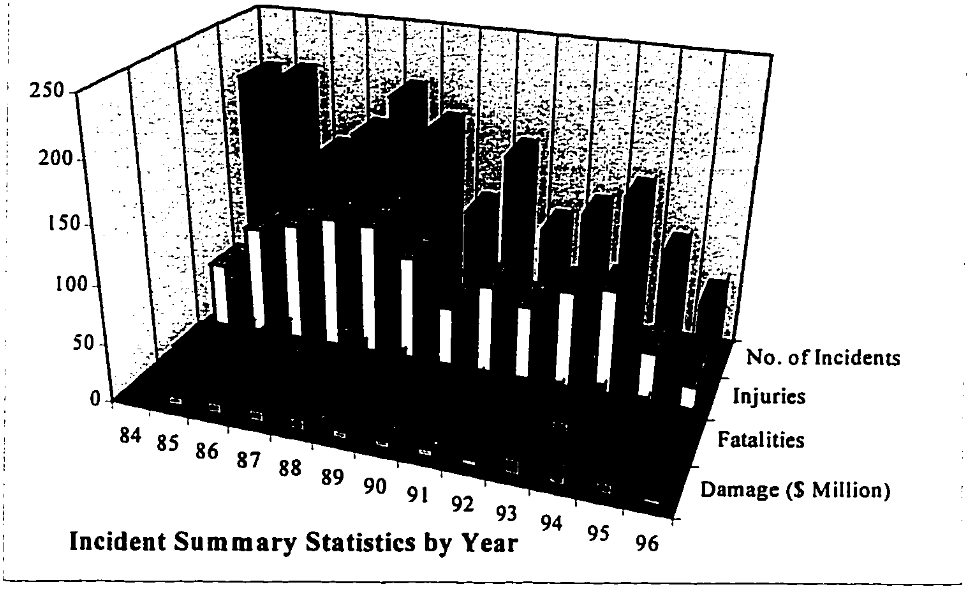

Figure CHAPTER 1 : .1: Office of Pipeline Safety: Natural Gas Pipeline Operators Incident Summary by Year (1/1/86 - 8/21/96). Adapted from web page: http://199.103.189.216/ng10yr1.htm

Construction and material defects have been primarily associated with the quality of the welds and joints linking pipe segments to form a line. Additionally, defects in the quality of pipe material may be the cause of immediate after construction or delayed incidents. Pipeline support depends also on construction procedures and quality.

Clearly, operator error can take many forms. An example is to load the medium or low pressure network in pressure mixing stations with high pressure gas. The same category includes "other causes", among them sabotage. In US transportation pipelines sabotage, let alone pilfering, is highly unlikely. Yet in distribution networks, tampering with residential meters is not rare, and can be the cause of serious incidents, especially when it leads to leaks that are not discovered timely. The leaked gas may end up filling a basement or cellar leading to devastating confined explosions.

Figure 1.1 shows the progress in distribution pipeline safety in the US during the past decade. Distribution pipeline failures correlate highly with the number of frost days in a year and the severity of winter in general. With the exception of the spike in incidents in 1994, progress during the past decade appears to be satisfactory.

Pipeline Safety Technologies and Practices

We divide safety technologies and practices into two categories, passive and active safety systems. Passive safety systems attempt to minimize damages after a failure cause has occurred. Active safety systems attempt to minimize the probability of a failure occurring in the first place. The latter are preventive approaches. We present the main safety systems by the failure cause they address. Most of these safety systems are internationally accepted, but some newer practices have less widespread following.

Third party Damage

As far as passive safety practices are concerned, the best known are increasing pipe wall thickness and using casings. In general, the larger the pipe diameter, the stronger a pipe is and consequently, the more difficult for it to be accidentally severed by farming or construction equipment. A smaller diameter pipe needs more upgrading of its nominal thickness (i.e. a higher safety factor or a lower design factor) to sustain external forces. Casings are either in the form of a larger diameter pipe surrounding the gas carrying pipe (and able to handle the working pressure in case of accident) or in the form of concrete walls (or metal plates) covering the top and possibly the sides of the pipeline. Concrete casings become more important when the soil surface on the top of the pipeline is about to be covered by a road or a rail line [Gauthier, 1987] .

An impressive active safety approach is the one-call system, where contractors can learn from a call to the gas utility or transportation company whether the site they are about to start construction on is atop or near a pipeline. The system has been in practice in the US since the mid-1970s [Voigt, 1987] , but it hasn't been fully implemented nationwide yet. Another practice is regular aerial supervision of the pipeline network by pipeline company personnel. It is anticipated that in the future satellite supervision will substitute the present day aerial patrols. Today foot patrols are the most common supervision practice.

Some more innovative technologies are advanced by the Gas Research Institute (GRI) [Gauthier, 1987]. These include pipe detection radars like TERRASCAN, water jet pipe identifiers and pipe proximity warning devices. A complementary line of soft excavation systems is also under development, including the supersonic air knife, the oscillatory soft excavator and the rotary boring soft excavator.

Environmental Effects

Again, the passive approach would be to increase the pipe wall thickness. Yet, to avoid corrosion a number of active safety systems are standard practice:

- Lining the pipeline with a coating externally or internally.
- Cathodic protection of pipes by charging them with a constant electric field.
- Inspecting the interior of the pipeline with a pig traveling inside the pipeline by the force of the gas behind it. This technique does not require service interruption. Technologies are improving, producing faster and more reliable intelligent pigs.
- Quality control of transported natural gas to avoid sour gas corrosion.
- For SSC, avoidance of stress cycles and decrease of maximum pressure to less than 50% to 60% of design pressure appear to have the desired effect but is judged to be uneconomic [Eiber, et al., 1994].

Material and Construction Defects

The typical preventive approach is quality control of pipe material, welds, joints, valves and other equipment during construction. Regular pipeline integrity assessment is also possible through use of hydrostatic testing. The pipe is filled up with water slightly over the design pressure. If a leak is observed, the pipeline part it was found on is repaired by techniques of varying complexity, from fillings to sleeves to complete rehabilitation of the pipe. Leaks and ruptures, due to a number of predisposing factors, are forced to occur, so the technique of hydrostatic testing manages many failure causes simultaneously. It doesn't come free of disadvantages however. The resulting waste water is a ground water pollutant, service interruption is required for operational pipelines and repeated tests may harm pipeline long term integrity.

Operator Error

The primary method of reducing operator errors is good training and sound management systems. Today, human factor analysis can help task design so that safety is maximized. Heavy use of information technology (e.g. expert systems, remotely controlled compressing stations) appears to be an attractive safety improvement direction to a number of practitioners.

Comprehensive Safety Management Practices

Emergency response plans are crucial to minimize damages in the event of an accident. The Clean Air Act Amendments of 1990 require that these plans are registered with EPA and local authorities in order to achieve the best coordination during emergencies. Drills on emergency response plans and training help reduce the probability of operator error in the difficult to cope with situations that arise after an accident.

Regional variations in either failure risk or risk of high damage are typically managed through different design factors. In areas of higher population density medium to low pressure pipelines operate only, and the ASME standards require a lower design factor (or higher safety factor) for pipe wall thickness. Similarly, in areas where the soil is more corrosive, the design factor decreases. More complicated recommendations have been proposed for earthquake risk management. The risk of excessively stressing a pipeline during an earthquake increases mainly in areas with certain geological characteristics only. There, more flexible pipeline designs are recommended, see [Nishio, 1994] for an analysis of the effects of earthquakes on pipelines.

Natural Gas Storage Safety

Underground Storage

Underground storage is considered to be a safer process than pipeline transportation because external interference is unlikely at the depths where the stored gas is situated [Ohsawa, 1994]. Well established or standard safety practices haven't evolved yet as is the case with pipeline transportation. The main safety considerations and the ways in which they are approached follow.

In the case of depleted oil or natural gas wells, the risks are small as long as the initial maximum well pressure is not surpassed during gas injection. There are many wells connected to the same underground cavern, some of them long not in use and maybe forgotten. If these wells are poorly sealed, they may lead to loss of containment. This risk is a major consideration during initial fill up.

The typical risks are associated with small releases due to equipment malfunction and operator error [Ohsawa, 1994] . The hazard with the most terrifying potential consequences is a well blow out. In this event, the gas escapes uncontrolled from the underground cavern, forming a vertical gas jet tens of meters wide and 200 meters high [Noe and Pigerskill, 1994]. This jet may cause fire and explosion hazards. Safety equipment are commercially available to lessen this risk.

Salt cavern storage faces the same well blow out hazard also. The most likely time for a blow out to occur is during initial fill up. Again, high construction standards appear to be the most important safety approach. Another failure mode for salt cavern storage is overfilling, in which case gas escapes from observation wells.

LNG Storage

After the terrible 1944 incident in Cleveland, Ohio, which caused the cessation of natural gas liquefaction for nearly two decades, high quality LNG facilities have been built and now enjoy a good safety record. The risks associated with LNG are low-probability high-consequence ones. The most severe impact can result from Boiling Liquid Expanding Vapor Explosions (BLEVEs) and from Unconfined Vapor Cloud Explosions UVCEs. Pool fires today are unlikely to have the devastating effects they had in Cleveland, because LNG tanks are surrounded by dikes that do not permit liquefied gas migration to nearby areas. Better more, some tanks are built in ground with their maximum liquid phase level being underground [Kato, 1994] .

Typical safety precautions include the use of high strength materials that retain their properties at cryogenic temperatures (contrary to the Cleveland experience), and building double walled tanks. The risk of BLEVE and UVCE is thus minimized but nonetheless not eliminated.

Regulatory Framework

Under the Natural Gas Pipeline Safety Act of 1968 (NGPSA), the US Department of Transportation (US DOT) has as its mission,

"... to protect the people and the environment of the United States through a comprehensive pipeline safety program. The Department develops, issues, and enforces minimum pipeline safety regulations." [OPS, 1992].

US DOT, through its Office of Pipeline Safety (OPS), issues and enforces specific technical regulations for the construction, operation, inspection and maintenance of pipelines [Pipeline Safety Regulations, 1994]; collects statistical information on pipeline incidents[1] and on pipeline company annual performance; and conducts pipeline operator training through its

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[1] Failures of pipeline systems leading to significant loss of fuel, injuries, fatalities or property damage. A detailed definition appears in [Pipeline Safety Regulation, 1994].

Transportation Safety Institute. Another federal agency, the National Transportation Safety Board (NTSB) is charged with conducting after incident investigations.

OPS specifications are based on American Society of Mechanical Engineers (ASME) and American National Standards Institute (ANSI) standards. They are technology based standards because they give a limited choice of technologies for the various construction and operation processes of pipeline systems. Conforming to legal terminology [Shavell, 1993], OPS specifications are publicly-enforced act-based rules[2]. It appears that the assessment of the law maker has been that without these specifications, establishing negligence and attributing the share of blame to the many parties involved in incidents would be very costly.

Another important observation revealing the spirit of NGPSA is that increases in housing density near a pipeline right of way have to be recorded by pipeline companies and if they are significant, then pipelines have to be reclassified (according to detailed OPS prescriptions [Pipeline Safety Regulations, 1994]). Pipelines operating in high density areas (Class A) conform to stricter safety standards so that they are less likely to fail. On the other hand, pipelines operating in low density areas do not abide by the same requirements and are more likely to cause harm. Overall, frequency and magnitude of losses throughout the service region of a pipeline network is desired to be balanced, making the spatial distribution of risk more homogeneous.

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[2] OPS specifications are not enforced by individuals after they are harmed, but preventively by OPS. In addition, the act of not conforming to regulations results in sanctions independent of whether harm was caused or not.

Throughout this work, spatial distribution of risk receives particular attention so the previous observation carries significant weight. The actual outcome of any specification standard is not guaranteed to conform to the intentions of the law maker, so in our example some deviations from spatial homogeneity of risk will exist. The performance of a technological system according to legal mandates cannot be ensured unless it is measurable. Standard specification systems are geared towards measuring deviation of production technologies from mandated standards and not deviation of actual performance from ideal.

Today, OPS is moving towards performance based standards in an effort to better target regulations (and thus reduce socially unwanted risks) and to reduce the compliance cost burden to the pipeline industry [Gas RAQT, 1995]. OPS uses the term “Risk Management” to describe this new approach. In this study, we will adhere to the more standard definition of Risk Management as risk reduction and control.

Overview of Following Chapters

Chapter 2 overviews the basic risk assessment methodologies and describes how they are applied in pipeline safety studies. It includes a qualitative analysis of pipeline failure modes organizing the technical information available on this subject. A synthesis of models used by safety engineers to analyze heat radiation hazards concludes this chapter. The basic functional relationships between risk control factors versus magnitude and local dispersion of losses developed there is used in the chapters to follow.

In chapter 3, we describe how spatial distribution of risk indicators can be generated using information on the risk performance of facilities in a region. Definitions of the concepts of "risk map" and "risk source" are offered. In addition, we present detailed notation (specific to chapter 3) needed for the mathematical derivations, which establish the validity of the methods proposed. Procedures to estimate risk maps both when the risk sources are independent and when they are dependent (as is the case during natural disasters) are furnished. The results are illustrated using computer simulations of a prototype region. The computer program in C Language used appears in the Appendix (see [Rudd, 1994] for a description of C).

Chapter 4 is the lengthiest and contains its own mathematical notation. A method for prioritizing pipeline segments is proposed in chapter 4. The objective considered is to maximize the benefit of risk reduction net of the cost of pipeline replacement. After a detailed mathematical description of the problem , we offer a specialized algorithm for its solution both in the presence of a budget constraint and in the absence of it. We apply this algorithm to the data given to us by the NGU of a major city in the US.

In chapter 5, we explain in qualitative terms risk maps and their use. We believe that their use in upper management decisions offers many advantages. We focus specifically on two problems, safety budget evaluation and defending or legitimating a spatial pattern in the regional distribution of risk. Finally, in chapter 6, we present in a comprehensive way the unique contributions of this study.

CHAPTER 2 : RISK ASSESSMENT METHODS APPLIED TO NATURAL GAS DISTRIBUTION

In this chapter, we describe the basic approaches used in assessing and improving pipeline safety. We begin with a review of the basic methodologies used in the assessment of technological risk. According to this perspective, we classify the basic methods used in practice. A lengthy section on consequence analysis of pipeline failures is included, containing both qualitative and quantitative analyses. The subsection on fire hazard analysis establishes the basic functional relationships to be used in the next chapter, where the generation of risk maps is discussed.

Risk Assessment Methodologies

There are many economic actors interested in the assessment and management of technological risk. A non exhaustive list includes, manufacturers of hazardous material, owners and operators of hazardous material distribution systems, insurance companies, safety technology manufacturers, regulatory agencies, applied technology research laboratories and institutions, concerned public, and venture capitalists. Depending on risk assessor knowledge base and on risk management objectives, the energies of a risk assessment study or a risk assessment system (performing risk assessments periodically or on demand) will be focused differently. A study or a system carried out internally for, say, a chemical manufacturer, would use a large number of details of plant operations. Because internal studies tend to have safety improvement as their goal and risk assessors (company employees) tend to have incentives to report information accurately, nominal attention only is paid to assessment validation. Risk assessments performed by outside parties, tend to focus on the most important verifiable factors and are averse to detail.

Decision analysis theorists (see for example [Lindley, 1971]) make clear that an analysis with the finest level of detail in risk information is not necessarily the most economically desirable. If extra information has a marginal effect only on the choice among risk control policies, then the excess cost of acquiring and processing this information may not be justified. A balance between the cost of proposing wrong recommendations and cost of extra information determines the optimal level of analysis.

The basic framework for a risk assessment study is described in Figure 2.1. The risk performance of a technological system is assessed by observing process details (e.g. manufacturing process diagrams), inputs (e.g. quality of raw material, level of expertise of inspection personnel), and outputs. Risk assessment may measure performance indicators directly or it may use estimates provided by experts. At the end, a risk indicator is produced that may be simple (e.g. average yearly risk of catastrophic loss), or complex (e.g. a set of simple indicators). This risk indicator is contrasted to a comparison basis. According to the deviation of actual from basis performance a control policy is chosen. The control policy, which might be no action at all, affects process efficiency or architecture and inputs. The comparison basis may be absolute (e.g. zero failures) or relative (e.g. benchmarking studies measuring deviation from average performance).

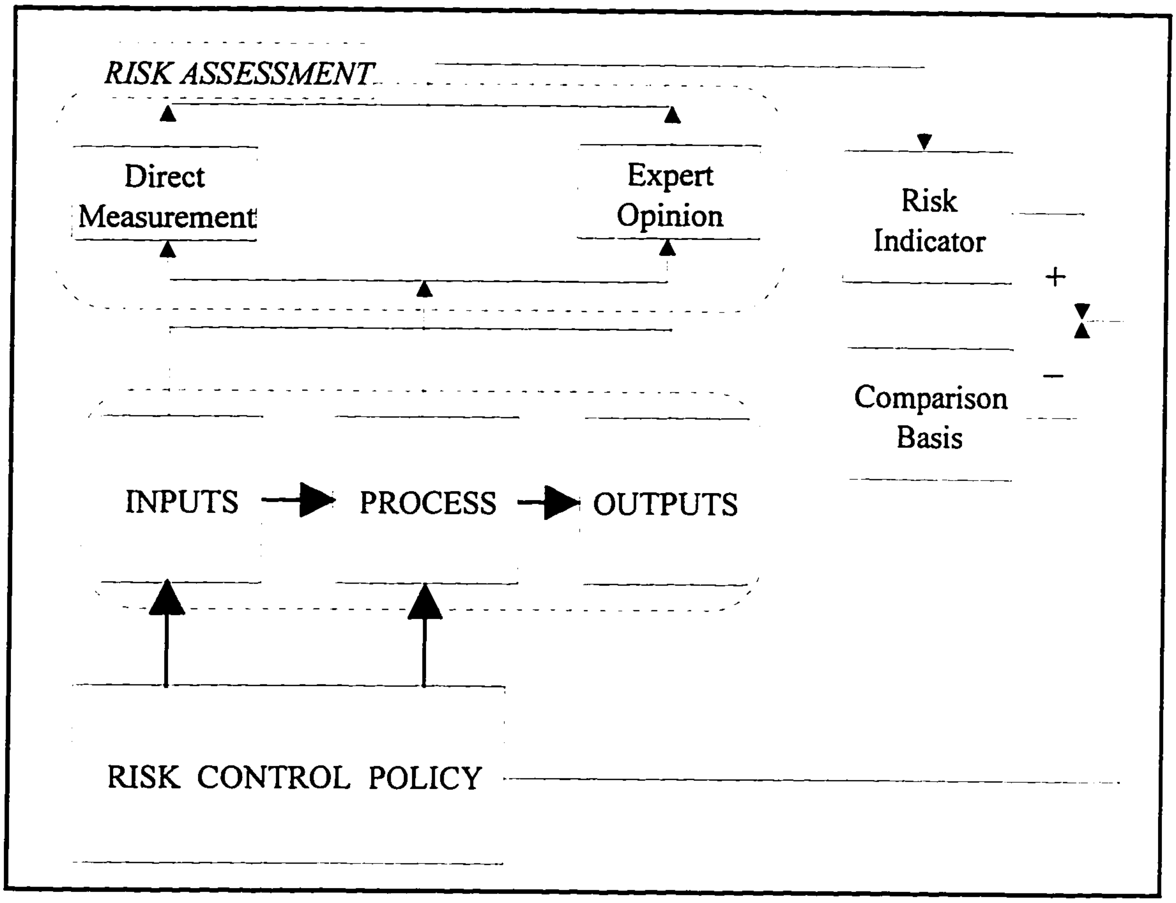

Figure 2.1 : Risk Assessment and Management for Technological Systems

Risk assessments rarely measure zero prior knowledge indicators. Statistics of property and mortality losses are unlikely to form adequate samples for analysis in reasonably run production processes. Proxies of loss variables are used instead. Figure 2.2 shows how observers chose proxies according to a model they have about the relation of proxies to loss variables. These models differ from one observer to the other, but certain proxies gain widespread acceptance when there is a consensus on the direction of their effects. For instance, it is easy to establish that near misses affect the overall risk performance negatively, but disagreements may occur on the actual efficiency of near miss control policies. It is essential, however, to make sure that the relation between proxies and actual losses is invariant with or improved by risk control policies. A policy that controls proxies but at the end leaves actual losses unaffected is of little use.

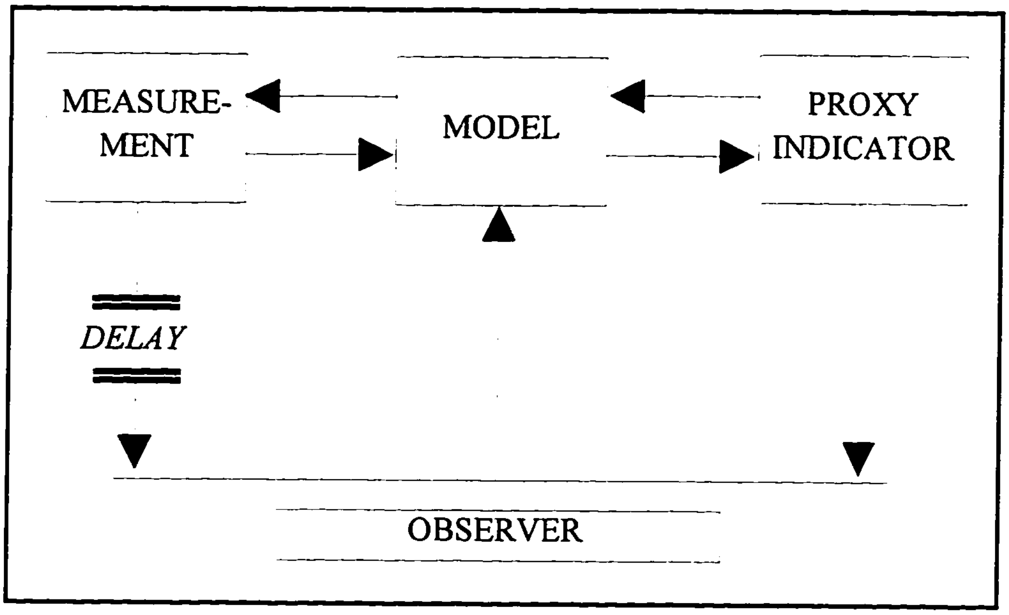

Figure 2.2 : Use of Proxy Indicators by Observers of Risk Performance

We will distinguish five classes of risk assessment methods:

1. **Heuristics:** Heuristics are imperfect decision rules carrying, nonetheless, predictive power. Examples include ranking systems based on attributes that can be trivially verified (concrete examples will be detailed in the next section).

2. **Statistical:** These employ statistical estimation to validate hypotheses and to determine trends of risk indicators. They tend to use limited assumptions about the technological system and so they are uniquely suited for risk analysis model validation.

Modern statistical methods and especially spatial statistics (e.g. [Ripley, 1981], [Boots and Getis, 1988]) provide new options for risk estimation and are expected to be utilized more often in the analysis of geographical risk distribution. It is important to note that because of the Low-Probability / High-Consequence nature of the losses technological risk analysis is concerned with, proxies and in particular near misses are easier to measure than the actual variables themselves.

3. **Risk Analysis:** In general, risk analysis is concerned with clarifying and organizing relationships between causal factors and system failures. After a risk analysis or given the results of one completed previously, one can integrate information on causal factors, subsystem performance, and system architecture to estimate overall risk indicators. Risk analysis methods can be viewed as complex heuristics requiring more experience and skills to use and implement.

4. **Benchmarking:** Risk assessments avoiding absolute comparison bases and contrasting risk indicators of similar technologies against each other fall under this class. Technologies contrasted against each other are rarely identical for risk assessment purposes, and consequently benchmarking studies often employ equivalence heuristics.

5. **Basic Research:** The purpose of basic research is to discover knowledge and its results are rarely delivered within the limited span of time available for risk assessment. The direct cost of basic research may also be high, but it is accompanied by high benefits. Basic research has a capital goods nature and whether it is used or not depends on the time preferences of economic actors interested in risk assessment. Basic research projects tend

to be undertaken cooperatively, possibly by industry associations. Government organizations might also help with financing these projects.

It is important to be in a position to easily assess the sensitivity of risk control recommendations to risk assessment assumptions. This may be called robustness analysis (according to statisticians), sensitivity analysis (in Operations Research), uncertainty analysis (according to technology policy experts [Morgan et al., 1985]), or finally verifiability analysis (which is the term we favor). It has value not only to outside parties evaluating the risk assessment recommendations, but to risk assessors as well in facilitating continuous improvement. Risk assessments should facilitate verifiability analysis by making assumptions transparent.

Risk Assessment in Pipeline Safety Practice

We classify risk assessment models and studies used in practice for pipeline risk assessment and management according to the previously described categorization:

Heuristics

Heuristic hazard analyses, like WHAT-IF and HAZOP, are widely used in hazardous material processing industries [Greenberg and Cramer, 1991]. They are easy to implement and serve as training tools for increased emergency preparedness. Moreover, regulatory agencies (e.g. OSHA) require HAZOP. Avoidance of pipeline joint leaks and improper handling of valves - both possible precursors to severe incidents - may be part of the objectives TQM programs have. Therefore, one should expect that many varieties of heuristics would be used for pipeline safety. Two representative systems follow.

RIPS The RIPS model was developed by Dow Chemical for liquid and gas pipelines. The following observations are based on the description of RIPS given in [Hill, 1992] . RIPS takes account of many failure causes, like external interference and corrosion. The output of RIPS is a risk index for each section of a pipeline network. According to Hill, this index is determined judgmentally by the developers of RIPS. Consequently, the verifiability of RIPS is expected to be such that it can be used internally to the company only.

British Gas Model The British Gas model [Fearnehough, 1985] uses statistics of failures per mile of pipeline. A main assumption of this study is that rupture is a "credible failure mode" on the rural pipeline system only (design factor 70) and not on the suburban one (design factor 30). The interpretation of safe distances from the pipeline after an incident involving a fire is left unclear. The results are given in societal risk curves and not in risk contours.

Statistical

Statistical analysis methodologies provide risk management alternatives and the rationale for selecting among them by a careful survey of accident reports. Such reports are produced in the US by the Department of Transportation (DOT) and are analyzed statistically by the American Gas Association. Similar surveys are conducted internationally (e.g. the Concawe report in Europe). Statistical surveys are supposedly as close to reality as possible, so they are unlikely to be challenged during the risk management process. Yet these surveys too need good models of reality and successful assumptions.

After incident investigations cannot determine exactly the conditions of event occurrence[3] or the corresponding consequences. The one number most easy to measure and most difficult to conceal, the number of fatalities after an incident, is still disputed in risk assessments (e.g. for fire hazard) [Lees, 1980]. If fatalities count the accident related deaths after the first day, they may miss counting injured victims who pass away in the hospital. Standards of measuring fatalities do apply (US DOT 30 day system), yet uncertainties in the parameters of the post accident reports are ubiquitous. In particular, precise meteorological conditions during the incident, quantity released and other key parameters for risk analysis maybe very difficult or impossible to decipher.

Risk Analysis

Risk assessments in the form of environmental impact assessments are required, as discussed in the previous chapter, before construction of major pipeline projects. Many projects vital to natural gas industry depend on acceptance of Low-Probability High-Consequence events by the public, and risk analysis studies are necessary to appraise these risks. An important example is Liquefied Natural Gas (LNG) installations, such as marine terminals and storage tanks. A study considering the risk of LNG vapor cloud transport and explosion is outlined in [Keeney et al., 1990].

CIMOS: A good example of a pipeline risk assessment system offering risk information on demand or for periodic decisions is CIMOS (Cast Iron Maintenance Optimization System). CIMOS takes in account static characteristics, like pipe diameter, segment length, pressure, soil type; and dynamic characteristics, like previous breaks, leaks, and age. The difference of CIMOS from heuristic methods is that it has been validated statistically [Kulkarni et al., 1990].

Benchmarking

Benchmarking studies of pipeline risk are common practice among natural gas utilities. Unfortunately, due to their sensitive nature, they are not available to the general public. In general, it is difficult to compare the pipeline networks of different companies, because of their heterogeneity. To have risk indicator comparisons reflect actual risk performance differences, one should discount for the effect of differentiation factors in pipeline network make up. One study, assessing what is an adequate yearly rate for pipeline replacement, communicated personally to us by pipeline safety engineers, controlled for network size effects and ratio of cast iron lines in the total.

Basic Research

One example typifying our assumptions on basic research is the National Bureau of Standards study of pipe corrosion in different soil and climate types. This study, which lasted 45 years

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[3] This is of paramount importance in the design of risk reduction policies.

and was published in 1957, is considered still the most authoritative piece of research in pipeline corrosion [Iocca et al., 1987].

Pipeline Failure Modes

Pipeline failures to contain natural gas passing through may lead to losses in human life and property neighboring a pipeline or storage facility. Loss of containment may be intermittent or permanent. An example of an intermittent containment loss is a release after an operator error that is quickly recovered before a fire occurs. Serious accidents tend to be caused by permanent loss of containment. We describe more precisely these failure modes, first for pipelines and then for underground storage facilities. A summary of incidents from the mid-1970s appears in Table 2.1 taken from [EPA, 1977].

Loss of containment begins with the opening of a usually small orifice. This orifice may be located along the pipe trunk or in the joint area. Construction defects are more likely to result to orifices on the joints. Corrosion is more likely to result to orifices along the trunk.

In the presence of high pressure or metal fatigue, a small orifice can rapidly evolve into a rupture. The crucial factor, however, in rupture formation is the magnitude of pressure compared to the maximum static pressure that the pipe material can withstand by design.

Fatalities & Injuries Total	**1320**	**100.0%**
Employee Fatalities	10	0.8%
Employee Injuries	149	11.3%
Non-Employee Fatalities	114	8.6%
Non-Employee Injuries	1047	79.3%
Incidents Total	**3327**	**100.0%**
Gas Ignited	1774	53.3%
Explosions Occurred	586	17.6%
Secondary Explosions & Fires	391	11.8%
Underground Facility Contributing	320	9.6%

Table 2.1: 1970-1973 Incident Report (Includes Gathering, Transmission, and Distribution)

To describe pressure magnitude authors usually quote the design factor, the ratio of working pressure over the maximum sustainable one under normal conditions. Design factors vary depending on population density around the pipeline. From 70% in rural areas to 30% in suburban areas in the UK for example [Fearnehough, 1985] . A rule of thumb is that design factors less than 60% to 50% are enough to avoid rupture formation [Eiber et al., 1994]. Fearnehough gives a more detailed model , recommending 30% as a very safe design factor limit [Fearnehough, 1985].

Ruptures propagate along the pipe trunk leading to orifices of significant size. Orifices of the same order of magnitude can result from pipeline severance due to external interference. Typical construction equipment can sever pipelines of small diameter only, but they can initiate ruptures to larger in diameter pipes. The conditions of rupture formation are such that ignition of escaping gas is more likely in ruptures than in leaks.

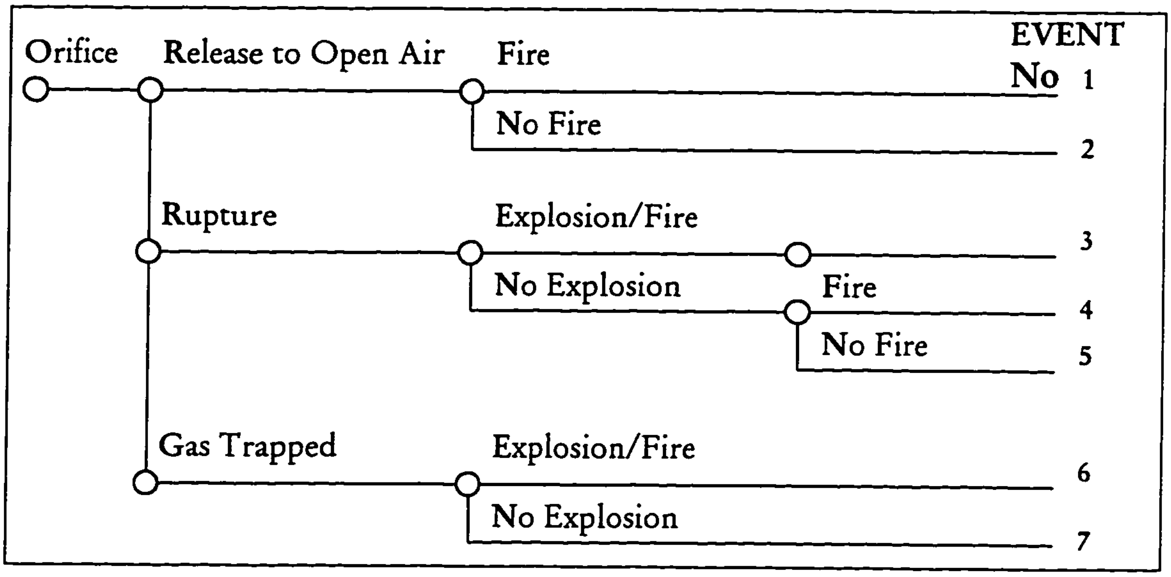

Figure 2.3: Basic Event Tree

Pipelines are buried typically three feet under the surface. Unless a pipeline is uncovered before rupture occurs, gas escaping through an orifice can open by the force of pressure a trench, thus finding its way to the surface. Alternatively an explosion can cause trench formation, in which case a jet fire occurs immediately after. Ignition depends on the presence of ignition sources near the unburned gas jet.

Orifices in cast iron mains, used typically in low pressure networks, may reach maximum size, due to the usual mechanism of their formation. Cast iron segments are likely to break because of bending stresses, resulting in orifices as wide as the internal diameter of the pipe.

Gas from leaks is not easy to result in trench formation. Gas may migrate though the small gap between the soil and the external diameter of the pipeline either to a point from which it can get to the surface or to nearby buildings and other closed rooms (e.g. sewer system) where it can become an explosion hazard. Ignition in the first case is not very likely. Small leaks cannot be detected from pipeline pressure drops and the usual way of detecting them is through ground patrols, which observe vegetation disturbances and use electronic gas detectors.

If gas is trapped in a room after migration, then people in the building this room is part of are exposed to confined explosion hazard. The hazard potential will depend on how big this room is and on how well it is sealed [Harris, 1983]. Rooms with glass windows do not permit high pressure built up after an explosion because the glass panels shatter before reaching maximum pressure (which may reach 8 bars). Inhabited rooms are likelier to provide ignition sources, but people are likely to detect the gas release early.

Symbol: Name		AFFECTS		
		Local Dispersion	Magnitude	Likelihood
DESIGN	d_p : pipe diameter	-	✓	✓
	t_p : pipe thickness	-	✓	✓
	A_p : pipe age	-	-	✓
	C_c : corrosion control	-	-	✓
	c_p : casings	✓	-	✓
OPERATION	P : line pressure	-	✓	-
	c_L : cycle loading	-	-	✓
	I_M : inspection policy	✓	✓	✓
	I_R : repair policy	-	✓	✓
ENVIRONMENT	C_P : corrosion potential	-	-	✓
	$\tilde{I}_E$: external interference	✓	✓	✓
	$\tilde{I}_N$: interference by nature	-	✓	✓
	u_∞ : wind speed	✓	✓	-
	V_l : local value density	✓	✓	-
	h_l : human life density	✓	✓	-
	e_l : employees exposed density	✓	✓	-
	i_l : interaction effects	✓	✓	-

Table 2.2: Pipeline Risk Control Parameters

In Figure 2.3 we outline the basic structure of the event tree after a release of natural gas from a pipeline as described qualitatively in the previous sections. The event tree points to 7 basic modes of failure. Risk Analysis or Statistical methods may be used to estimate the frequency of the 7 basic events for each pipeline segment. In the following section we will address the estimation of the magnitude and spatial distribution of losses after a natural gas jet fire occurs.

As a qualitative summary of the pipeline risk factors we include Table 2.2 containing the most important factors affecting magnitude, frequency, and local dispersion of losses. A risk control policy needs to act upon some or all of the factors in Table 2.2.

Analysis of Heat Radiation Hazard

The primary hazard indicator for jet fires after leaks or ruptures is heat released by radiation. If a surface of 1 m^2 is exposed to heat radiation at a rate I KW/m^2 then the total heat absorbed (no reflection is assumed) by it after s seconds would be:

$$H_a = s \cdot I$$

It is often considered [Lees, 1980], [Lees, 1994] that the hazard of injury and fatality from burns is better described by:

$$H_a = s \cdot I^{\eta} \quad \text{with} \quad 1.15 \le \eta \le 2$$

We will use the estimates developed by Eisenberg and accepted by Lees (see [Lees, 1980]):

$$H_a = s \cdot I^{4/3}$$

As it is clear from the previous models, the heat flux I has more weight in assessing the hazardousness of heat radiation than the time an individual is exposed under it. We will use a well known engineering model of local heat flux dispersion, the one that represents the flame as a point source of heat radiation located at the center of the flame length.

Consider the occurrence of an orifice of effective diameter[4] $d\ mm$ on a trunk line operating at pressure $P\ bar$. A mass of gas, depending on pressure and orifice diameter, will be released at the atmosphere at a rate of $\dot{m}(P,d)\ {}^{kg}\!/_{sec}$. The radiant heat flow from the burning gas may be obtained as follows:

$$H_R = \chi \cdot \dot{m} \cdot H_c = \chi \cdot H_T$$

Where:

H_C is the calorific value of natural gas. In these calculations we will use a value of 40 *MJ/kg*. A more precise value may be obtained, if the quality of the natural gas transported is better determined. Typical ranges for calorific values are: 52-46.7 (North Sea Gas) or 42.7-32.5 (Groningen Gas) [Medici, 1974].

H_T is the total heat flow from the burning gas in *MJ/kg*

χ is the emissivity factor (ratio of total heat released to the one radiated). In these calculations we use a value of 0.2. The emissivity factor ranges form 0.1 to 0.3 for natural gas flares. It varies with jet velocity u_j according to the rule $\chi = 0.21 \cdot e^{-0.4 \cdot u_j} + 0.11$ [Chamberlain, 1987].

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[4] The orifice of a non circular area of surface A has effective diameter: $(A/\pi)^{1/2}$.

The heat absorbed by a black surface located at point *(x,y)* and pointing to the center of the flame where the ideal point source is located is given as follows:

$$H_a(x, y; u_\infty) = \frac{H_R}{4 \cdot \pi \cdot \left[\left(x - x_p\right)^2 + y^2 + z_p^2 \right]}$$

where:

x is the downwind distance of the black surface from the point of release on the pipeline.

y is the crosswind distance of the black surface from the point of release on the pipeline.

x_p, z_p is the the downdwind and vertical coordinates respectively of the point source relative to the release point on the pipeline.

When a black surface is facing a radiant heat source it receives the maximum radiation it can possibly receive. If the surface is tilted from this position less radiation is received according to the view factor. We do not consider view factors in this study because we study the effect of heat radiation on objects of complex geometry (e.g. humans, buildings). Damage to one part of these objects is sufficient to cause a fatality or total destruction.

To calculate the location of the radiant heat point source we refer to a graph from [Cook et al., 1987 (figure 1)]. By measuring their regression line on a log - log diagram we obtain the following relation for the flame length L :

$$L = 10 \cdot \sqrt{\frac{\dot{m} \cdot H_c}{60}} = 1.291 \cdot \sqrt{\dot{m} \cdot H_c} \qquad \text{in } \textit{meters}$$

From the same source we obtain the relation of flame tilt α to relative wind speed (figure 2(a) of [Cook et al., 1987]):

$$\alpha = 1500 \cdot \frac{u_\infty}{u_j} \quad \text{for} \quad 0 \le \alpha \le 60 \qquad \text{in } \textit{degrees}$$

where:

u_∞ the wind velocity in *m/sec*

u_j the velocity of gas after combustion in *m/sec*

The model for heat formation after a rupture is described in detail in Table 2.3 . For ruptures the gas release is considered to be flow limited (unchoked). For leaks, the model is orifice limited (choked) flow, described in detail in Table 2.4 . The inputs in the two scenaria are different. For ruptures, the inputs are gas mass flow and effective orifice diameter. For leaks the inputs are pipeline pressure and orifice diameter.

For risk estimation calculations the inputs are considered to either be known precisely (e.g. mass flow, line pressure) or to have a known probability distribution (e.g. orifice diameter). Parameters need also to be determined ahead of the risk estimation calculation and are known either precisely or probabilistically. Depending on the information base of the risk estimator. the degree of uncertainty on inputs and parameters varies. A pipeline company may have very precise information on pipeline pressure and on heat value of gas passing through its pipelines. In addition precise knowledge may be available about the variations of pipeline pressure and heat value, as far as our two example parameters are concerned. This knowledge may not be available to a regulatory agency. Assessors in regulatory agencies may use probabilistic measures for risk estimation, presumably obtaining their final estimates with higher uncertainty.

In all tables describing inputs and parameters, we characterize their uncertainty as low or high depending on its effect on the overall result (i.e. we give a robustness estimate). Uncertainty is reducible if more detailed information may be obtained. For estimates of model uncertainty, in particular on the choice of point versus continuous heat sources we refer the reader to [Cook et al., 1987] .

In Table 2.5 we summarize the model of local heat dispersion from the point source. The heat flow at each point in the local vicinity of the flame is adequate to provide estimates for risk to life and property. Clearly, other hazards also exist close to the flame. Burns may result from heat conduction and convection. Injuries may also result from the earth blasted from the high pressure gas escaping to the open air.

$$H_R(\dot{m}) = \left(0.21 \cdot e^{-0.4 \cdot u_j} + 0.11\right) \cdot \dot{m} \cdot H_C$$

$$u_j\left(M_j\right) = M_j \cdot \left[\left(\frac{2}{2+(\gamma-1)\cdot M_j^2}\right) \cdot \left(\frac{\gamma \cdot R_c \cdot T_s}{W_{gk}}\right)\right]^{\frac{1}{2}}$$

$$M_j(F) = \left(\frac{\left(1+2\cdot(\gamma-1)\cdot F^2\right)^{\frac{1}{2}} - 1}{\gamma - 1}\right)^{\frac{1}{2}}$$

$$F\left(\dot{m}, d_0\right) = 3.6233 \cdot 10^{-5} \cdot \frac{\dot{m}}{d_0^2} \cdot \left(\frac{T_s}{\gamma \cdot W_{gk}}\right)$$

Inputs:	$\dot{m}$	mass flow	in $kg/\sec$
	d_0	orifice diameter	in *meters*
Parameters:	*Value*	*Range*	*Uncertainty*
H_c	40 *MJ/kg*	32-55	reducible
γ	1.314		low
R_c	8.314 *J/(mol K)*		none
T_s	300 *K*	250-330	low
W_{gk}	0.016 *kg/mol*	0.016 - 0.019	reducible
References:	[Chamberlain, 1987 (Appendix)] [Medici, 1974]		
Assumptions:	• Gas flow is unchoked in ruptures. • All pipeline gas flow is released to the environment.		
Glossary:	*Symbol*	*Interpretation*	*Units*
	M_j	Mach Number	
	F	Aux. Variable	

Table 2.3 : Summary description of heat formation equation for ruptures in high pressure natural gas pipelines.

$$H_R(\dot{m}) = \left(0.21\cdot e^{-0.4\cdot u_j} + 0.11\right)\cdot \dot{m}\cdot H_C$$

$$u_j\left(M_j\right) = M_j\cdot\left[\left(\frac{2}{2+(\gamma-1)\cdot M_j^2}\right)\cdot\left(\frac{\gamma\cdot R_c\cdot T_s}{W_{gk}}\right)\right]^{\frac{1}{2}}$$

$$M_j\left(P_c\right) = \left(\frac{(\gamma-1)\cdot\left(P_c/P_0\right)^{\frac{\gamma-1}{\gamma}} - 2}{\gamma-1}\right)^{\frac{1}{2}}$$

$$\dot{m}\left(P_c, d_0\right) = 0.2724\cdot P_c\cdot d_0^2\cdot\left(\frac{2\cdot T_s}{(1+\gamma)\cdot\gamma\cdot W_{gk}}\right)^{\frac{1}{2}}$$

Inputs:	P_c	line pressure	in *pascal*
	d_0	orifice diameter	in *meters*
Parameters:	*Value*	*Range*	*Uncertainty*
H_c	40 *MJ/kg*	32-55	reducible
γ	1.314		low
R_c	8.314 *J/(mol K)*		none
P_0	$1.013\cdot 10^5$ *pascal*		reducible
T_s	300 *K*	250-330	low
W_{gk}	0.016 *kg/mol*	0.016 - 0.019	reducible
References:	[Chamberlain, 1987 (Appendix)] [Medici, 1974]		
Assumptions:	Gas flow is choked.		
Glossary:	*Symbol*	*Interpretation*	*Units*
	M_j	Mach Number	
	$\dot{m}$	mass flow	in $kg/\sec$

Table 2.4 : Summary description of heat formation equation for leaks in high pressure natural gas pipelines.

$$H_a\left(x,y;u_\infty\right)=\frac{H_R\left(\dot{m},P_c,d_0\right)}{4\cdot\pi\cdot\left(\left(x-x_p(\alpha)\right)^2+y^2+z_p^2(\alpha)\right)}$$

$$x_p(\alpha)=1.29\cdot\sqrt{\dot{m}\cdot H_c}\cdot\sin\alpha$$

$$x_p(\alpha)=1.29\cdot\sqrt{\dot{m}\cdot H_c}\cdot\cos\alpha$$

$$\alpha=1500\cdot\frac{u_\infty}{u_j}\quad\text{for}\quad 0\le\alpha\le 60$$

Inputs:	P_c	line pressure	in *pascal*
	$\dot{m}$	mass flow	in $kg/\sec$
	d_0	orifice diameter	in *meters*
	u_∞	wind speed	in *m/sec*
Computed from previous Tables when missing: u_j , $\dot{m}$			
Parameters:	*Value*	*Range*	*Uncertainty*
H_c	40 *MJ/kg*	32-55	reducible
References:	[Chamberlain, 1987 (Appendix)] [Medici, 1974]		
Assumptions:	• Flame acts as point heat source located at the center of the flame length. • No View Factor is considered / Alternatively the maximum View Factor of 1 is used.		
Glossary:	*Symbol*	*Interpretation*	*Units*
	M_j	Mach Number	
	α	Flame Tilt	*degrees*

Table 2.5 : Summary description of radiant heat dispersion equation high pressure natural gas pipeline fires.

CHAPTER 3 : GENERATION OF RISK MAPS

In this chapter a method for the calculation of Risk Maps given risk source and regional information is developed. We follow the well known approach of risk analysis (see for example [Frankel, 1984]), using information on geographic layout of risk sources, their individual risk profiles, and interrelations between them. Two risk source types are considered, point and line sources. Point risk sources are potentially hazardous facilities, occupying an area that can be considered minuscule compared to the region under evaluation. Consequently, for a large metropolitan area a large oil refinery may be considered a point source, a pipeline traversing a good part of the region may not. Line risk sources have one of their dimensions much larger than the others (e.g. pipelines, roads).

We focus mainly on heat radiation risk, but the proposed model may be easily adapted for the generation of explosion impact risk maps. The latter risks have been studied extensively for the purposes of the chemical process industry ([Lees, 1980], [Kletz, 1994]) and of the military [Baker et al., 1983] . The model may be used in the design and evaluation of risk management strategies for facilities that produce, store or consume hazardous material and for their distribution systems. The general problem of risk management for hazardous material transportation has received considerable attention (representative analyses include [Batta and Chiu, 1988], [Saccomanno and Cassidy, 1994] and [Erkut and Glickman, 1997]), but the mathematical analysis of risk maps has not been studied extensively. Determining the optimal layout of oil refineries or gas processing facilities, however, requires an analysis similar to the one proposed here (see for example [Tsuchiya et al., 1989]).

The following sections provide a set of definitions laying the foundations of the proposed analysis, a mathematical derivation of risk maps for independent and dependent risk sources, and results of a computer simulation using the derived model.

Definitions

REGION $:\Re \equiv \{(x,y) \mid x_l \leq x \leq x_u, y_l \leq y \leq y_u\}$ or

$: S \equiv \{(k,l) \mid k,l \in N; 0 \leq k \leq R_x, 0 \leq l \leq R_y\}$

Region of Study represented by the rectangle between the upper and lower limits of x and y. In order to create maps of the region , we will represent the region as a grid of distinct points (S) with resolutions R_x and R_y in the x and y coordinates respectively.

SUBREGION $: S_A \subseteq S$

Subsets of contiguous points in the region having the same properties.

POINT PROPERTIES:

Value Exposed $: v(x, y)$

Value in dollars at a point in the region exposed to risk because of the existence of one or more risk sources. This value will depend on the population density. In calculations of injury risk (e.g. fist degree burns, second degree burns, fatalities) v will represent the expected number of people at location (x,y) .

Protection Probability : $p_d(x,y)$

The ratio of value affected by a catastrophic event over v , after investments in protection technologies at point (x,y) have made it less vulnerable to risks. An example technology relevant for the type of risks considered here is the use of flame resistant building material.

Wind Factor : $f_w(x,y)$

Any factor having the following properties: 1) affecting the level of damage at a point in the region after a catastrophic event, 2) depending on the orientation of the point relative to the risk source causing the damage, and 3) independent of factors other than orientation from risk source. The archetypical example is the effect of the prevailing wind in fire propagation and the distribution of the resulting damage in the region. It is measured as a ratio of damage given the prevailing wind to damage without any wind at all.

DAMAGE : $D(x,y)$

A loss arising from an accident occurring at the risk source, measured usually in dollars. It is afflicted to the proprietor of the risk source, employees, passers by, near by residents or any other party that can claim a loss due to an accident at the risk source. Difficult to monetize damages (e.g. loss of confidence in the region) should be taken in account in risk management decisions too. To achieve this, one can use widely accepted monetization schemes, if they exist, or weigh them qualitatively after the quantitative analysis is complete.

RISK MAP : $R_{(R_x \times R_y)}$

Is a matrix containing the values of the risk metric for each point in S. We will be concerned with metrics of the following form: $R_{k,l} = \Pr(\tilde{D}_{k,l} \geq D)$

RISK SOURCE : $s \in NS$

A facility or a transportation line in the region under study, which may potentially cause damage to its surroundings during its life cycle (e.g. a storage tank for flammable material, a road line used for hazmat trucks). The damage may be due to causes internal to the risk source (e.g. unsafe operation), or external (i.e. natural disaster). We will use the symbol E_S for the set of internal to s risk causes (events) and Q for the set of external events affecting the performance of all risk sources in the region. NS is the set of all risk sources.

RISK PROFILE AT SOURCE : $\Pr(\tilde{L}_s \geq L)$

Probability distribution used to predict the frequency of future accidents of a given loss potential and over. The risk profiles can be determined either empirically or by using some technological risk assessment method (e.g. Failure Mode Analysis). They are characterized by high probabilities of near zero damage (i.e. normal operation), and low probabilities of relatively high consequence events.

In this study we consider separately risk maps conditional to an event affecting the entire region simultaneously (e.g. earthquakes). As these events are not known to affect positively the operations of facilities, the frequency of accidents after an earthquake can only be the same as or higher than the one under normal conditions, i.e. : $\Pr(\tilde{L}_i \geq L | Q) \geq \Pr(\tilde{L}_i \geq L)$

We measure the effects of an accident in loss potential L (e.g. heat flux from fire, explosion impulse). If little value is exposed to a risk source, then a big explosion will result in little damage. The explosion will still be considered high in loss potential. The damage $\tilde{D}(x,y)$ at point $(x,y) \in S_A$ in the presence of loss potential $\tilde{L}(x,y)$ at the same point is :

$$\tilde{D}(x,y) = \tilde{L}(x,y) \cdot v(A) \cdot p_d(A)$$

ATTENUATION FACTOR : $\alpha_s(x,y)$ such that $\tilde{L}(x,y) = \alpha_s(x,y) \cdot \tilde{L}_s$

The ratio of damage at a point away from the source, to the damage that the same catastrophic event would afflict if the point were adjacent to the source. Attenuation is typically a ratio lower than one, hence the name. It maybe the case, however, that the attenuation ratio is greater than one[5] (e.g. when there is flammable material between the point and the risk source where a fire occurs).

BENCHMARK DAMAGE LEVEL: D_{BL} for simplicity D

We focus on risk of serious and catastrophic events resulting in damages exceeding the quarterly revenues of a plant or in severe injuries requiring hospitalization. Regulatory agencies (e.g. OSHA, US DOT OPS) have precise definitions for reportable incidents. The extent of damages in these definitions offer useful suggestions for the selection of D_{BL}. Each D_{BL} defines one Risk Map, according to our previous definition. Generation of Risk Maps for multiple damage levels provides a better understanding of the risk picture for the purposes of both risk reduction policy selection and model sensitivity analysis.

Calculation of Risk Map due to Point Risk Sources

Let the set of point risk sources be: $NPS \subseteq NS$. Each point source $s \in NPS$ is positioned at a point (x_S, y_S). The operation of s results in loss potential $\tilde{L}_S$. Where $\Pr(\tilde{L}_S \geq L)$ is known. L is measured in different units depending on the type of loss considered. For example, in the risk analysis of explosions a usual indicator of loss potential is blast overpressure, measured in $pa\ (\equiv {}^{Newton}\!/_{meter^2})$. If the overpressure is known, empirical tables can give estimates of damages to exposed people and property. Another example of a

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[5] In this case snowballing effects should be expected.

loss potential indicator is heat flux, measured in $\frac{Joules}{meter^2}$. Heat flux is used in the risk analysis of fire hazards.

Note that if L_{cat} is a value of loss potential high enough to cause catastrophic damage, then the following needs to hold for s to be accepted in a populated region:

$$0 < \Pr(\tilde{L}_s \geq L_{cat}) \cong 0$$

That is the non zero risk of catastrophic events must approach zero. How near to zero the risk will be is determined by cost benefit studies, yet catastrophic events have to be low probability events in the context of our analysis.

$\tilde{L}_s = \tilde{L}_s(\vec{d}, E_s, Q)$ depends on a vector $\vec{d}$ of design parameters, on causes internal to source s, and on external events. The design parameters affect the initial configuration of the risk source and its operations, but can only partially control it.

In the literature of risk analysis the rules describing the attenuation of loss potential are of the form:

$$L_p = \frac{L_s}{(1+r)^u}$$

where r is the Euclidean distance between point (x, y) and the source s:

$$r = \left((x - x_s)^2 + (y - y_s)^2\right)^{1/2}$$

and $L(x,y)$ (or equivalently L_p) is the attenuated loss potential from s at point $p \equiv (x,y)$, when s is the only risk source considered.

These rules are local in nature. That is, they describe attenuation close to the source. We haven't seen any models predicting losses away from the source, presumably because these losses are typically very small and unpredictable. We propose the following rule, which helps calculations and follows the previous rule closely for small r.

$$L_p = L_s \cdot e^{-ru}$$

When the vector $\bar{r}$ which starts at (x_s, y_s) and ends at (x,y) traverses through subregions with different u factor, the average $\bar{u}$ is substituted in the previous formula.

It is important for certain risks (e.g. fire) to consider the effect of local meteorological conditions. By orienting the coordinate system so that the X axis points to the direction of the prevailing wind, the following cosine rule can be used:

$$L_p = f_w \cdot L_s$$

with:

$$f_w(\theta) = b + w \cdot \sin(\theta) \quad , \quad \theta = \arctan\left(\frac{x - x_s}{y - y_s}\right)$$

where b is a base value (usually equal to 1) and w is a factor proportional to the windiness of the region.

We may also write:

$$L_p = f_w(\theta) \cdot e^{-r \cdot u} \cdot L_s = f(\theta, r) \cdot L_s$$

by writing θ and r in terms of x, y we get the following:

$$f_a(x, y) = \left(b + w \cdot \frac{x - x_i}{\left((x - x_s)^2 + (y - y_s)^2 \right)^{1/2}} \right) \cdot e^{-\left((x - x_s)^2 + (y - y_s)^2 \right)^{1/2} \cdot \bar{u}}$$

Risk at a Point

By summing up all effects and considering all sources we obtain the damages at a point (x, y) given an instance of the $\{\tilde{L}_s | s \in NPS\}$: $\{L_s^t | s \in NPS\}$

$$D^t(x, y) = v_c \cdot d_l \cdot \left(\sum_{s \in NPS} f_w(\theta_i) \cdot e^{-r_i \cdot \bar{u}_i} \cdot L_s^t \right) \tag{3.1}$$

or

$$D^t(x, y) = \sum_{s \in NPS} \alpha_i(x, y) \cdot L_s^t$$

with

$$\Pr(\tilde{D} \geq D) = \Pr\left(\sum_{s \in NPS} \alpha_s(x, y) \cdot \tilde{L}_s \geq D \right) \tag{3.2}$$

or

$$
\begin{aligned}
\Pr(\tilde{D} \geq D) = {} & \sum_{s \in NPS} \Pr\left(\alpha_s(x,y) \cdot \tilde{L}_s \geq D \middle| \tilde{L}_{s'} = 0 \ \forall s' \neq s\right) \\
& + \sum_{s \in NPS} \ \sum_{s' \in NPS \setminus \{s\}} \Pr\left(\alpha_s(x,y) \cdot \tilde{L}_s + \alpha_{s'}(x,y) \cdot \tilde{L}_{s'} \geq D \middle| \begin{array}{l} \alpha_s(x,y) \cdot \tilde{L}_s < 0 \\ \alpha_{s'}(x,y) \cdot \tilde{L}_{s'} < 0 \\ \tilde{L}_{s''} = 0 \ \forall s'' \in NPS \setminus \{s, s'\} \end{array} \right) \\
& + \cdots
\end{aligned}
\tag{3.3}
$$

That is the probability of exceeding the damage level D at a point is equal to the probability of a single source causing this to happen, plus the probability of a combination of two sources causing damages of level D or higher, plus the effect of the combination of tree sources and so on.

Independent Risk Sources

When the risk sources operate independently, that is when the causes of catastrophic events are the internal to each source s only (E_s), it is reasonable to assume that the probabilities of two or more accidents occurring simultaneously is very low. Therefore second order terms in equation (3.3) may be ignored, obtaining the following[6]:

$$
\Pr(\tilde{D} \geq D) = \sum_{s \in NPS} \Pr\left(\tilde{L}_s \geq {}^{D}\!/_{\alpha_s}\right) \tag{3.4}
$$

---

[6] Note that: $\alpha_s(x,y) \geq 0$

Equation (3.4) doesn't hold if loss potential at one risk source can excite catastrophic events at a nearby risk source. In the latter case, an analysis similar to the one proposed in the following for dependence of all sources simultaneously needs to be considered.

Dependent Risk Sources

When a catastrophic event excites all sources simultaneously[7], then the independence assumption seizes to hold. No appropriate simplification has been found for the calculation of risk maps in the case of natural disasters. The probability in equation (3.3) cannot be produced in closed form.

The general effect of an external event Q is captured by the following equation:

$$\Pr\left(\tilde{D} \geq D\right) = \Pr\left(\tilde{D} \geq D \middle| Q\right) \cdot \Pr\left(Q\right) \tag{3.5}$$

Whether $\Pr\left(Q\right)$ is known or not, the interesting part in equation (3.5), as far as regional risk distribution is concerned, is $\Pr\left(\tilde{D} \geq D \middle| Q\right)$. We propose two ways of estimating the conditional risk maps using Monte Carlo simulation: a hit or miss method and a variance reduction technique using control variates.

---

[7] Dependence of all risk sources simultaneously may be viewed as the opposite extreme of source independence. There is plenty of room for cases occupying the space in between. These cases would require concrete and detailed assumptions about source dependence and are beyond the scope of the general model developed here.

Hit or Miss Method

Consider the estimator of $\Pr\left(\widetilde{D}(x,y) \geq D \mid Q\right)$:

$$\hat{y} = \frac{\sum_{t=1}^{n} y_t}{n} \qquad \text{with}$$

$$y_t = 1\{ \sum_{s \in NPS} a_s \cdot L_s^t \geq D\}$$

where $\{L_s^t\}$ is a realization of the system of risk sources given an external event Q, with generating law for each source s known and equal to : $\Pr\left(\widetilde{L}_s \mid Q\right)$. Each L_s^t is obtained from a random number generator for the purposes of simulation. Note that the members of $\{\widetilde{L}_s\}$ are mutually independent with respect to s and t.

This estimator is unbiased:

$$E(\hat{y}) = \Pr\left(\widetilde{D} \geq D \mid Q\right)$$

Its variance depends on *n*. To obtain high accuracy estimates in our computer using this estimator, a number n of the order of one million experiments are needed. In general, about $|NPS| \cdot n \cdot R_x \cdot R_y$ random numbers need to be generated (where $R_x \cdot R_y$ is the grid size). This is not practical, so we employee one of the usual variance reduction techniques in Monte Carlo simulation.

Control Variate Method

Consider now an alternative estimator of $\Pr\left(\widetilde{D}(x,y) \geq D \middle| Q\right)$:

$$\hat{y}^c = \frac{\sum_{t=1}^{n} y_t^c}{n_c} \quad \text{with}$$

$$y_t^c = 1\left\{ \sum_{s \in NPS} a_s \cdot L_s^t \geq D \right\} - \sum_{s \in NPS} 1\left\{ a_s \cdot L_s^t \geq D \right\}$$

The expectation of $\hat{y}^c$ is given as follows:

$$\mathrm{E}\left(\hat{y}^c\right) = \Pr\left(\widetilde{D} \geq D \middle| Q\right) - \sum_{s \in NPS} \Pr\left(\widetilde{L}_s \geq {}^{D}\!/_{\alpha_s} \middle| Q\right)$$

This estimator is biased, but the bias is known. By repeating the experiment n_c times we get an estimator with low variance, much lower than the one the hit or miss method produces. To establish this, we introduce some extra notation:

- $1_s = 1\{\alpha_s \cdot L_s^t \geq D\}$
- $1_\Sigma = 1\{\sum_{s \in NPS} \alpha_s \cdot L_s^t \geq D\}$
- $p_s = \Pr(\alpha_s \cdot L_s \geq D | Q)$
- $p_\Sigma = \Pr(\sum_{s \in NPS} \alpha_s \cdot L_s \geq D | Q)$

The variance of $\hat{y}^c$ is given as follows:

$$E^2\left(\hat{y}^c - E\left(\hat{y}^c\right)\right) = \left[\frac{E\left(\sum_{t=1}^{n_c}\left(y_t - E(y_t)\right)^2\right)}{n_c^2}\right] = \frac{E^2\left(\hat{y}_t^c - E\left(\hat{y}_t^c\right)\right)}{n_c}$$

but

$$E^2\left(\hat{y}_t^c - E\left(\hat{y}_t^c\right)\right) = E^2\left[\left(1_\Sigma - p_\Sigma\right) - \sum\left(1_s - p_s\right)\right]$$

$$= E\left[\left(1_\Sigma - p_\Sigma\right)^2 + \left(\sum\left(1_s - p_s\right)\right)^2 - 2\cdot\left(1_\Sigma - p_\Sigma\right)\cdot\sum\left(1_s - p_s\right)\right]$$

$$= Var\left(1_\Sigma\right) + \sum Var\left(1_s\right) - 2\cdot\left[\sum E\left(1_\Sigma \cdot 1_s\right) - p_\Sigma \cdot \sum E\left(1_s\right) - \sum p_s \cdot E\left(1_\Sigma - p_\Sigma\right)\right]$$

and

$$E\left(1_\Sigma \cdot 1_s\right) = E\left(1_s\right) \quad \text{and} \quad E\left(1_\Sigma - p_\Sigma\right) = 0$$

hence

$$Var\left(y_t^c\right) = Var\left(1_\Sigma\right) + \sum Var\left(1_s\right) - 2\cdot\left[\sum E\left(1_s\right) - p_\Sigma \cdot \sum E\left(1_s\right)\right]$$

$$= Var\left(1_\Sigma\right) + \sum p_s \cdot \left(1 - p_s\right) - 2\cdot\sum p_s \cdot \left(1 - p_\Sigma\right)$$

$$= Var\left(1_\Sigma\right) - \sum p_s \cdot \left(1 + p_s - 2\cdot p_\Sigma\right)$$

Note that: $p_\Sigma << 1$

and for the Hit or Miss method:

$$Var(y_t) = Var(1_\Sigma)$$

Therefore the following is obtained:

$$Var(y^c) \le Var(y)$$

The final expression for the risk estimate at a point is:

$$\hat{\Pr}(\tilde{D} \ge D | Q) = \frac{\sum_{t=1}^{n_c} y_t^c}{n_c} + \sum_{s \in NPS} \Pr\left(\tilde{L}_s \ge D/a_s | Q\right) \tag{3.6}$$

Lower variance gives lower sample size n_c. In our computer simulation we got good results with only a 1000 system realizations.

Calculation of Risk Map for Line Risk Sources

Consider a line risk source $s \in NLS$, where NLS is the set of line risk sources. The following extensions to our previous definitions are needed to fully describe line sources:

LOCUS OF s : $X_s \equiv \{\vec{x}(\lambda) = \lambda \cdot \vec{x}_s^b + (1-\lambda) \cdot \vec{x}_s^e | 0 \le \lambda \le 1\}$

The set of points in the linear segment beginning at $\vec{x}_s^b$ and ending at $\vec{x}_s^e$, where the line risk source lies.

LOSS POTENTIAL : $\widetilde{L}_s(\lambda)$

The loss potential at position λ within the locus of source s, with $\Pr\left(\widetilde{L}_s(\lambda) \geq L\right)$ known.

We view $\widetilde{L}_s(\lambda)$ as the effect of two independent processes, one determining where within X_s a catastrophic event takes place, and another determining the extent of loss potential after the occurrence of the previous event. So we accept:

$\Pr\left(\widetilde{L}_s(\lambda) \geq L\right) = f(\lambda) \cdot \Pr\left(\widetilde{L}_s \geq L\right)$ where $f(\lambda)$ is a *pdf.*

When the independence assumption holds the risk measure at a point *(x,y)* due to the line source s becomes:

$$\Pr\left(\alpha(\lambda; x, y) \cdot \widetilde{L}_s(\lambda) \geq D\right) = \int_{X_s} \Pr\left(\widetilde{L}_s \geq {}^{D}\!/\!{}_{\alpha(\lambda; x, y)}\right) \cdot f(\lambda) \cdot d\lambda$$

In order to extend our previous results for point sources to line sources we introduce the concept of effective attenuation $\alpha_s^{eff}(x,y)$ from the line source s to the point *(x,y)*, as the unique[8] solution to the following equation:

$$\Pr\left(\alpha_s^{eff} \cdot \tilde{L}_s \geq D\right) = \int_{X_s} \Pr\left(\tilde{L}_s \geq D / \alpha(\lambda; x, y)\right) \cdot f(\lambda) \cdot d\lambda \qquad (3.7)$$

Now equation (3.4) can be extended from the set of point risk sources *NPS* to *NS=NPS+NLS*.

When $f(\lambda)$ is the uniform pdf, $\alpha_s^{eff}(x,y)$ exhibits a regularity away from the end points of X_S. This makes the calculation of the risk map easy for line sources. For a number of risk sources this assumption appears to be very reasonable. A notable example is transportation pipelines. In our work with distribution pipelines we have discovered that risk control parameters and population density varies widely along the pipeline axis. Therefore approximation of the pipeline segments as series of point risk sources is very satisfactory for course grids. In the next we develop an illustrative example that includes point sources only.

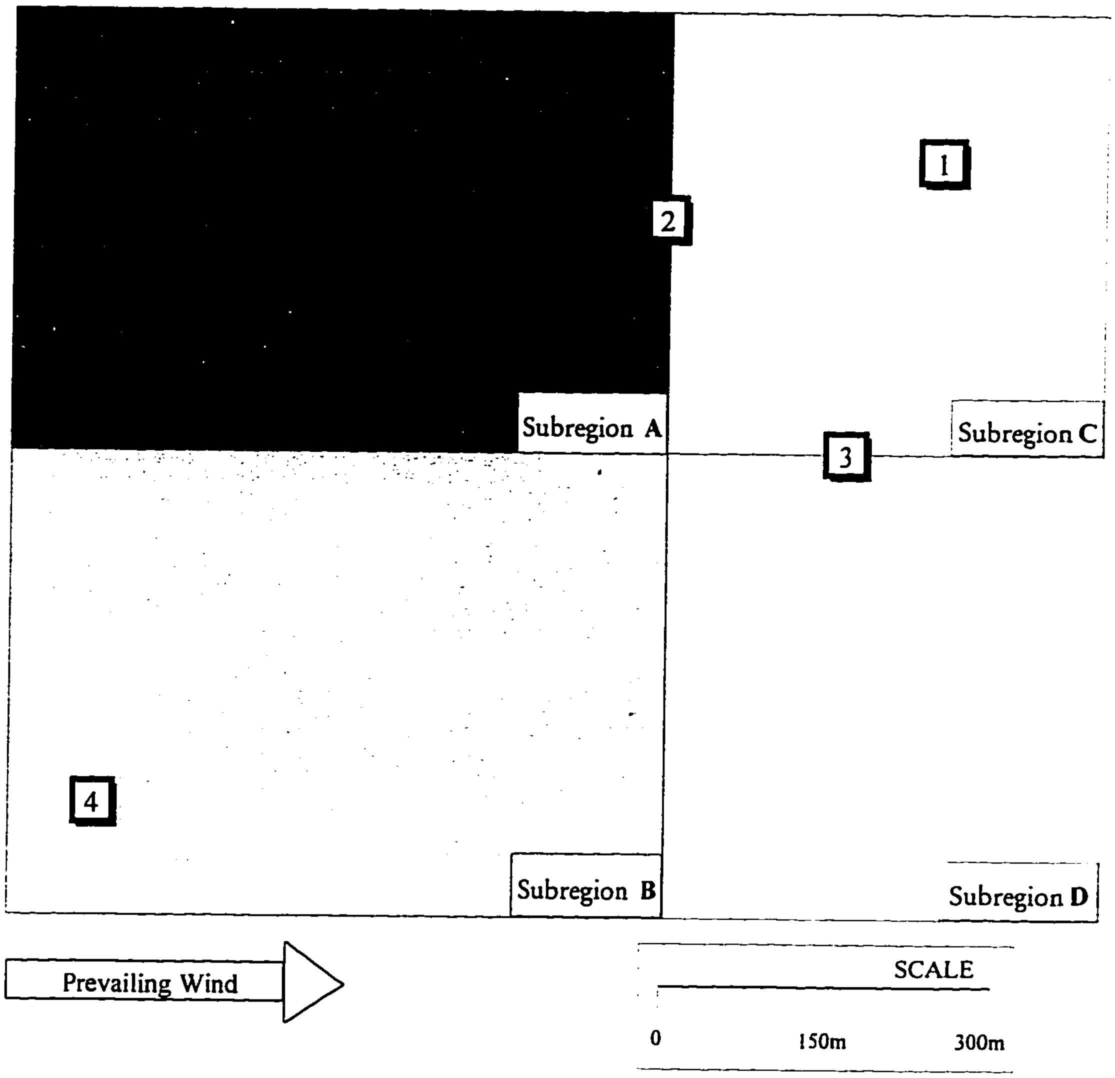
---

[8] Additional assumptions are needed to ensure existence and uniqueness of a solution to equation (3.7). Elaboration on these assumptions lies outside the scope of our study.

Illustrative example

We illustrate the concepts presented previously using a prototype region (see Figure 3.1) with four point risk sources. This 800 meter by 800 meter region is comprised of four subregions. Point properties differ between subregions. The prevailing wind is westerly , that is it points at the X direction in our maps.

In general, risk sources have different risk profiles, even though each individual probability mass function (pmf) for loss potential looks essentially the same as the pmf of source 4 on Figure 3.2. Loss potential is measured in relation to a known maximum value. This value may be the historical maximum for loss potential of similar risk sources, or it may be the estimate of an engineering analysis of the individual risk source. The chosen pmf for the simulation assumes high probability of zero losses under normal operation (90% for damage level of 0% and 99% for damage level of 10% or lower). During natural disasters the probability of zero loss becomes 60%. It should be noted that strong dependence of risk sources would require very low probabilities of zero loss during natural disasters (close to 0%), but this is unrealistic for the type of industrial facilities we consider.



Dimensions	800m x 800m
4 Point Sources	No1,No 2,No 3,No 4
Prevalent Wind	Westerly

Figure 3.1: Model Region

To experiment with the prototype region, we introduced for the purposes of simulation the hazard multiplier $h(s)$, acting on the loss potential of source s. A risk source having a hazard multiplier of 2 is roughly twice as hazardous as one having a unit hazard multiplier. The hazard multipliers are depicted in the box showing the position of the risk sources, for all risk contour plots (Figures 3.3, 3.4, and 3.5).

Damage Level	Independent Risk Sources	Dependent Risk Sources
0%	0.9	0.6
10%	0.09	0.1
50%	0.005	0.11
70%	0.003	0.08
80%	0.001	0.001
85%	0.0005	0.1005
95%	0.0004	0.0004
100%	0.0001	0.0081

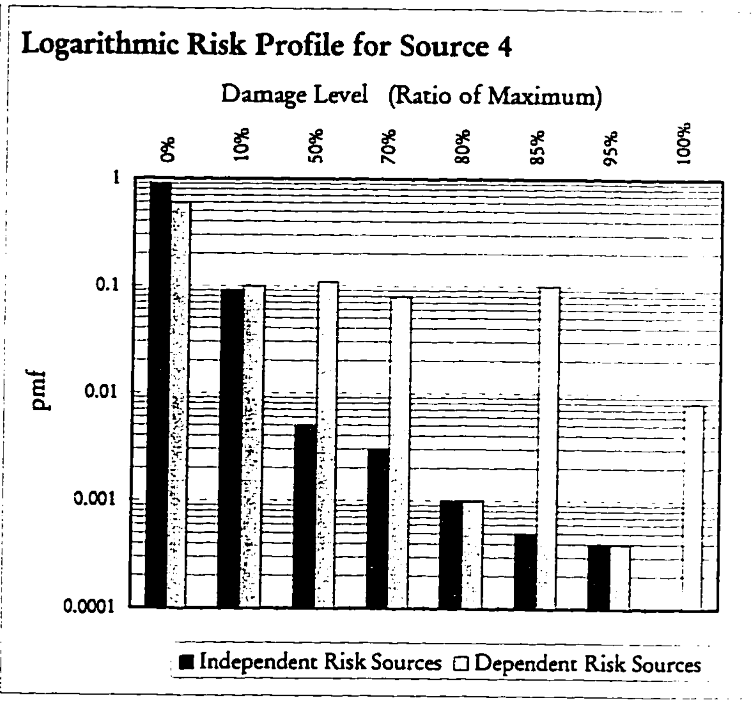


Figure 3.2: Risk profile for risk source 4 in logarithmic scale as used in the simulation. This profile is representative of values used in simulation for other sources. The probability of losses of magnitude equal to 85% of the maximum loss is 0.05% (pmf=.0005) for independent sources and 10.05% (pmf=.1005) for dependent sources.

We have used two types of representation for a risk map. One is a surface of the risk measure $\left(\tilde{D}(x,y) \geq D_{BL}\right)$ at each point in the region, so that the higher the elevation of the surface from the base, the higher is the expected frequency of damages greater than the benchmark level (Figures 3.6 and 3.7). The other is a contour plot of the risk map, where successive frequency levels of the risk measure are plotted on a two dimensional plot. The contour plots can be integrated with regional information (e.g. annotation of region boundaries and properties, risk source positions and hazard multipliers) without loss of clarity in representation (Figures 3.3, 3.4, and 3.5). This raises their value as platforms for risk management decisions.

All risk maps are normalized, so that the average frequency of the risk measure in the region is given a value of 1000. A value on the risk map of 500 indicates an expected frequency of the risk measure half that of the average frequency. This way generic programs for 3D representation of data may be used (like MATHCAD), thus avoiding the use of expensive specialized plot generators. In addition, the risk maps have been smoothed. This makes them clearer at the cost of two drawbacks: edge effects at the border of the region (changes to zero level are in reality abrupt and not smooth), and unrealistic smoothness between subregions (changes in values between subregions are discrete and thus changes in risk measures should be discontinuous at subregion borders). As can be seen in Figure 3.3, for example, the two latter effects do not cause significant distortions to the risk map.

Figure 3.3 is the risk contour map for independent risk sources. The isolated risk source (1) has a small impact on the region despite the relatively high hazard multiplier (h(1)=.2). This is attributed to the low exposed value and high attenuation factor at subregion B (v(B)=30, u(B)=0.008).

Figure 3.4 presents the risk contour map for dependent risk sources. The inputs are indicated in the risk map and they are different from the ones in Figure 3.3. Figure 3.4 should be contrasted to Figure 3.5 depicting the simulation result with the same input values calculated as if the risk sources were independent. It becomes clear that the area impacted by dependent risk sources is relatively larger. The areas of influence for each individual source are less clear when the risk sources are dependent.

Figures 3.6 and 3.7 depict surface plots of the same risk maps. Three dimensional views make obvious the following observations. First, the isolated risk source has the same risk map in its neighborhood, which is unaffected by independence assumptions. And second, due to the nonlinear nature of the attenuation law the sphere of influence of each risk sources forms domes with fairly distinct boundaries. This is very important information in the calculation of transboundary[9] risk [Kunreuther, 1993].

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[9] Transboundary risk is the risk burdening a community neighboring the one hosting a risk source (noxious facility). If the sphere of influence of the risk source is wholly within host neighborhood limits then benefits from possible compensation packages for siting may be negotiated at the neighborhood level. If not, negotiations should take place at the regional level.

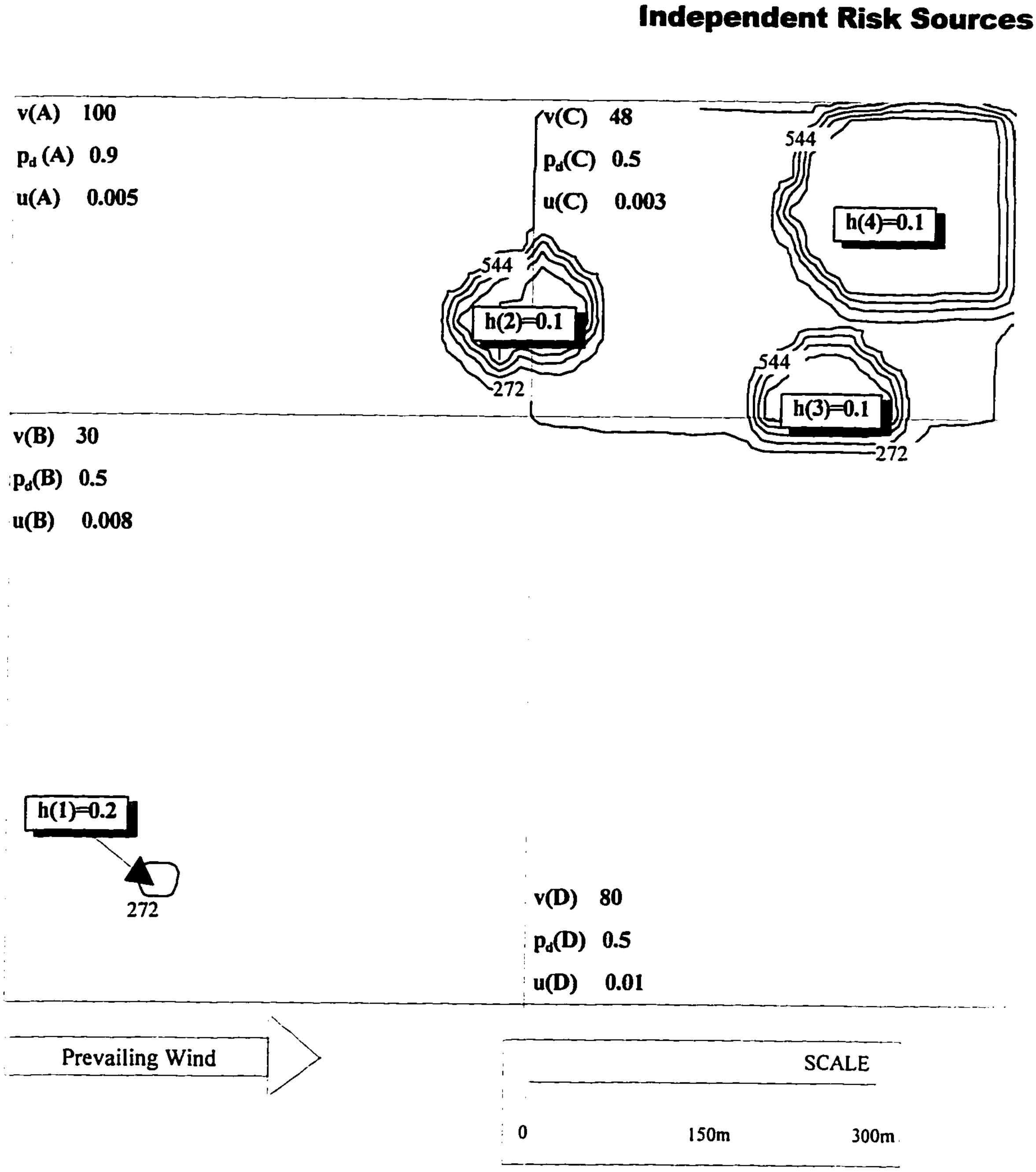


Figure 3.3: Risk Contour Map for Independent Sources.

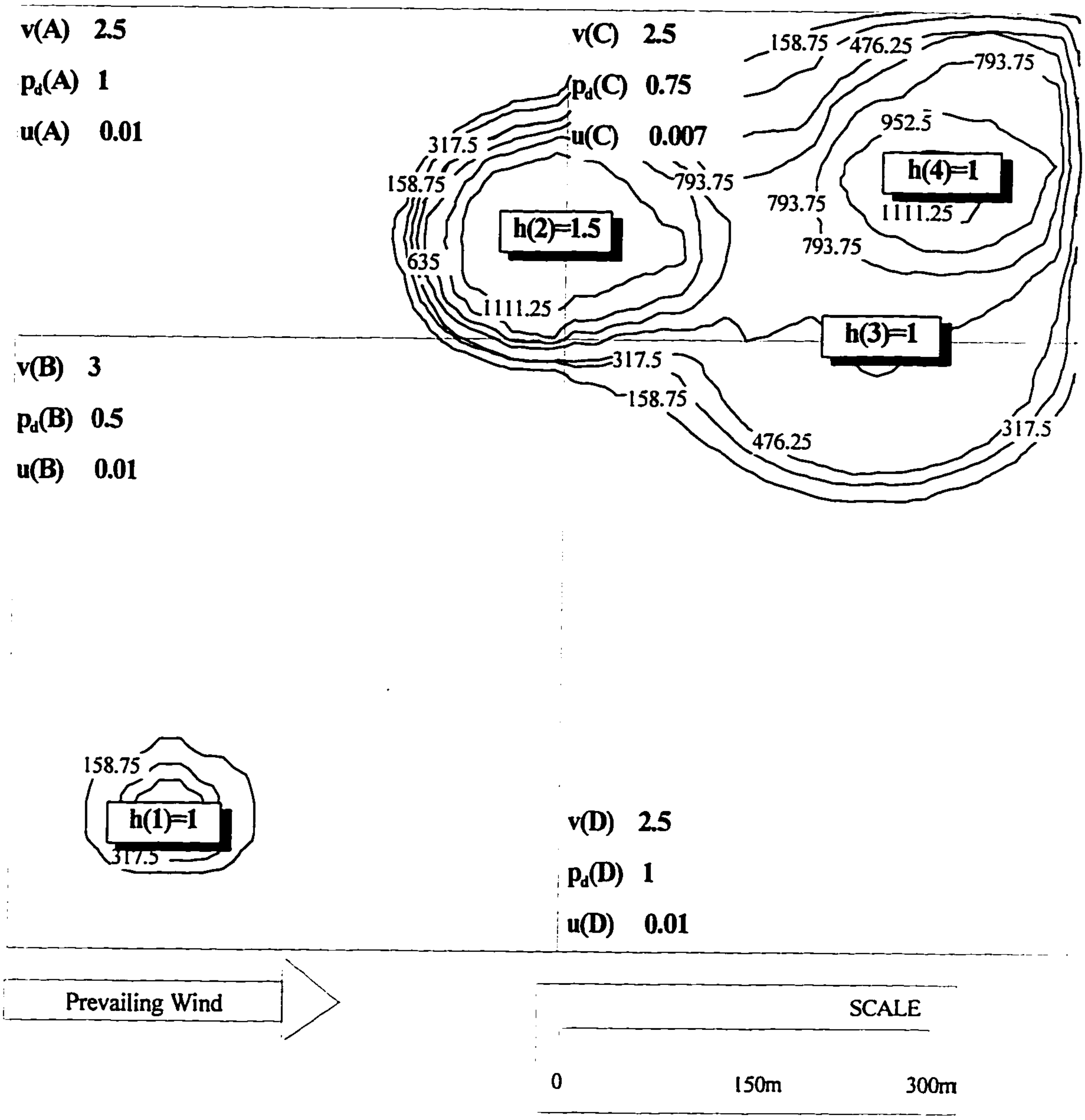


Figure 3.4: Risk Contour Map for Dependent Sources.

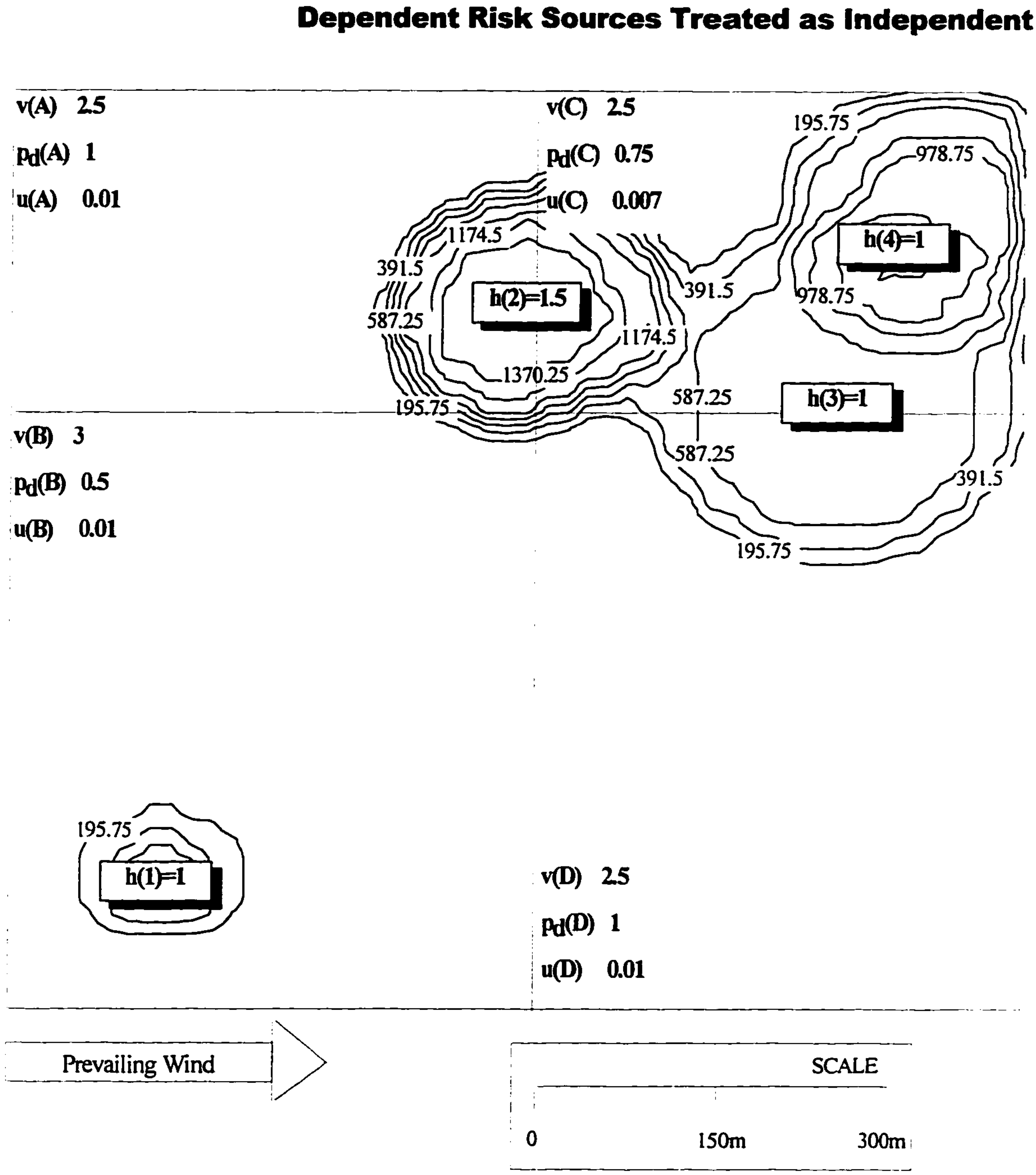


Figure 3.5: Risk Contour Map for Dependent Sources when they are treated as Independent for simulation purposes.

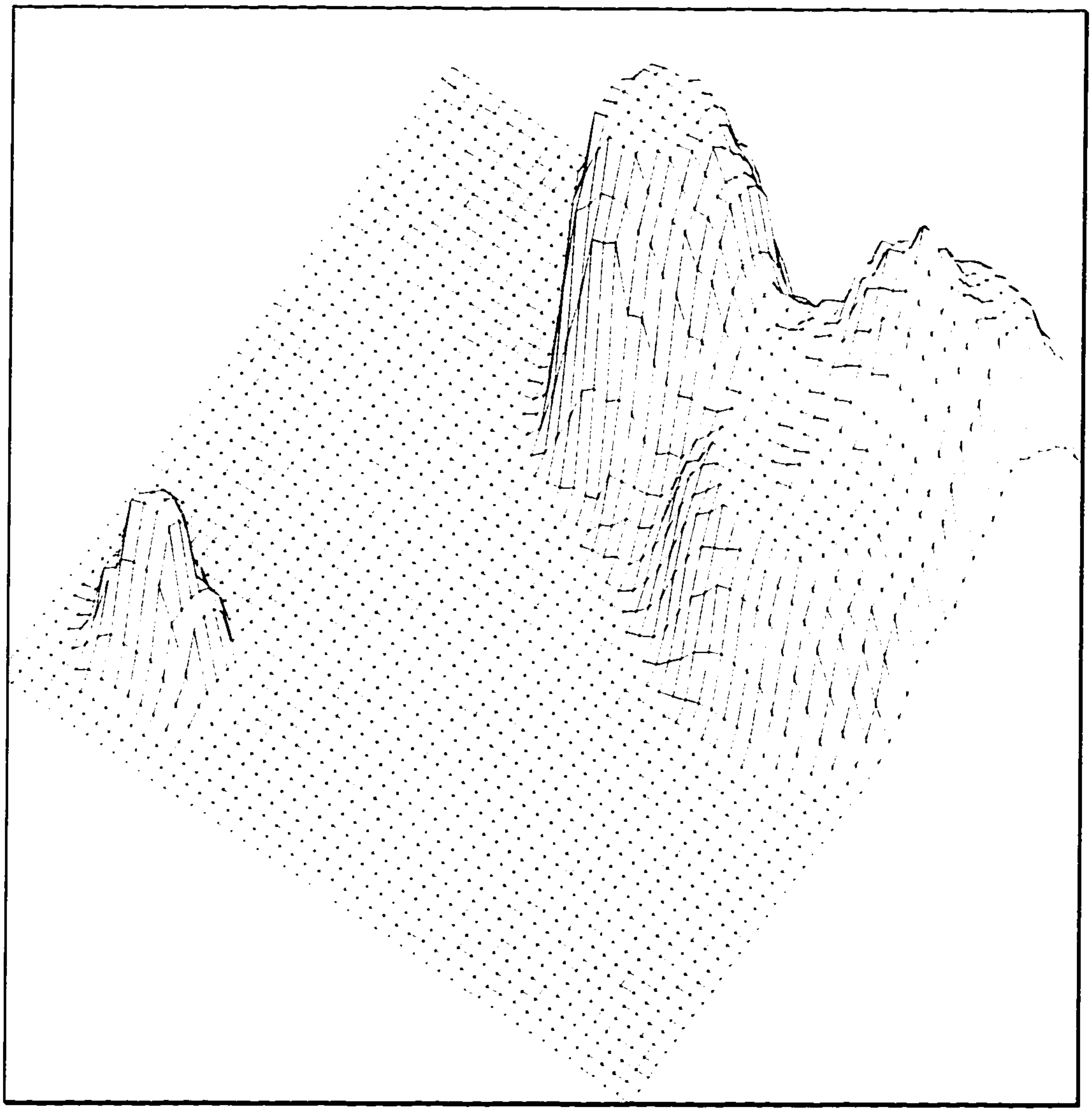
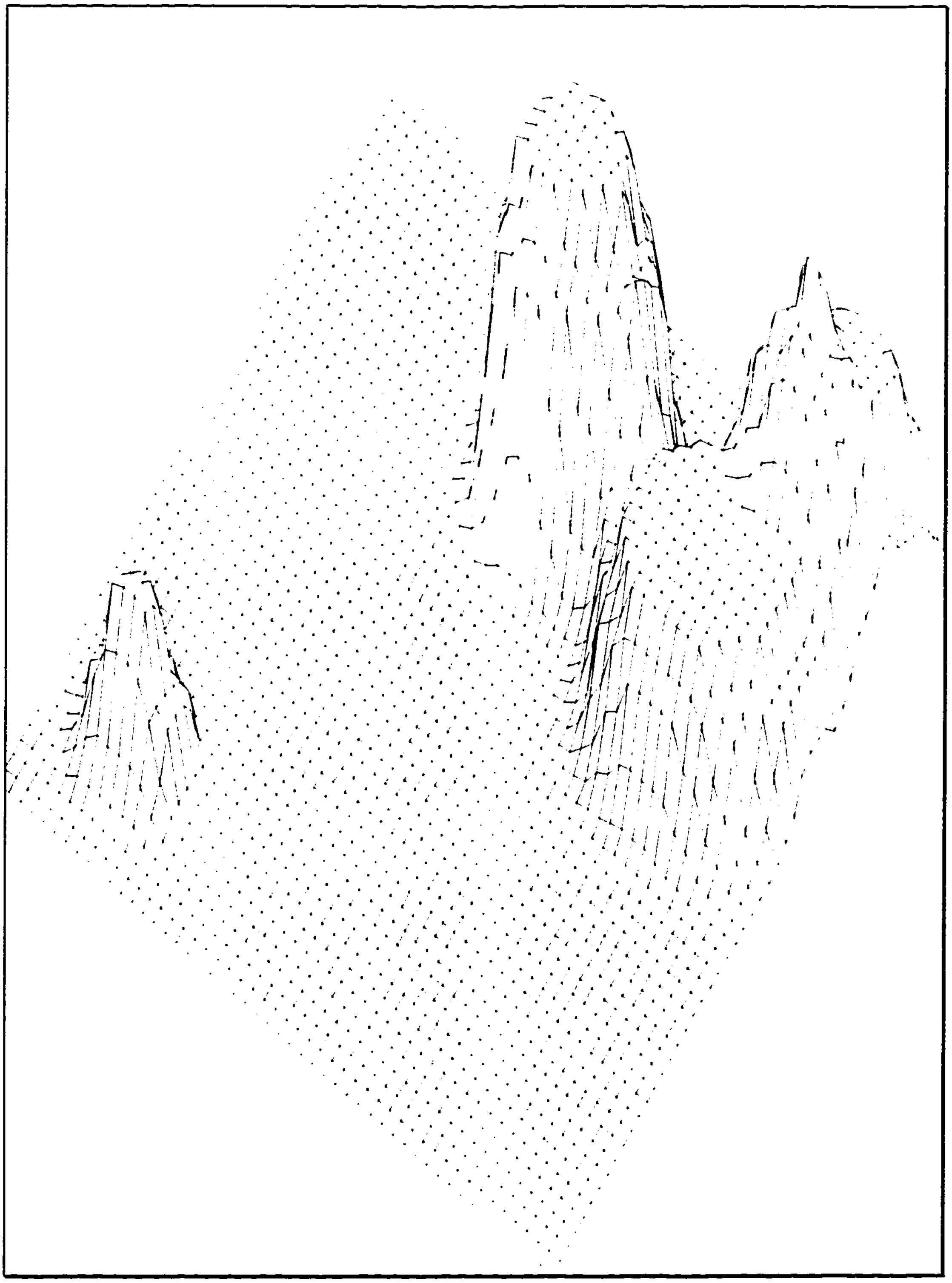


Figure CHAPTER 3 : .6: Surface plot of the risk map when the risk sources are dependent. The map has been rotated to show details, subregion B is at the front left and

Dependent Risk Sources Treated as Independent



This example makes clear that risk maps can be generated using computer simulation even when the risk sources are dependent. The risk contour maps appear to be better platforms for risk management decision support systems, because regional information is easier to be included with the risk map as an additional map layer. Surface plots appear to be better suited to analysts interested in developing insights in the spatial distribution of risk. They are difficult to be understood by the untrained eye. For instance, finding the best perspective view for the examples in Figures 3.6 and 3.7, required significant time and number of trials. The program in (C-code) used to calculate the risk maps in Figures 3.3 to 3.7 appears in the Appendix.

CHAPTER 4 : OPTIMAL NETWORK MAINTENANCE RECOGNIZING COST STRUCTURE NONLINEARITIES

We consider the problem of preventively maintaining a network of pipelines carrying a hazardous gas (or liquid). Probable extensions of this work maybe sought in areas, like the maintenance of surface transportation networks or the general problem of risk management for hazardous material transportation. We propose a normative risk management model for nonlinear maintenance cost structures.

Each pipeline segment *s* in the network may lose containment of the hazardous gas causing annuitized losses $\tilde{l}_s$ with known probability distribution $P(\tilde{l}_s \leq L)$ and overall risk $r_s = E(\tilde{l}_s)$[10]. The losses will become liabilities to the owner of the pipeline network under a strict liability framework. At an annual equivalent cost c_s the pipeline segment *s* may be replaced eliminating the risk r_s (see, e.g. [Wilson, 1990] for currently used analysis of natural gas pipeline maintenance decisions). The following plausible maintenance cost structure is examined:

$$tc_s = c_s + F_{s|t}$$

---

[10] r_s maybe viewed alternatively as the excess risk over a base case r_0 (e.g. excess risk of worn pipe versus a new pipe or of cast iron versus plastic).

Thus, the total cost of replacing the segment s equals the direct pipe replacement cost c_S together with a fixed cost of positioning a crew and equipment at the location of s from a home position or from a nearby location. If any segment t contiguous to s is also to be replaced, then no new repositioning costs are required. If a crew is working at a segment located two or more blocks (segments) from s, then a smaller repositioning cost is required. If the distance between s and the previous position of a crew is longer than a certain number of blocks, repositioning costs exceed moving the crew from home position, so transferring the crew directly from home position would be preferred. Crew positioning costs may be generalized to include less tangible costs, like the nuisance from disrupting road traffic or the extra cost of redirecting flow of gas in order to preserve continuity of service.

We formulate the problem of optimally maintaining the whole network as a mathematical network problem. The formulation of this problem is designed to be as general as possible, so that other important risk management problems related to it, like the maintenance portfolio selection problem (determining priorities among prevention, response and maintenance process improvement programs) or the distribution of risk burden problem, can all be solved using the tools developed here. Observe that more complicated objective functions than the one utilized here may be optimized fairly easily, after the fundamental problem we are discussing here is solved.

In the following, we describe the model we use in our analysis in terms of the physical, risk and cost properties it encapsulates. The problem of maximizing the overall net benefit of replacing deteriorated segments is formulated and solved. In the subsequent section we formulate and solve the same problem in the presence of a budget constraint. The proposed solution procedure follows a Lagrangean Relaxation approach. The procedure is applied to a model region, in order to illustrate the performance of the proposed approach. The cost of pipe replacement and the risk data for the model region bare a close relationship to real data for the cast iron pipe network of a Gas Utility in a major U.S. city. We include in the Appendix algorithms in pseudocode for nonstandard subtasks in the solution procedure, so that the computational time calculations become more concrete.

The Model

We begin with a network similar in form to a physical pipeline network, then by two transformations we obtain another network mathematically equivalent to the original. This latter network is amenable to a combinatorial optimization algorithm [Edmonds, 1967] that produces a list of pipe segments to be replaced, so that the replacements result in the maximum net benefit. The first transformation joins contiguous segments with positive net benefit of replacement without consideration to repositioning costs. The joined segments form sites where crews originating from a home position or transferred from nearby will perform maintenance work. The second transformation produces the network of crew positioning costs from the origin and from one site to another.

After the two transformations above, a directed network can be formed on which one can operate using Edmonds' Optimum Branching Algorithm. A directed arc in the optimum branching points to a site to be maintained, the source of which indicates the point a maintenance crew would be transferred from. Each arc has a weight equal to the benefit of replacing the site pointed to, net of direct maintenance costs and repositioning costs. A branching has two properties. The arcs it is constituted from form a tree, and no arc points to the same node (site). In addition, the origin of the branching (the one node with zero in-degree) is a home position (i.e. basis of operations for maintenance crews). The optimum branching is the branching maximizing the overall net benefit of replacement. Arcs with negative weight are not permitted, so the branching doesn't span all possible nodes (sites).

In the presence of a budget constraint all maintenance work with positive net benefit may not be possible. This second problem is again solved using Edmonds' algorithm after a Lagrangean Relaxation of the budget constraint. The optimal solution to the Lagrangean Relaxation Problem is augmented when appropriate using a heuristic to approach the unknown optimal solution to the primal problem.

The overall procedure can be implemented in polynomial time. Therefore, applying it on a computer with data from a typical gas distribution network[11] doesn't result in impractical run time requirements. It is demonstrated, that this method is far superior to alternative Integer Programming models with respect to computational complexity.

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[11] The number of pipeline segments (with length similar to a street block) may be in the order of hundreds of thousands for a large metropolitan area.

Definitions

Network Description

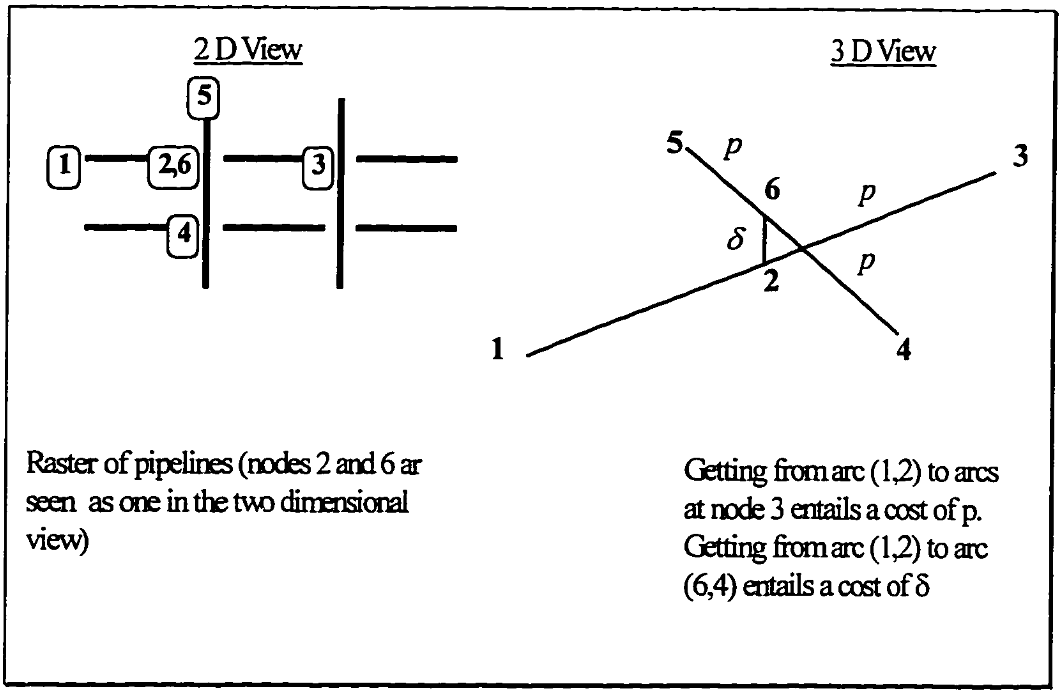
$s = (e,h)$	arc (segment) s connecting nodes e and h
$S \equiv \{s : s=1,2, .., I\}$	Set of all arcs (segments)
$V \equiv \{e : e=1,2,..,N\}$	Collection of nodes
$G \equiv \{S, V\}$	Network with arcs S and nodes V

Cost - Benefit Structure

r_s	risk value of segment s before replacement.
c_s	cost of replacing segment s
$b_s = r_s - c_s$ or b_{eh}	net benefit of replacing segment $s=(e,h)$
$F_e \geq 0$	cost of positioning a crew from the home position to node e
$p \geq 0$	cost of repositioning by one segment on the same line
$\delta \geq 0$	cost of repositioning to a new line at the same node

Consider the following transformation on network G:

- Contract all arcs with positive attribute b_S
- Record node indices in the resultant composite nodes



Raster of pipelines (nodes 2 and 6 ar seen as one in the two dimensional view)

Getting from arc (1,2) to arcs at node 3 entails a cost of p. Getting from arc (1,2) to arc (6,4) entails a cost of δ

Figure 4.1: Repositioning costs in a two dimensional and a three dimensional view

A composite node m in the set of composite nodes V_m will have the following properties:

N_m is the set of nodes in G covered by node m, i.e.

$N_m \equiv \{e,h \mid (e,h) \in S \text{ and } b_{eh}>0;\ \text{if } (d,f) \in S \text{ with } b_{df}>0 \text{ and } \{e,h\} \cap \{d,f\} \neq \varnothing \text{ then } \{d,f\} \subseteq N_m\}$

$E_m \equiv \{(e,h) \mid e,h \in N_m;\ b_{eh}>0\}$ set of positive arcs covered by the composite node m

$A'_R \equiv \{s \in S \mid s \notin E_m\ \forall m \in V_m\}$ set of remaining arcs not contracted

The introduction of composite nodes necessitates renaming the nodes in V_R. Let $h{:}V \to V \cup V_m$ be a renaming function with the following property:

$$h(e) = \begin{cases} m \text{ if } \exists m : e \in N_m \\ e \text{ otherwise} \end{cases}$$

The resulting network after contraction $G_R \equiv \{A_R, V_R\}$ will be described as follows:

$$V_R \equiv V - \bigcup_{m} N_m + V_m = h(V)$$

$$A_R: \quad (d,e) \in A'_R \Rightarrow (h(d), h(e)) \in A_R$$

We can view a composite node as a site where replacement work can be performed on contiguous nodes in a way that no intermediate repositioning cost is necessary. Each composite node (site) can be visited by a crew located at the home (base of operations) or at a nearby node according to the aforementioned repositioning cost structure. In Figure 4.2, we show a map of a city neighborhood depicting the locations of natural gas pipelines in service. The segments with positive net benefit of replacement are highlighted. The encircled regions contain contiguous segments that form composite sites. This city neighborhood will be used throughout this paper to illustrate the various steps in the maintenance procedure we propose. For more information on the specifics of the neighborhood, refer to page 98.

The composite nodes have the following properties:

$F_m = \min\limits_{e \in N_m} F_i$	minimum crew positioning cost to m from origin
$T_m = \sum\limits_{e,h \in N_m} \max(b_{eh}, 0)$	total direct net benefit from replacing positive segments in m

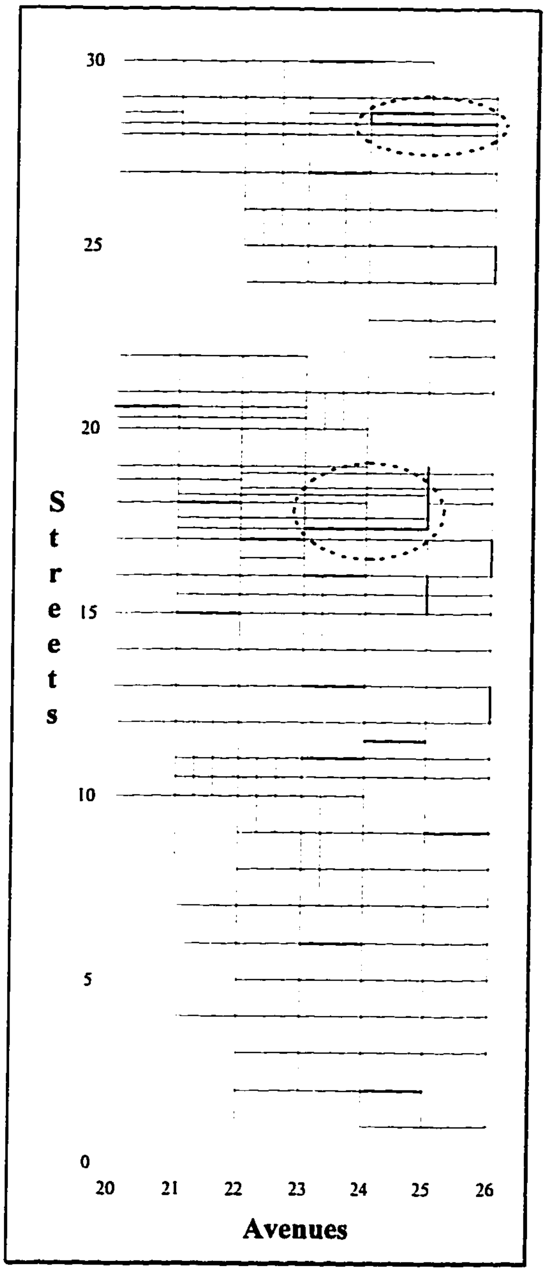


Figure 4.2: Contraction of arcs with positive net benefit of replacement into composite nodes. Encircled blocks form a composite node (site).

Let m, n be two composite nodes, a path P_{mn} between them is defined as:

$$P_{mn} \equiv \{(i_{k-1}, i_k) \in A_R | \exists K : i_0 = m, i_K = n, \{i_0, i_1, \cdots, i_K\} \subseteq V_R\}$$

The repositioning costs from composite node m to composite node n is given by:

$$F_{mn} = \begin{cases} F_n \quad if \quad m = 0 \\ \underset{P_{mn} \subseteq A_R}{MIN} \left(\sum_{s \in P_{mn}} L_s \right) \end{cases}$$

where L_s is the repositioning cost along an arc $s \in A_R$, taking values p or δ. Individual values may also be assigned to each segment s, a long as $L_s \geq 0$.

Note that if, for example, one of the E_m segments leaves composite node m, then the new set of repositioning costs $\{F'_{mn}\}$ will obey the following condition:

$$\forall mn \quad F'_{mn} \geq F_{mn}$$

that is crew positioning costs from both the origin and nearby nodes will either remain the same or increase, but never decrease.

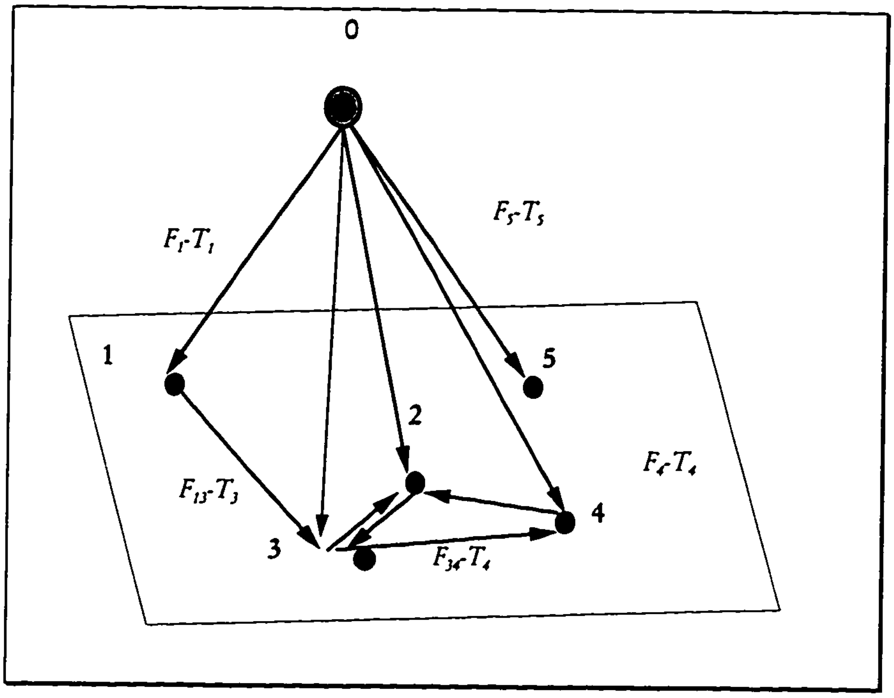


Figure 4.3: A Cost Network example: T_i *is the net benefit at composite node* ***i*** *;* F_{ij} *the crew positioning cost from* ***i*** *to* ***j****. Note that the origin* ***0*** *has an in-degree of zero and out-degree 5 (as many as the nodes on the plane).*

The interlink distances form the set $A_P \equiv \{(i,j) | F_{ij} \le F_{oj}\}$ which together with the node set V_P , comprised of all composite nodes together with the origin (named 0 without loss of generality), form a graph similar to the one in Figure 4.3. By giving to this graph arc properties, we form the directed network G_P:

$G_p \equiv \{V_p, A_p ; \{P_{ij}\}\}$

where:

$P_{ij}=F_{ij} - T_j$ with $i,j \in V_P$; $i \neq j$, $j \neq 0$

The same physical network may also be viewed as an undirected network having arc and node properties:

$G_F \equiv \{V_P, A_P; \{T_j\}, \{F_{ij}\}\}$ (note that: $F_{ij} = F_{ji}$)

Problem 1: The Unconstrained Problem

Consider the problem of minimizing the total net cost of replacing network segments with positive net benefit, including crew positioning costs.

$$\underset{A \subseteq A_p}{MIN}\ f(A) \quad ; \qquad f(A) = \sum_{(i,j)\in A} P_{ij}$$

or equivalently

$$f(A) = \sum_{(i,j)\in A} \left[\left(\sum_{s\in E_j} c_s + F_{ij} \right) - \sum_{s \in E_j} r_s \right]$$

such that

$$\forall i, j \in V_P \quad (i, j) \in A \quad \Rightarrow \quad \forall k \neq i \quad (k, j) \notin A \tag{4.1}$$

that is the in-degree of all nodes in the resulting network is less than two (i.e. each node is represented at most once in the resulting optimal network).

$$\forall \hat{A} \subseteq A \ |\{i,j|(i,j) \in \hat{A}\}| \ \leq |\hat{A}|+1 \tag{4.2}$$

That is the resulting arc set forms a tree. The following condition should also hold:

$$\forall (i,j) \in A \qquad P_{ij} \leq 0 \tag{4.3}$$

This Problem is the optimum branching problem described in [Edmonds, 1967]. Edmonds' algorithm is fairly easy to implement even though its analysis is fairly involved. Robert Tarjan [Tarjan, 1974] remarks: "it would be useful to find a "practical" application of this interesting but esoteric algorithm." It seems more likely now that other applications exist for Edmonds' Algorithm in the analysis of network industry operations.

Computational Requirements

The tasks that need to be performed, in order to complete the solution procedure for Problem 1, have the following requirements in computational time.

Contract Arcs of G with positive net benefit b_S

$O(|S| \cdot M)$ time is required for this task, where $|S|$ is the cardinality of set S and $M \; (= \max\limits_{m}(E_m))$ the cardinality of the composite node with the most elements (see Appendix :Algorithm for the contraction of arcs with positive net benefit in pseudocode).

Determine site interlinks F_{ij} *and then* P_{ij}

Note that G_R is an undirected network with positive costs. We will assume that a constrained version of the Dijkstra algorithm is used (for the original algorithm see for example [Lawler, 1976]). The constraint is:

$$F_{ij} < F_{0j} \quad \forall i \in V_m \, , \forall j \in V$$

i.e. repositioning from another site should not cost more than positioning a crew from home.

This way, determining optimal repositioning costs from one site to another is accomplished faster. Given the known crew positioning costs from home and the repositioning costs from one end of an arc to another, one can easily determine a radius R (maximum number of nodes) over which the search for possible interlinks will be constrained.

Completion time for this stage is $O(|V_m|\ R\ |V_R|)$ (see Appendix : Algorithm for the determination of site interlinks in pseudocode).

Solve for G^*_p

After constructing G_P from F_{ij}, B_j, T_j, V_m, solve for G^*_p using Edmonds Algorithm [Edmonds, 1967]. The complexity of the procedure at Stage 3 is $O((|V_P|+CR)\cdot|V_P|)$ [Tarjan, 1974]; where CR is the number of circles created during graph contraction, clearly $CR \leq |V_P|$.

Complexity of procedure for the solution of Problem 1

It is expected that in the usual case, the following is a reasonable assumption:

$$R \cdot |V_R| > |V_P| + CR \qquad \text{(normality condition 4.1)}$$

Hence, the complexity for the solution of Problem 1 is dominated by Stage 2. The solution of Problem 1 requires $O(|V_m|\ R\ |V_R|)$ time.

Contract arcs with positive net benefit	$O(\|S\|\cdot M)$
Determine site interlinks	$O(\|V_m\| R \|V_R\|)$
Solve for G^*_p	$O((\|V_P\|+CR)\cdot\|V_P\|)$

Table 4.1: Summary of Task Complexities

Problem 2: The Budget-Constrained Problem

We proceed by examining the problem of optimal maintenance when an arbitrary budget D is available only. We name it Problem 2. It consists of the same objective and constraints as Problem 1 with the addition of the following:

$$\sum_{(i,j)\in A}\left[\sum_{s\in E_j} c_s + F_{ij}\right] \le D \qquad (4.4)$$

Let

$AP_1 \equiv \{A | A \text{ is a feasible solution to Problem 1}\}$ and
$A\beta \equiv \{A | A \text{ satisfies constraint (4.4)}\}$

By definition, the solutions to Problem 2 lie in the intersection of the two sets above. When the cardinality of Aβ increases, determining this intersection becomes a very laborious exercise. We consider first the Lagrangean Relaxation of constraint (4.4). It takes the following form.

$$\underset{\lambda\geq 0}{MAX}\,\vartheta(\lambda) = \underset{\lambda\geq 0}{MAX}\left(\underset{A\subseteq A_p}{MIN} \sum_{(i,j)\in A}\left[(1+\lambda)\cdot\left(\sum_{s\in E_j} c_s + F_{ij}\right) - \sum_{s\in E_j} r_s \right] - \lambda\cdot D \right)$$

such that (4.1), (4.2) and (4.3) are satisfied.

This will be called the Lagrangean Relaxation Problem. λ is the dual cost of the budget constraint, it acts on all costs in the same way, but leaves benefits (r_s) unaltered. Given a value for λ, one can determine $\theta(\lambda)$ by solving a problem equivalent to Problem 1. The resulting tree of arcs in $A(\lambda)$ necessitates an expense not necessarily the same as the available budget. The cost overrun will be given as follows:

$$\beta(\lambda) = \sum_{(i,j)\in A(\lambda)}\left(\sum_{s\in E_j} c_s + F_{ij}\right) - D$$

CASE 1: If $\beta(\lambda) = -\varepsilon$, then $\lambda = \lambda^*$; with λ^* being the solution to the Lagrangean Relaxation Problem and ε being a remainder that is not high enough to accommodate any new arc to $A(\lambda)$ without constraints (4.1), (4.2) and (4.3) being violated.

CASE 2: If $\beta(\lambda) > 0$, then $A(\lambda)$ is infeasible for Problem 2, so a better λ may exist.

CASE 3: If $\beta(\lambda) < -\varepsilon$, then: A) a better λ may exist or B) $\theta(\lambda)$ is maximum but the budget D is high enough for an additional arc to be introduced, without violating the budget constraint.

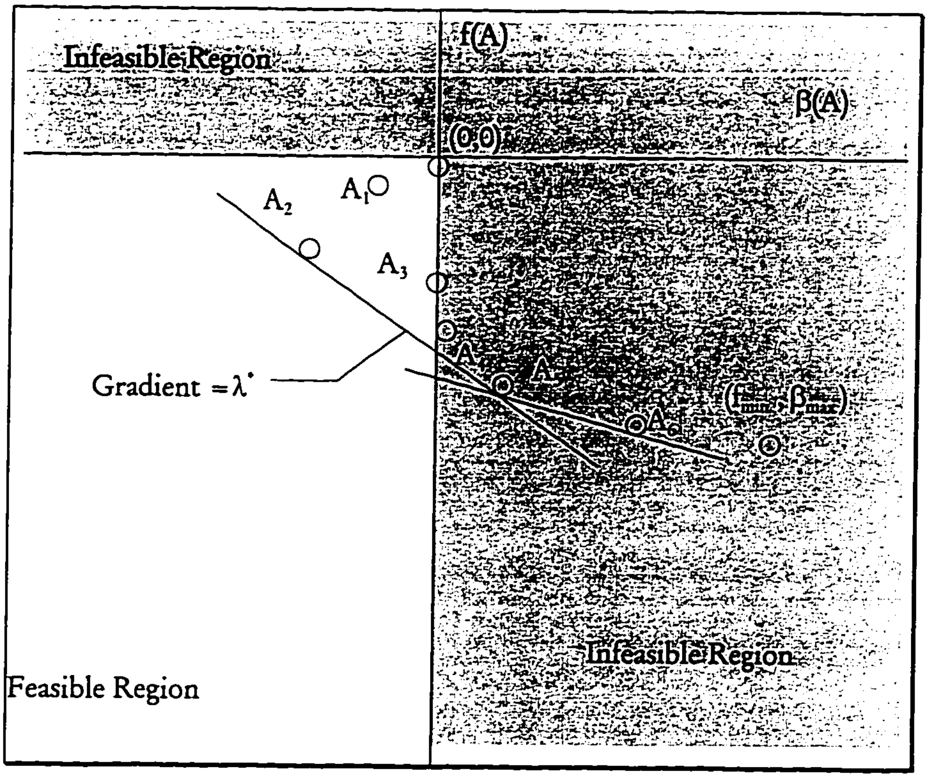


Figure 4.4: Projection of feasible solutions for Problem 2 in (β(A),f(A)) space and Potential Duality Gap

It is well known that $A(\lambda^*)$, maximizing the Lagrangean Relaxation Problem, may not correspond to the minimum for Problem 2. This phenomenon is commonly referred to as duality gap (see for instance [Bazaraa and Shetty, 1979]). Figure 4.4 depicts how feasible solutions are projected to the (β(A),f(A)) space. Solutions to the Lagrangean Relaxation Problem form an efficiency frontier represented by the convex combination of points undominated in this space (e.g. A_2, A_5, A_6). The value of θ(λ) for any λ is the lowest intersection of a line with slope λ crossing a point in the image of AP_t on (β(A),f(A)). The optimal solution to the Lagrangean Relaxation Problem is given by λ^* in Figure 4.4. In the same example one observes the existence of a duality gap:

$f(A_3)<f(A_2)$ where: A_3 is the primal optimal solution (Problem 2), and
A_2 is the feasible $A(\lambda^*)$[12].

In the following, we offer a solution to the Lagrangean Relaxation Problem originally encountered in exercise 6.23 of [Bazaraa and Shetty, 1979]. Then we illustrate the reasons for the optimality of this method as a solution procedure for our problem versus other alternatives.

Solution to Lagrangean Relaxation Problem

PROCEDURE:

Initialize: If $D > \underset{s \in G}{MIN}\left(F_s + c_s\right)$[13] then the budget is insufficient; stop.

$$\underline{\lambda} = 0$$

$$\bar{\lambda} = \underset{s \in G}{MAX}\left(\frac{b_s}{c_s}\right)$$

Determine $\vartheta(\underline{\lambda})$ (this gives also $f(\underline{\lambda})$ and $\beta(\underline{\lambda})$).

If $\beta(\underline{\lambda}) \le 0$ then stop. D is sufficient for all maintenance opportunities.

Determine $\vartheta(\bar{\lambda})$ (this gives also $f(\bar{\lambda})$ and $\beta(\bar{\lambda})$)

---

[12] Note that an infeasible $A'(\lambda^*)$ also exists, A_5 in Figure 4.4.

[13] $F_{(i,j)} = \min(F_i, F_j)$. It is presumed that the triangle inequality holds for crew positioning costs from the origin (i.e. $\forall i,j \in V_P : F_{(0,j)} \le F_{(0,i)} + F_{(i,j)}$).

note that $\beta(\bar{\lambda}) = 0$, because $A(\bar{\lambda}) = \varnothing$ by construction

Step 1: $\lambda_w = \dfrac{f(\bar{\lambda}) - f(\underline{\lambda})}{\beta(\underline{\lambda}) - \beta(\bar{\lambda})}$

if $\lambda_w = \bar{\lambda}$ or $\lambda_w = \underline{\lambda}$ then stop.

Step 2: Determine $\theta(\lambda_w)$; $f(\lambda_w)$, $\beta(\lambda_w)$

If $\beta(\lambda_w) > 0$ then $\bar{\lambda} = \lambda_w$

If $\beta(\lambda_w) < 0$ then $\underline{\lambda} = \lambda_w$

If $\beta(\lambda_w) = 0$ then stop

To prove this procedure converges to $A(\lambda^*)$, we need to show that throughout it:

$$\vartheta(\underline{\lambda}) \geq \vartheta(\lambda) \quad \forall \lambda \leq \underline{\lambda} \tag{4.5}$$

$$\vartheta(\bar{\lambda}) \geq \vartheta(\lambda) \quad \forall \lambda \geq \bar{\lambda} \tag{4.6}$$

and that the following holds true:

$$\lambda_w = \underline{\lambda} \quad \text{OR} \quad \lambda_w = \bar{\lambda} \quad \Rightarrow \quad \vartheta(\underline{\lambda}) = \vartheta(\bar{\lambda}) \tag{4.7}$$

Note that according to Theorem 6.3.4 in [Bazaraa and Shetty, 1979]:

$$\vartheta(\lambda_1) \leq \vartheta(\lambda_2) + \beta(\lambda_2) \cdot (\lambda_1 - \lambda_2) \tag{4.8}$$

The only assumptions of the above theorem are that: $f(A)$ and $\beta(A)$ are continuous, and $AP_1 \cap A\beta$ (the feasible region) is not empty, which is checked at the initialization step. Therefore both assumptions hold.

But,

$\beta(\underline{\lambda}) \geq 0$ by construction

putting λ in the place of λ_1 and $\underline{\lambda}$ in the place of λ_2 one gets:

$\vartheta(\lambda) \leq \vartheta(\underline{\lambda}) + \beta(\underline{\lambda}) \cdot (\lambda - \underline{\lambda})$ which implies (4.5)

Also

$\beta(\bar{\lambda}) \leq 0$ by construction

putting λ in the place of λ_1 and $\bar{\lambda}$ in the place of λ_2 one gets:

$\vartheta(\lambda) \leq \vartheta(\bar{\lambda}) + \beta(\bar{\lambda}) \cdot (\lambda - \bar{\lambda})$ which implies (4.6)

Now to prove the first part of (4.7) we proceed as follows:

$$\lambda_w = \underline{\lambda} \quad \Rightarrow \quad \frac{f(\bar{\lambda}) - f(\underline{\lambda})}{\beta(\underline{\lambda}) - \beta(\bar{\lambda})} = \underline{\lambda} \quad \Rightarrow \quad f(\bar{\lambda}) + \underline{\lambda} \cdot \beta(\bar{\lambda}) = f(\underline{\lambda}) + \underline{\lambda} \cdot \beta(\underline{\lambda}) = \vartheta(\underline{\lambda}) \quad (4.9)$$

therefore

$$\vartheta(\bar{\lambda}) = \underset{A \subseteq A}{\mathrm{MIN}} \left(f(A) + \bar{\lambda} \cdot \beta(A) \right) \leq f(\bar{\lambda}) + \underline{\lambda} \cdot \beta(\bar{\lambda}) = \vartheta(\underline{\lambda}) \qquad (4.10)$$

yet

$$\bar{\lambda} \geq \underline{\lambda} \quad \wedge \quad \beta(\bar{\lambda}) \geq 0 \quad \Rightarrow \quad \vartheta(\underline{\lambda}) = f(\bar{\lambda}) + \underline{\lambda} \cdot \beta(\bar{\lambda}) \leq f(\bar{\lambda}) + \bar{\lambda} \cdot \beta(\bar{\lambda}) = \vartheta(\bar{\lambda}) \qquad (4.11)$$

finally

$$(4.10) \quad \wedge \quad (4.11) \quad \Rightarrow \quad \vartheta(\bar{\lambda}) = \vartheta(\underline{\lambda})$$

In the same way the second part of (4.7) is obtained.

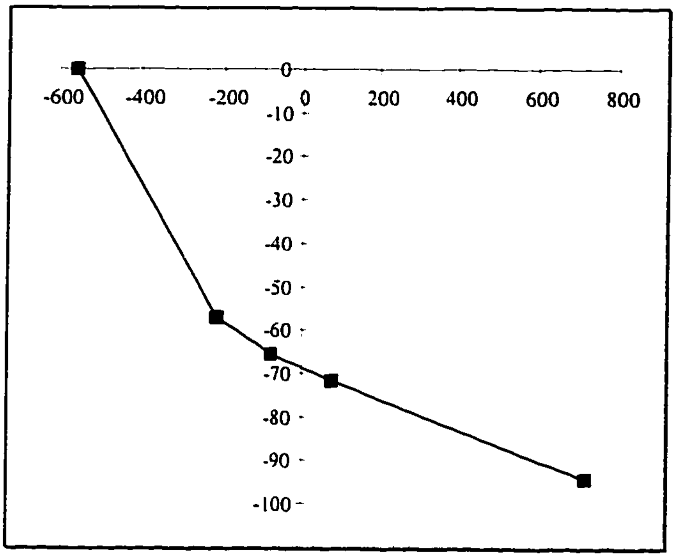
From (4.8) we also obtain that :

$$\underline{\lambda} \leq \lambda_w \leq \bar{\lambda}$$

In particular:

$$\lambda_w \neq \lambda^* \quad \wedge \quad (4.7) \quad \Rightarrow \quad \underline{\lambda} < \lambda_w < \bar{\lambda}$$

This concludes the proof of convergence of λ_w to λ^*.



BUDGET 560 K

λ	θ(λ)	COST in K	NET BNF in K
0.000	-94.3	1282.7	94.3
0.038	-68.8	634.4	71.6
0.039	-68.7	634.4	71.6
0.049	-69.6	482.2	65.8
0.073	-73.1	345.6	57.4
1.000	-560.0	0.0	0.0

Figure 4.5: (β(A),f(A)) Graph of points produced while solving the Lagrangean Problem for the illustrative example (figures divided by 1,000)

The (β,f) graph for our illustrative example is depicted in Figure 4.5. The primal solution given by the Lagrangean Relaxation leaves a remainder enough for one augmentation of the solution set[14].

Alternative Line Search

Let $LR \equiv \{(\beta(A), f(A)) | A \in AP_1\}$ and the set of Pareto optimal points of LR in the (β, f) space be $PLR \equiv \{(\beta, f) \in LR | \forall (\hat{\beta}, \hat{f}) \in LR \quad f \le \hat{f} \quad \text{OR} \quad \beta \le \hat{\beta}\}$. The number of values λ_w takes during this procedure doesn't exceed the number of elements in PLR. In the following, we compare the procedure described in the previous section to another commonly used procedure, that selects λ_w at a fixed proportion of the interval $[\underline{\lambda}, \bar{\lambda}]$. That is λ_w is chosen not as in step 1, but in a way that the following relation is satisfied:

$$\lambda_w - \underline{\lambda} = \gamma \cdot (\bar{\lambda} - \underline{\lambda}) \quad ; \quad 0 < \gamma < 1$$

As an example consider the case when $\gamma = \frac{1}{2}$ (note that this value for γ minimizes the final interval of uncertainty for a given number of iterations). When the budget D is an arbitrary number it is unlikely that one hits a λ_w that makes the budget constraint binding, so we focus on the number of iterations needed to reduce the interval of uncertainty $[\underline{\lambda}, \bar{\lambda}]$. To reduce the original interval 2^ν times one needs ν iterations. Clearly, if ν is higher than the number of elements in PLR, the procedure proposed in the previous section is more efficient than a fixed proportion procedure.

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[14] See page 98 for details.

Moreover our preferred procedure produces always the exact λ^* (or one of the λ^*s, if multiple solutions exist), and the best primal feasible solution (A_f) corresponding to an element in PLR together with the least over budget element in PLR. This information is necessary to determine the usefulness of the solution (A_f).

Implementations of our procedure, however, must guaranty completion after a prespecified number of line search iterations. To achieve this, one may use a combinations of the line searches we have considered. The following procedure for stage 1 terminates after $N_{PS} + N_{FP}$ steps:

Step (a) Begin the line search as proposed. If after N_{PS} (a predetermined number) steps the optimal solution hasn't been obtained, proceed with the next step.

Step (b) Apply the fixed proportion method to reduce the uncertainty interval N_{FP} times. The accuracy for λ^* will be given by $(\bar{\lambda} - \underline{\lambda})\big/2^{N_{FP}}$.

Augmentation of the Lagrangean Relaxation Solution

Figure 4.6 is a blowup of Figure 4.4 near the intersection of the f-axis and the supporting line with slope λ^*. For the example in Figure 4.6:

$A_f = A_2 = A(\bar{\lambda})$ for the last value of $\bar{\lambda}$

$A_5 = A(\underline{\lambda})$ for the last value of $\underline{\lambda}$

A_3 is the solution to Problem 2

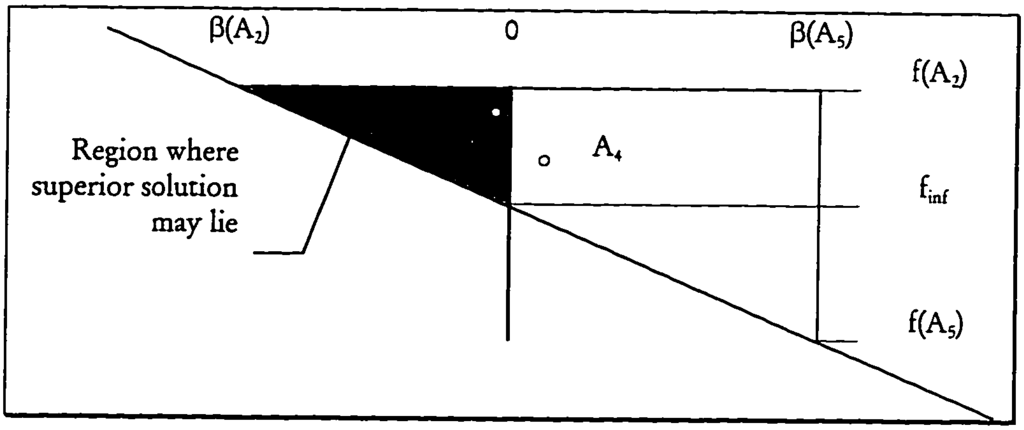

Figure 4.6: Superior solution to the ones produced by Lagrangean Relaxation (A_3)

f_{inf} is the intersection of the f-axis and the line passing through ($\beta(A_2)$,$f(A_2)$) and ($\beta(A_5)$,$f(A_5)$).

Clearly, if $f(A_2)$ is close to f_{inf}, then extensive search to find A_3 may not be justified. When the latter is not the case and $\beta(A_5)$ is close to zero, then A_5 may be an attractive solution. If the two previous tests fail, then a local search heuristic may be employed to find a better solution to Problem 2 than A_f.

It has to be emphasized, that the optimum branching problem doesn't belong to the class of problems where optimal marginal improvements lead to the global optimum (see theory of matroid intersections in [Lawler, 1976]). Therefore, determining A_f doesn't necessarily lead to finding the solution to Problem 2. Even though a number of heuristics maybe utilized to improve A_f , we conjecture that a procedure that solves Problem 2 exactly will require enumeration of all subsets of $AP_1 \cap A\beta$. The latter procedure is expected to be highly complex when all the cost parameters take values that describe a pipeline network system and the budget D is similar to the ones usually available for network maintenance. We describe in the following a myopic search, that augments A_f by appending successively to it the arc with the highest benefit to cost ratio out of all arcs not in the solution already. This process continues until the budget constraint becomes binding.

After the determination of the Lagrangean Relaxation Solution the following are known. From the last pair $\left(\underline{\lambda}, \bar{\lambda}\right)$ we obtain the decision parameters for the next stages:

$A(\bar{\lambda})$	The best feasible (under budget) solution from the ones obtained at Stage 1.
$f(\bar{\lambda})$	The value of the Problem 2 objective function for $\bar{\lambda}$.
$-\beta(\bar{\lambda})$	The budget remainder for $\bar{\lambda}$.
$A(\underline{\lambda})$	The least over budget solution from the ones obtained at Stage 1.
$f(\underline{\lambda}), \beta(\underline{\lambda})$	The value of the Problem 2 objective function and the budget remainder for $\underline{\lambda}$.
$f_{\inf} = f(\bar{\lambda}) - \dfrac{f(\underline{\lambda}) - f(\bar{\lambda})}{\beta(\underline{\lambda}) - \beta(\bar{\lambda})} \cdot \beta(\bar{\lambda})$	The infimum of the Problem 2 objective function.

Clearly,

$$\beta(\bar{\lambda}) = 0 \quad \Rightarrow \quad f_{\inf} = f(\bar{\lambda})$$

Obviously, $A(\bar{\lambda})$ is an optimal solution to Problem 2 when the above condition holds true. We proceed with a search over the pipeline segments remaining after $A(\bar{\lambda})$ is implemented to find the arc with the highest benefit-cost ratio. Then, we augment the current solution until the budget remainder has been used up. This is a variant of the knapsack problem (see for example [Lawler, 1976]). Due to the nonlinear nature of Problem 2, this is a mere heuristic.

The following objects are needed to describe the augmentation procedure:

$V_O \equiv V + \{\text{Origin}\}$	The overall set of original nodes.
$E \equiv \{(i,j) \mid i \in V_O; j \in V\}$	A set of arcs.
$G_O \equiv \{V_O, E\}$	The resulting graph.

$$W \equiv \{(w_{ijk}, y_{ijk}) \mid i,j \in V; w_{ijk} = F(k) + c_{ij} - b_{ij} \text{ , } y_{ijk} = \frac{b_{ijk}}{c_{ijk} + F(k)} \text{ , } F(k) = \begin{cases} F_i & \text{if } k = -1 \\ 0 & \text{if } k = 0 \\ F_j & \text{if } k = 1 \end{cases} \}$$

$W^{+} \equiv \{(w_{ijk}, y_{ijk}) \in W \mid w_{ijk} \leq 0\}$	The set possible candidates for the Augmentation Procedure.
RL	The set of arcs in $A(\bar{\lambda})$ scheduled for replacement.

RP The set of arcs to be used for crew repositioning, so that $A(\bar{\lambda})$ be possible.

$V_{acc} \equiv \{i \in V_O | \exists j \text{ s.t. } (i,j) \in RL \cup RP \text{ OR } (j,i) \in RL \cup RP\}$ The set of accessed nodes.

Let RM be the maximum number of blocks that may be maintained given the budget remainder. The complexity of the Augmentation Procedure is O(|W|·RM) (see Appendix : Algorithm for the Augmentation of the Lagrangean Solution in pseudocode).

Evaluation of obtained solution

There are three candidates to serve as a solution to Problem 2:

A_f when

CASE 1: $\beta(\lambda^*) = 0$

CASE 2: No augmentation of A_f may be performed, because the budget remainder after the Lagrangean Relaxation ($-\beta(\bar{\lambda})$) is not sufficient for one

A_{aug} when

CASE 3: $f(A_{aug})$ is close to $f_{\inf}$

$A(\underline{\lambda})$ when

CASE 4: $f(A(\underline{\lambda}))$ is much higher than $f(A_{aug})$, and

the budget overrun ($\beta(\underline{\lambda})$) is not high

It is instructive to consider the alternative of using Integer Programming. The Integer Linear Programming (ILP) problem belongs to the class of NP-Complete Problems (see for instance [Papadimitriou and Steiglitz, 1982]). Moreover, the usually employed procedures to solve this problem depend on the number of constraints considered. Edmonds has proposed a formulation of the Optimum Branching Problem as an ILP [Edmonds, 1967], according to which $2^{|V_{P0}|}$ constraints are required. When $|V_{P0}|$ is as low as 20, more than a million constraints are required. It is difficult to even write a problem this big, let alone solve it. Consequently, our approach is a radical improvement over ILP formulations.

Clearly the Augmentation Procedure gives results very fast compared to the Lagrangean Relaxation Procedure. Therefore the overall complexity to obtain the solution of Problem 2 is

$O\left(\left(N_{PS} + N_{LS}\right)\cdot|V_m|\cdot R\cdot|V_R|\right)$

Illustrative Example

We consider in the following the application of the previous methodology to a prototype region of 30 Streets by 7 Avenues. There are 386 cast iron pipeline segments in the prototype region. A summary description of the pipeline network characteristics appears in Table 4.2.

Size	Segments	Failure Probability[15]	Replacement Cost
3"	2	7%[16]	$58,000
4"	188	7%	$61,000
6"	147	4%	$67,000
8"	4	2%	$78,000
12"	4	4%	$149,000
20"	25	4%	$319,000
30"	16	1%	$388,000
Crew Repositioning Cost:			
From Origin			$15,000
From Next Segment			$5,000

Table 4.2: Summary description of Prototype Region Characteristics

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[15] This refers to the probability of a break per year. All breaks do not lead to catastrophic events, but they have to be repaired immediately after they are discovered.

[16] Unknown, assumed same as 4'' value.

Pipe network used, replacement cost values, and risk values have a close correspondence to actual values of a Gas Utility's cast iron network. The repositioning costs and the budget level have been selected to demonstrate the full capabilities of the proposed method.

Segments for which the calculated risk net of direct cost is positive are depicted in Figure 4.7. The segments between squares are of high enough risk, that their risk value exceeds the direct cost and the repositioning cost from the origin to them. If no contiguity discount is considered, then these 9 segments are the optimal segments to replace in order to maximize the overall net benefit of replacement.

The two problems have been solved for the cost structure in Table 4.2. The solution to the unconstrained problem (Problem 1) appears in Figure 4.8 . Problem 2 has been solved for a budget of $560,000[17]. Both the Lagrangean Relaxation solution and the result of the Augmentation Procedure appear in Figure 4.9 . A summary of the results of Problem 2 appears in Table 4.3 . The Lagrangean Relaxation solution leaves a remainder of $77,800. Its deviation from the resulting infimum is

$$f(A_f) - f_{\inf} = 2.8 \text{ K}$$

The result of the augmentation heuristic leaves a small remainder:

$$D - \beta(A_{aug}) = 10.8 \text{ K}$$

---

[17] The city neighborhood we consider is small, so the chosen budget level will sound excessive to practitioners. In practice repair of pipes (costing much less than replacement) will be used also. Furthermore, this city neighborhood has many high risk pipe segments and is not representative of the entire region of service.

The value of the objective function for the augmented solution (F_{aug}) is:

$f(A_{aug}) = 68.8\ \text{K} \quad \Rightarrow \quad f(A_{aug}) - f_{\inf} = 0.1\ \text{K}$

Solution	*Overall Net Benefit*	*Direct Cost*	*Repositioning Cost*	*Budget Remainder*
Unconstrained	$94,300	$1,211,000	$71,700	
Linear	$46,500	$445,000	$63,500	$51,500
After Lagrangean Relaxation	$65,800	$445,000	$37,200	$77,800
After Augmentation	$68,800	$512,000	$37,200	$10,800
BUDGET: $560,000	$f(A_{aug}) = $-65.8 K		$f_{\inf} = $-68.9 K	

Table 4.3: Summary of Results for the illustrative example

The proposed procedure for the optimization of network maintenance has two important advantages: it accommodates nonlinear cost structures, thus avoiding unnecessarily simplistic assumptions about the nature of maintenance costs, and it can produce results in polynomial time, hence it can be programmed on a computer and yield results quickly despite the large size of gas distribution networks.

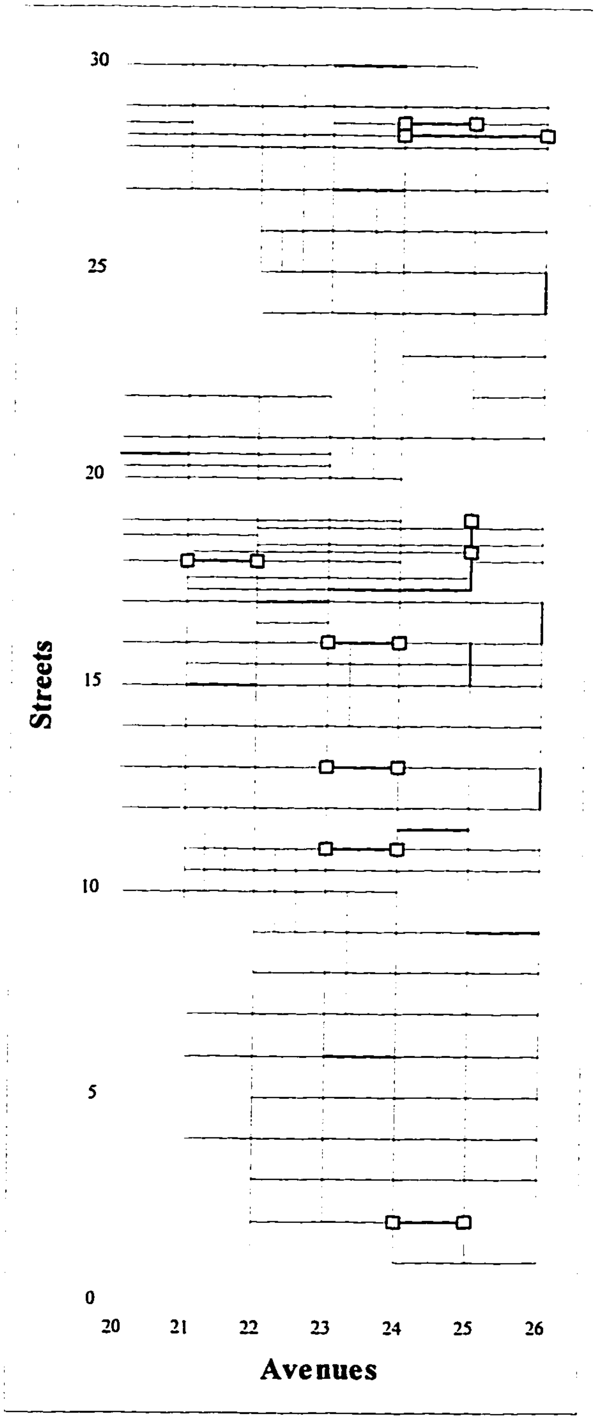

Figure 4.7: Blocks with positive benefit of replacement net of direct maintenance cost are represented by thick lines. Segments between squares have positive net benefit.

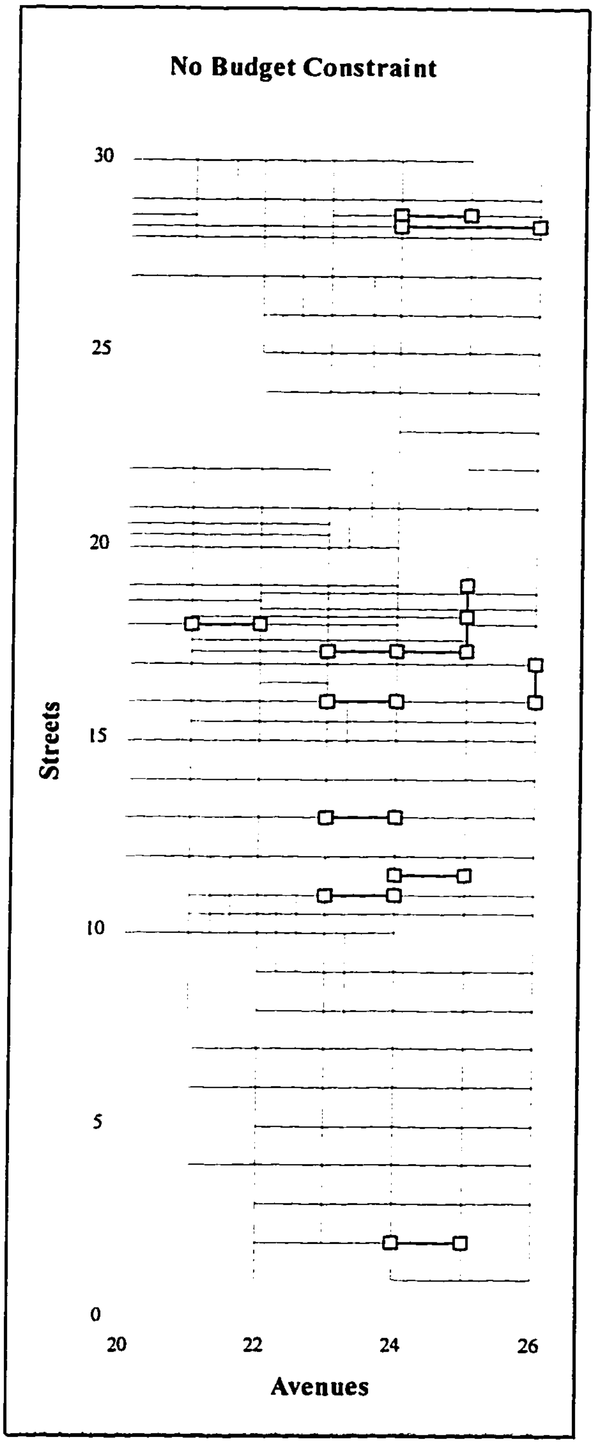

Figure 4.8: Solution to Problem 1 (No Budget Constraint). Segments between squares are to be replaced according to the proposed method.

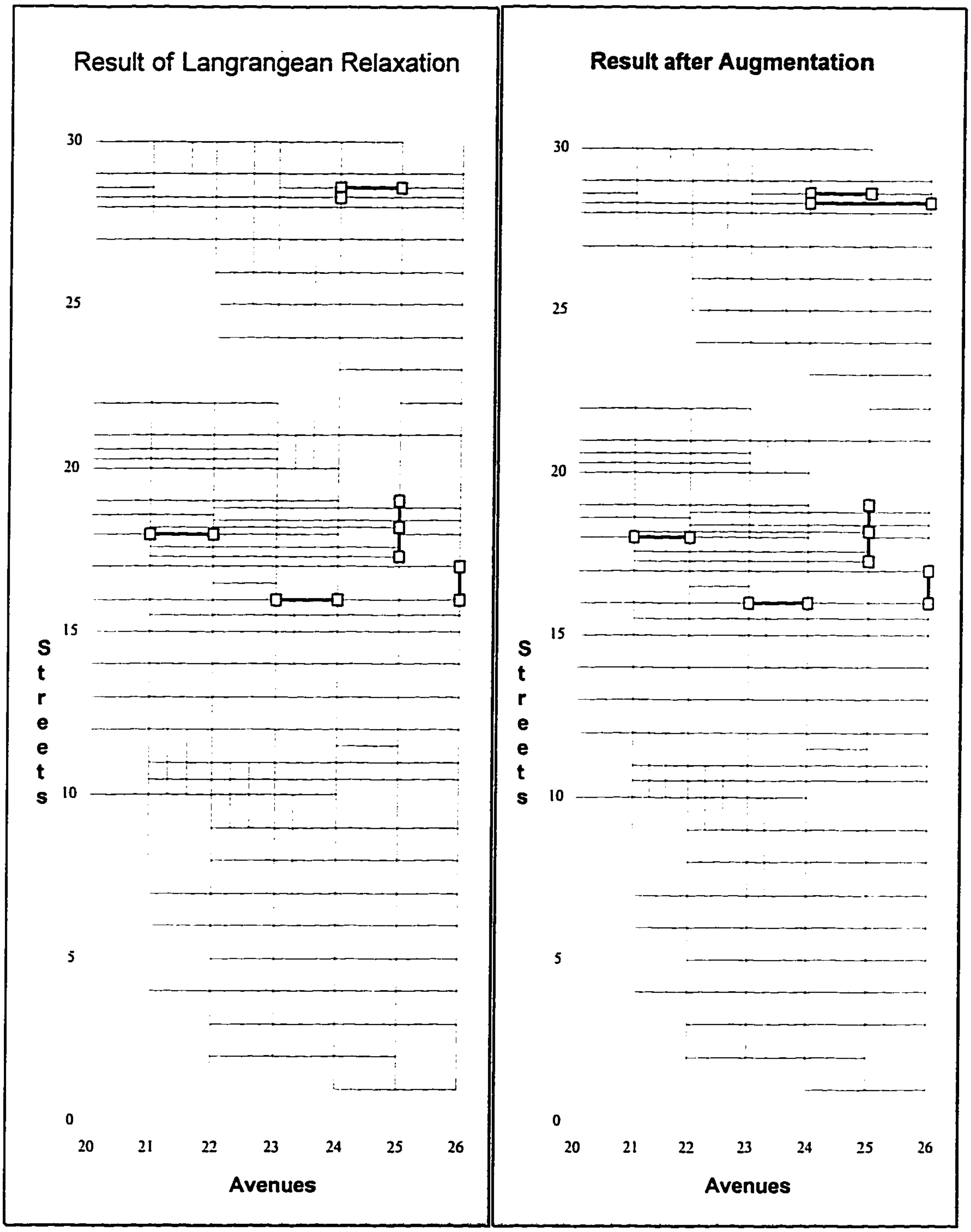

Figure 4.9 : Segments to be replaced according to Lagrangean Relaxation Procedure and according to Augmentation Procedure when the available budget is 560K.

Seen as a risk control policy, this procedure has the following characteristic, it assures that high risk segments [18] will be replaced, due to condition (4.3). In contrast, the resulting list of low risk segments selected for maintenance under this policy will depend highly on the structure of repositioning costs (nonlinearities). Hence, a sensitivity analysis of the results will be difficult for low risk segments.

In [Fisher, 1985] two important observations on Lagrangean Relaxation methods are made that are relevant to our problem. First, the most efficient method for finding the optimal Lagrangean multiplier λ^* is problem specific. That is it depends on the values of the data set considered. In our illustrative example five iterations were sufficient to produce the Lagrangean optimal. It appears this low number of iterations is not a coincidence. Other exploratory runs produced the Lagrangean solution at the same fast rate. Further analysis, however, of the convergence rate for the Lagrangean line search is beyond the scope of this study. Second, the primal optimal (solution to Problem 2) is not necessarily obtained. General purpose heuristics may lead to an objective value close to the calculated infimum, but a specialized heuristic (say, visual inspection) may lead to an even better solution. Furthermore, one may chose to accept an over budget solution.

The Operations Researcher using our procedure to design a decision process for the maintenance of natural gas networks should take a careful note of the fact that the results

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[18] Segments with risk exceeding the direct cost and the crew positioning cost from the origin are viewed as high risk segments.

obtained lack mathematical certainty, usually expected from the analysis of similar problems (a notable example is maintaining a network when the cost structure is linear). If for instance one party provides the budget limit and another a proposal for the allocation, systematically over budget proposals may introduce points of friction. Moreover, if one party is interested in maximizing the benefit of a safety budget and another in assuring that a consistent and equitable replacement process is in place, difficult to reconcile disputes may arise. The subtleties this procedure exhibits should be clarified, so that potential entrants in a decision process using the algorithms we propose consent to it after pros and cons are balanced.

In preventive maintenance programs for Natural Gas Distribution, pipelines are coupled with enforced maintenance programs driven by water distribution network failures. It would be interesting to consider modifying our model to take account of the crews working in blocks where enforced maintenance takes place.

The dynamics of the above modeling approach also deserve further study. In effect, what has been proposed here is a year-by-year optimization approach, in which the risk and cost values r_s and c_s change over time as segments become older or as additional information on their relative risk changes. However, it should be clear that a truly dynamic optimization would anticipate changing values in r_s and c_s and incorporate these into the calculation of replacement synergies.

Another useful extension of these results would be to develop a procedure for the determination of the set PLR (the efficiency frontier of the Lagrangean Relaxation Solutions). In this way the selection of a maintenance budget can be more informed. If a small increase in the budget introduces a step increase in the objective value, then it is reasonable to prefer a slightly increased maintenance budget.

CHAPTER 5 : RISK MAPS IN UPPER MANAGEMENT DECISIONS

In this chapter we describe the use of Risk Maps for Technological Risk Management within the organizational structure of the firm. Two specific problems will be addressed: safety budget productivity evaluation, and the problem of establishing the consistency of company safety policy and defending to external stakeholders risk management priorities.

These two problems carry significant weight when developing corporate strategy for firms whose assets are distributed within a region and may cause catastrophic accidents with spatially concentrated impact. Examples, aside from natural gas distribution, include distribution systems for chemicals, fuels, or hazardous waste. To make arguments more concrete, we will draw examples exclusively from the Natural Gas Utilities experience.

Natural Gas Utilities own a vast network of typically low and medium pressure pipelines carrying predominately natural gas. In chapters 1 and 2 we have described how natural gas pipelines may lose containment of their gaseous fuel via a break, rupture, or leak depending on material and pressure. The result of containment loss is not necessarily catastrophic but may result in rapidly advancing fires and in confined explosions. The direct burden in loss of life, injuries and monetary losses is assumed by people and buildings in the vicinity of these incidents. These people tend to be company employees, customers and contractors operating near a utility's pipelines.

Both problems we address concern the upper management of these firms. The behavior of operation managers and line personnel firstly, and of external stakeholders (e.g. regulatory agencies, courts, customers, contractors, political entrepreneurs) secondly, have to be understood also. The performance of the former is easier to predict, given that they have to conform to internal rules, policies and procedures, have been selected and trained by the company, they receive a competitive benefits package (all reasonable assumptions for the purposes of this study). It is assumed, therefore, that the main factor determining the efficiency of safety operations is utilization of risk information in sufficient and not excess detail. The behavior of external stakeholders is more difficult to predict, despite the presence of detailed technical regulations for the Natural Gas Industry. It seems of paramount importance, however, to have a way to describe risk information to external stakeholders in a way that two arguments become clear: on the one hand, that company safety performance is at least as good as common practice[19] suggests it should be; and on the other, that the company manages risk in a way that no subregion in the area of operation is unjustifiably burdened over the others.

In the next, we will define and describe qualitatively the risk map as a risk indicator (a precise mathematical description for a risk map has been offered in chapter 3). We will argue that representations of operations using a risk map is an efficient way to describe information to decision makers facing the two problems above. We will suggest the long and short term

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[19] Common practice is presumed to be at a minimum conforming to regulatory requirements. Industry wide practices may result in lower risks than prescribed by regulators.

benefits of this approach. Given the low cost of today's information technology the only significant cost appears to be retraining.

With respect to the question of presenting risk maps to external stakeholders when a company has a poor safety record, decision making of this sort is context specific and contingent to upper management good judgment, legal advice, and risk communications counseling. We are not attempting to offer broad brush prescriptions substituting inputs of the latter kind in designing strategy and coping with crises. We view risk maps, however, as necessary complements to other decision factors.

The Nature of Technological Risk

Technological Risk Management involves the prevention of and response to unwanted or unexpected consequences arising from failure to sustain normal operation of a technological system. Typically, incidents are directly caused by design error, operation error, or natural disasters and not by opportunism. In this respect, Technological Risk Management differs from other types of Risk Management (e.g. Financial Risk Management).

In the case of catastrophic risk we focus on, normal operations cause ordinarily no adverse consequences at all[20]. Disputes arise, however, while determining the level of care to avoid losses and the acceptability of risk. Frequently, the perpetrators of incidents are the ones

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[20] This is not the case with environmental risks from voluntary emissions to air and water. The regional distribution of these risks requires a different analysis which usually considers the discharges of more than one company.

shouldering the heaviest toll of injuries and property losses (e.g. employees maintaining a pipeline or contractors digging near live pipes). In other cases, lack of care may be the result of opportunistic behavior[21], and understanding this behavior may be important. The main focus, however, of Technological Risk Analysis is on understanding the mainly technical and organizational[22] factors affecting the magnitude and likelihood of technological failures.

In order to focus on the right technical parameters, more than technical expertise is required. It is necessary to understand the tight couplings of production processes with decision processes within the corporation and between the corporation and its environment. Risk reduction is rarely the single consideration in Technological Risk Management. Cost effectiveness, corporate strategy, ethics, societal norms, defensibility of corporate actions in a court of law or in public meetings, conformance to regulatory rules and trends are all factors carrying decision weight and important in understanding the risk management decision context.

Understanding technological risk is as fundamental a requirement for the firm as understanding operational efficiency. A company attains a good reputation for safe and reliable operation of a complex technological system after some time of operation. New competitors are usually untested and therefore have a disadvantage, so they are discouraged

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[21] Pilfering in oil and natural gas pipelines or pandering with the gas meter may cause catastrophic incidents, either during the act or after a delay period.

[22] Often organizational performance improves with better application of information technology. Conversely, the reliability and productivity of a technological system is influenced by organizational factors. Organizational and technological requirements are highly intertwined. See [Tuli and Apostolakis, 1996] for a detailed analysis of how organizational factors are incorporated in risk analysis.

from entering the market. In addition, safety tends not to be offset by price discounts. Consequently, a good safety record may be translated in higher profits.

Key attributes of the distribution network, such as pipe material (steel, cast iron, plastic), pipe pressure (low, medium and high gas pressure), storage and compression technologies, and use of LPG/LNG lines, have significant effect on the nature of the risk a company is posing to its surroundings. In network industries and in natural gas distribution in particular the technological base changes slowly by adding arcs to the existing network or by taking lines out of service. Radical network changes tend to be prohibitively costly. If, for example, a company wants to go from a mainly cast iron network to a steel and plastic network, many decades may be required before the mix of assets is recognizably altered. Changes in the technological base have a significant impact on technological risk, but take a long time to implement. This makes maintenance and safety efficiency improvements to be more attractive risk reduction policies.

There are many ways to improve efficiency in maintenance operations and in risk reduction. The range of options for improvement possibilities will be limited by the information and skills available to the company (knowledge base). The knowledge base may be expanded by acquisition of information from the company's own operations, acquisition of information from the operation of companies in the same industry (e.g. through benchmarking studies), hiring and renting of new skills, cultivation of existing skills, and by scientific research. It is essential to have a prioritization system that helps single out the best improvement opportunities from the many available.

What constitutes risk reduction may vary drastically depending on point of view. The various stakeholders have different information needs and, due to their differing skill sets, different verifiability requirements. Disaggregated measures of risk, if properly designed, may accommodate different points of view. The verifiability gaps, in turn, may be reduced, by using the least common denominator in verifiability requirements, or by bridging the gaps with the help of third parties of guaranteed impartiality that can credibly attest to the quality of information available.

Regional Risk Maps as Technological Risk Indicators

The role of a good risk indicator is to reduce and clarify decision complexities. Unnecessary details increase information processing time and may have an increasingly detrimental effect when decisions are made collectively (upper management decisions tend to be made by groups). Lack of any detail is more appropriate for mechanistic decisions. Decisions at the upper management level tend to be more complex and require well developed insights and experience.

Historically, the indicators used in risk management have been:

1) Average loss. This is a very aggregative risk indicator, that becomes useful when very many options need to be considered. In general, little information is conveyed by this indicator so the accompanying executive summary seems likely to carry the most weight for the decision makers.

2) Worst Case Loss. This is a simple, but not always straight forward indicator. If a risk control policy oriented towards worst case risks leaves unaffected or impacts negatively on representative risks, then controversies are likely to arise. In addition, it is difficult to estimate accurately worst case losses unless fairly precise engineering/scientific conventions are in place.

3) Quantile loss. Magnitude of losses that is not likely to be exceeded more often than a reference frequency indicates, for example the one in a hundred years loss. It may have the same problems worst case indicators have.

4) Average loss together with a loss variability measure A loss variability measure (e.g. variance, semivariance) accompanies the average loss estimate and is typically used in risk premium calculations. This indicator also is aggregative and useful when many options need to be considered; thus it is not typically relevant to upper management decisions.

5) Conditional loss. In a Scenario Analysis framework aggregate benefits and losses are calculated given a number of events of interest.

6) Loss probability curve. This can be derived from scenario analysis when the probability of the events of interest is estimated. This indicator may require familiarity with the mathematics of Probability Theory.

7) Risk Maps These are risk indicators providing information on the spatial distribution of risk. This is the most disaggregative risk indicator of all mentioned here. They have been

used in the design of oil refining facilities and in facility siting for complex technological systems (e.g. LNG Terminals).

Risk Maps are of particular importance and usefulness to the network industries. Natural Gas Distribution companies in addition to having their assets laid out in a spatial network, have to prevent and respond to catastrophic events which have locally concentrated losses. The magnitude and spatial pattern of losses varies by geographic location of the event taking place (see chapter 2 for methods to estimate the loss pattern near a natural gas jet fire). Therefore, integration of technological and geographical information (e.g. housing concentration, distribution of property values, location of hospitals-schools) is essential for risk management.

The risk burden may also exhibit a geographical pattern. Manifestations of a geographic bias of the risk burden include a history of concentration of incidents in certain areas in the region of service, or higher than usual losses for a type of incidents in a certain area. A geographic bias in the risk burden may also become evident after a risk assessment study. The geographical distribution of risk needs to be either eliminated or explained by easy to justify factors (more on this in following sections).

Risk maps, contrary to other risk indicators, provide information on the geographical distribution of risk burden. One may produce two types of network risk pictures. One before a risk management action is taken or an external event with possible effects on network deterioration takes place, specified as ex-ante risk. And another, after risk control actions or significant events take place, technically termed ex-post risk. Alternatively, the risk after the application of control measures is called residual risk.

Risk management consists of actions that reduce the frequency of incidents and the magnitude of losses. Risk management parameters, like network age, pipe material and hoop pressure, tend to have a clear spatial pattern. Actions on these parameters can affect the geographical distribution of risk. For instance, if more pipe leaks are observed in neighborhoods serviced predominately by cast iron lines, focusing on the maintenance of cast iron pipe will tend to make risk distribution more spatially homogeneous.

In addition, using risk maps to evaluate actions that have an unclear spatial pattern gives even more important insights. Consider two examples. First, in a situation where many risk control actions are taken together and the productivities of specific actions are unclear, maps of residual risk may elucidate productivity assumptions if an unexpected geographical pattern emerges. Second, residual risk information in risk maps may provide better insights than mere quality control information. If a maintenance crew operates in areas that are tough or costly to operate on, then worse than average quality results should be expected.

The improved analysis capabilities offered by risk maps are accompanied by further advantages. If the risk map represents the window in the risk performance world that upper management observes, then better resolution in the risk picture will have effects on learning. Verification of information and assumptions after presumably many years of service in the industry by the upper management group will be more effective with the utilization of risk maps. In addition, given the importance of risk distribution in obtaining insights for risk management, understanding the risk map in one year will make analysis of risk maps for years to come faster and more effective. A summary of the advantages risk maps provide in upper management decision making appears in Table 5.1 .

Risk management decisions within the corporation or between the corporation and outside stakeholders involve many individuals, who tend to focus on different attributes of the risk indicators and put different weights on the various indicators. By being richer in information, risk maps make the identification of foci different individuals have easier, and are more likely to serve as a board for drawing compromise solutions. For instance, using a risk control policy to influence the cumulative risk curve, may provoke confusion. Changing the distribution of risk on a map, is easier understood and thus compromise solutions may be easier to design, and bargain for.

Table 5.1: Reasons for the particular importance of Risk Maps to Network Industries	
I.	Local Concentration of Losses
II.	Spatial Distribution of Risk Control Factors
III.	Understanding Distribution of ex-ante Risk Burden
IV.	Understanding Distribution of Residual Risk Burden
V.	Knowledge Acquisition by Upper management

Risk maps may be drawn using a variety of formats. A low resolution map is shown in Figure 5.1. Higher resolution maps with more detailed risk contours, many colors and symbols may be drawn. The term risk map encompasses all risk indicators depicting a geographical distribution of risk.

The specifics of risk map design are left to specialists (i.e. risk communication professionals, technical writing specialists, and human factors engineers) with one important exception. The information interlayed with risk distribution lines, such as neighborhood boundaries, should be carefully selected to be appropriate for specific decision contexts. The following can serve as choices of background information:

1) Political boundaries (e.g. municipality, county, state lines)

2) Topographical information (e.g. describing the transportation network and topographical details)

3) Technological information (e.g. subregions with distinct characteristics with respect to the network attributes - network density, pipe pressure, predominant material)

4) Scientific information (e.g. soil type)

5) Organizational information (e.g. service jurisdictions of operational units)

It is easy to interlay this information in any combination at the touch of a button using G.I.S. (Geographic Information System) technologies. Nonetheless, upper management should not be confounded by endless versions of the same map. Sometimes it is easy to adopt one map background, when organizational, political and topographical boundaries essentially coincide.

We proceed with a brief description of how risk maps can be used for better decisions in budgeting for maintenance and in evaluating the consistency of corporate risk prioritization rules.

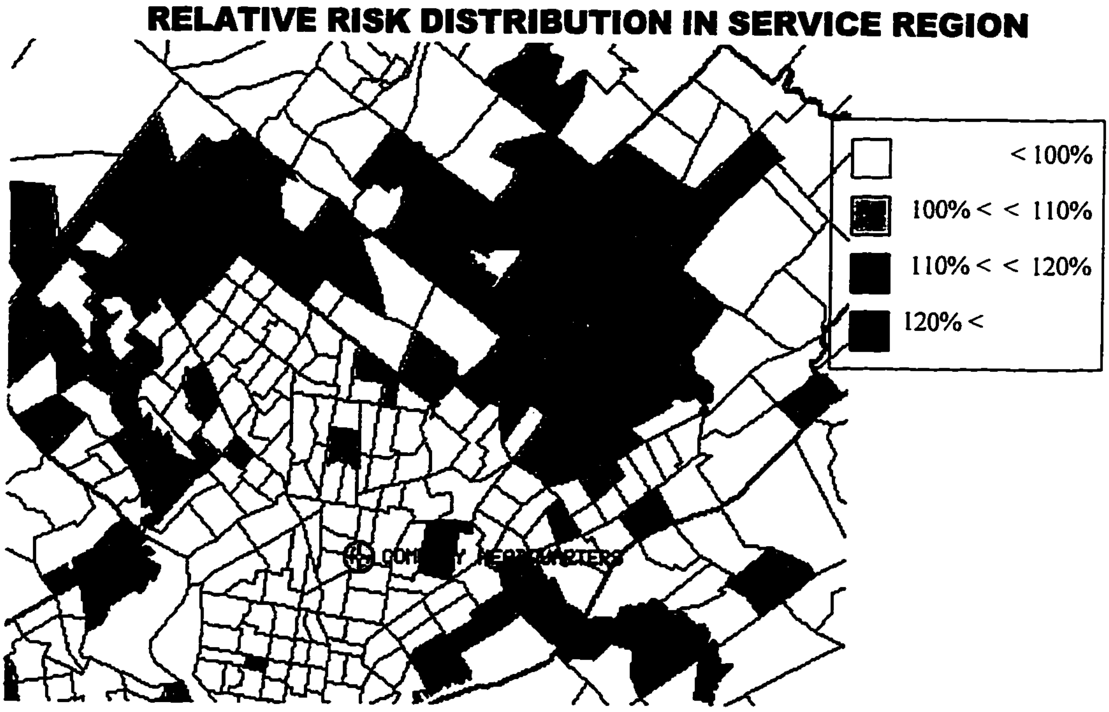

Figure 5.1: Regional Risk Map example for a fictitious Natural Gas Utility. The average risk in the region is normalized to 100%. It appears risk is not distributed homogeneously. A statistical analysis is needed however to establish this hypothesis.

Safety Budget Evaluation

Consider now the problem of evaluating the yearly safety budget. Budget evaluation will typically take place before the budget for the following year is determined. The role of upper management is to monitor the productivity of the maintenance/operations department, assess the appropriateness of the budget level, and form insights that will help in developing a corporate strategy for safety and handling crises related to catastrophic events.

This decision process takes place within the corporation, so verification requirements are assumed to be low. Upper management understands the basic operations and processes for risk management. Operations people follow corporate procedures, have incentives to produce satisfactory results and disincentives to avoid disasters, and information about possible misbehavior is likely to become known through informal communication channels within the organization. Shareholders, banks and insurers may also want to be informed on these decisions but here we focus mainly on internal monitoring.

In the network industries and particularly in a natural gas distribution network, inspection and maintenance is very complex mainly because of the large network size (measured in thousands of pipeline miles for instance). Consider a Gas Utility evaluating its pipeline inspection, maintenance and safety budget. The previous year's risk picture is presented as follows. The budget in constant dollars is the same it has been for a decade, but pipeline risk is judged to be up due to a significantly increased number of leaks that needed repair the previous year. It is known that no major addition or retirement of assets has occurred in the pipeline network over the past years.

What is the cause of the increase in pipeline risk? Is it that the network has been aging as a whole so major network replacement has to be carried out (and at what rate)? It may be that cheap opportunities for risk reduction (e.g. through replacement of easily accessible worn pipe) have been running out. Or it may be that operations people do not efficiently target the right opportunities for risk reduction in the network, because of some sort of bias. The answers to these questions are rarely obvious, but the use of more analytic risk indicators and in particular risk maps is likely to provide a significantly improved monitoring device.

Local conditions (e.g. population density, accessibility to maintenance crews, soil type) vary throughout the region of service. The network is also not homogeneous in factors that determine pipeline risk (e.g. pipe size, gas pressure, material). As a result there are many interactions between factors affecting local risk and these affecting local maintenance productivity. It is likely that the distribution of local risk indicators (e.g., joint leaks, pipe breaks) will produce recognizable patterns in space in the form of clustering.

The spatial risk and safety productivity patterns are difficult to analyze, but they are also difficult to manipulate. Risk map analysis for safety budget evaluation will produce three important benefits:

1) In the effort to explain to upper management the reasons for spatial patterns in the risk map important insights will be obtained. Upper management also may offer its wisdom to the operations department, especially when experience and a better vantage point makes their input indispensable.

2) Manipulation of the spatial patterns in the Risk Map is clearly more difficult than manipulation of the overall risk numbers. If one attempts to show a better or worse risk map than one representative of reality, the proposed map would have to be consistent with

the presumed beliefs of upper management. Given the difference in vantage point, it is easier to dumbfound the perpetrators.

3) The Risk Map may provide the impetus to increase the total level of spending (or to redistribute the budget) so that the risk performance of a heavily burdened subregion may be improved, in addition to achieving satisfactory overall risk performance.

Legitimation of Risk Reduction Prioritization

As we have described in chapter 1, the spirit of the US pipeline safety law is that the spatial distribution of risk should be homogeneous[23]. That is, locations where the magnitude of losses is expected to be high (due to high population density) should have stricter local technical regulations, so that catastrophic incidents are less likely. Spatial homogeneity of risk is not legally required, even though it may be perceived as a signal of lack of compliance to technical regulations by government agencies.

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[23] For more precise definitions of stochastic homogeneity in space and its statistical analysis see [Getis and Boots, 1988].

Given the rarity of pipeline failures leading to catastrophic events, residents of city neighborhoods with a history of failures may organize to protest for being unfairly treated. These complaints may be based on a statistical analysis of pipeline incidents in the region, or they may be substantiated by a myopic analysis of the past few incidents. Both cases may constitute a crisis for a Natural Gas Utility, potentially leading to a multitude of adverse scenaria for the company. Examples include:

1) Attraction of unwanted attention by a regulatory agency overseeing risk performance through increased safety audits.

2) Negative press spoiling the image of the company.

3) Loss of cooperation from customers throughout the region, hurting the prospects of projects to increase natural gas consumption (e.g. through promotion of natural gas heating), reduce delinquent accounts, or finally secure rights of way for network expansion. These are just three examples where cooperation from citizens, media and local politicians has high value to the company. A strategic analysis for each individual company may reveal further risks of this sort.

4) Triggering chain reactions with adverse effects for every company in the industrial sector (e.g. lack of confidence in natural gas as a legitimate source of energy, or iron clad regulation at the federal level).

It is presumed that different crisis management approaches will be pursued depending on whether or not the company believes a spatial risk bias exists. We will show that risk maps can have a determining role both in selecting and supporting a defense strategy for a company facing a claim of spatial bias in its risk performance. When a valid risk map is available internally to the company, the distribution of near misses (e.g. leaks, breaks) will be obvious and quite likely statistically verifiable. No spatial bias in near misses is a strong indication for lack of bias in actual risk. After an analysis of the risk map, the company may chose among three strategies:

A) **"Acknowledging Poor Performance":** The company should facilitate law enforcement and appropriately punish personnel not fulfilling their duties. Legal and media damage control policies should also be pursued.

B) **"Establishing No Spatial Bias Exists":** It is debatable whether a homogeneous risk map is sufficient to satisfy the demands of angry citizens and customers complaining about pipeline failures. However, if the analysis of risk homogeneity has been performed according to an acceptable statistical method, the risk map may be of paramount importance for legal defense purposes. Comparisons of incident records of the neighborhood in question with other typical city neighborhoods, is likely to have significant results if it is not the most burdened neighborhood in service. If this is not the case, then comparison with other cities serviced by a similar network may make clear that random variations may lead to perceptions of bias even if one doesn't exist.

C) "**Substantiate That a Bias Exists Which Is Beyond Company Control":** A number of causal factors for an undue spatial burden of a subregion (e.g. a neighborhood) may be in place, despite mitigation efforts by the company. First, the prevalence of risk increasing pilfering (i.e. bypassing gas meters or pandering with their accuracy) may be higher in one subregion than it is in others. As a result frequent pilfering areas face higher risk despite actions of the company to prevent it. Second, variable soil corrosivity or other technical factors may make an area serviced by pipelines according to regulations to be riskier than others[24]. And third, replacing an old pipeline network (typically in service for more than fifty years) may take a long time even if significant funds are devoted to construction. Areas not yet visited by construction crews may be shouldering a higher risk burden. In the latter case, a company may face the curse of everyone trying to beat a bad record, despite excellent efforts in the present, results are influenced by past actions.

As it becomes clear from the previous analysis, the presence of a risk map is necessary when risk equity issues have to be addressed. The important argument advanced in this paper is that both efficiency and equity may be advanced when risk maps are used in network industries. Implementation of risk maps for upper management decisions used to be very difficult in the past, but today barriers have been dropped due to improvements in information technology.

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[24] Just following the regulations is hardly a defensible and ethical policy for a company. Until recently the pipeline industry was regulated with respect to both price and safety, thereby leaving little freedom for a company to show its ethical nature.

CHAPTER 6 : SUMMARY AND CONCLUSIONS

As we noted in introduction, natural gas is widely considered to be an environmentally friendly energy source, therefore a low risk one. Long term benefits from lowering pollution by increased natural gas usage need to comfortably balance out the risks of extra catastrophic events from possible pipeline failures, in order for the natural gas industry to capitalize on its environmentally friendly image.

The public has a long experience with natural gas as a fuel for residential heating and cooking. Therefore, according to [Slovic et al., 1979], familiarity would make pipeline risk relatively easier to accept than other catastrophic risks. Furthermore, there do exist insurance policies for natural gas fires at homes and for liabilities of natural gas companies. One can surmise that insurers consider pipeline risk to be well understood and satisfying insurability conditions (e.g avoidance of moral hazard and adverse selection). It seems that high powered quantitative techniques usually associated with Systems Engineering and Operations Research (e.g. Computer Simulation, Combinatorial Optimization, and Multicriteria Optimization) can be applied more easily to pipeline risk analysis and management than to other risks depending on imponderable factors.

Quantitative risk management techniques legitimable to the public may provide the opportunity for a different form of organization to the natural gas industry. Indeed such a movement away from strict command and control is at works in the US and it is accepted as a concept from regulators and industry. The essence of this new framework is that risk management plans, created possibly individually for each company's specific needs, will be submitted to regulators for approval. If these plans are considered to guaranty the risk to the public is at least as low as the status quo, then the company is left to manage its risks on its own.

Clearly a formal analysis for the acceptance of risk management plans will be needed, both because acceptance will occur on routine basis and because a common standard should be legally imposed to all companies. Moreover a more refined analysis will be needed for the design of risk management plans.

From the point of view of Systems Engineering research the problem of designing a good risk management plan is more interesting than that of approving it. This is why all analysis presented in this work is from a company's the point of view and not that of the regulator. It is essential, however, for people imposing informational requirements to industry to study analyses like the one presented here, in order to understand what constitutes attainable and verifiable risk assessment accuracy.

The innovation we introduce is the risk map as a platform for risk management decisions. The existing risk assessment systems and in particular the widely accepted CIMOS do not control the spatial distribution of risk. We showed in chapter 5 that this is not the best strategy, because public image crises after pipeline failures are easier to cope with when management systems based on risk maps are present, and it is easier to evaluate the efficiency of a safety budget by considering risk maps.

On the low side, risk maps put a considerable information load to decision makers, so they in turn have to be experienced with the realities of a pipeline system and with risk maps. In addition, when risk maps are created using near misses, they are not verifiable by external parties unless a rigid near miss reporting system is in place. On balance, risk maps are not significantly more costly to obtain than other risk indicators and offer significant opportunities for improved corporate governance.

In chapter 3 we showed how risk maps can be generated using risk analysis. Alternatively, one may use maps of the distribution of near misses. We expect that in the near future higher availability of Geographic Information Systems will make studies of the latter type easier to implement. The informational requirements for risk maps according to our approach are: network layout, including distribution of risk control factors, and functional relations between them and after failure losses. Some of the control factors are easy to verify (e.g. size, material), others are not as easy (e.g. condition of cathodic protection, leak history). To the extent that difficult to verify factors leave the spatial distribution of risk unaffected, risk maps are verifiable by external parties.

It was shown that when risk sources are independent it is easy to generate a risk map, given the usual computing capabilities companies have. For dependent risk sources, corresponding to after natural disaster behavior, more complicated computations are required. Crude Monte Carlo Simulation can be radically improved over, when the control variate method is applied. It is important to note, that variance reduction techniques increase the complexity of computer programs calculating risk maps in terms of lines of code, as opposed to run time which is reduced. *This complexity increase doesn't decrease verifiability*, because a more verifiable tool (the crude Monte Carlo method) exists to attest risk map accuracy.

Additional work with simulation will be very useful in analyzing cases where risk source dependence takes specialized forms. Particularly when failure at one point can excite or inhibit a risk source at another point.

In chapter 4 we have developed a procedure for optimal segment replacement in a network so that the net benefit of risk reduction is optimized. This procedure may find applications to the maintenance of all infrastructure systems representable by a network (eg. Highway, Railway, Power line networks). For this maintenance procedure, risk, cost and location information for each individual network segment are necessary inputs. Clearly, a GIS system is required in order for the benefits from applying our procedure to be realized. The trend in the pipeline industry and in other network industries is that GIS systems are becoming standard tools for managing operations, hence this procedure appears to have a promising future.

The intuitive idea that segments in the same neighborhood will be replaced together, so that relative location of construction sites is a factor to take account for, is formalized in chapter 4. We also show that general purpose methods like integer programming are not practicable when network size increases.

As far as verifiability is concerned, this procedure is relatively difficult to communicate to external stakeholders and in the typical case it returns approximations to the absolute optimum allocation instead of exact solutions. These factors, as we explained in Chapter 5, introduce complexities in designing legitimable risk management processes. On the other hand, if a risk map analysis shows that a company implementing our procedure shows safety improvements for all stakeholders after some years of implementation, then it is reasonable to assume that our procedure will not only be attractive to the company, but also defensible to external parties.

Clearly much remains to be done in extending and verifying the practical utility of the models and approaches presented. Verifying the computational robustness of the maintenance models of Chapter 4 and extending or modifying these to account for multi-year dynamics present fascinating opportunities for continuing research. Similarly implementing risk maps and associated management interfaces for natural gas or other risk areas (e.g., propane and chlorine) represent important areas for future applied research.

The unifying principle of all models presented here is that quantitative techniques, so important in continuous safety improvement, have the potential to gain acceptance both from upper management and from external stakeholders despite their inherent complexity. The goal of future research must be to establish clearly the conditions under which these methods have more explanatory power and better prescriptive performance than current heuristic methods. It is hoped that this dissertation has provided a foundation and a beginning for pursuing this goal.

APPENDIX

Computer Code in C for Risk Map Generation

```
#include <math.h>
#include <stdio.h>
#include <stdlib.h>
#define CYCLES 100000
#define CYCLES_MC 1000
#define RAND_START 33333
#define N_SOURCES 4
#define P_VALUES 8
#define REGIONS_X 2
#define REGIONS_Y 2
#define D_ 1.
/* GRID Characteristics */
#define GRID_RESOLUTION 50
#define XMIN 0
#define XMAX 1000
#define YMIN 0
#define YMAX 1000

static float rand_range=2147483648.;

struct i_pair
{
  int i;
  int j;
};

struct location_s
  {
    float x;
    float y;
  };

struct prob_s
  {
    float v;
    float p;
  };
```

```
static struct region_s
{
  float v;
  float p;
  float u;
  float xmin;
  float xmax;
  float ymin;
  float ymax;
} region[2][2];


static struct source_s
{
  struct location_s location;
  float hazard;
  struct prob_s prob[P_VALUES];
} source[N_SOURCES];


float (*risk_at)(struct location_s loc);

float one_cdf(x,p)
struct prob_s p[P_VALUES];
float x;
{
  float result=0.0;
  int i=0;

  if (x>1.0) return 0;

  if (x<0.0)
    {printf("ERROR: Wrong input in one_cdf() \n");
     return (1.0);  }

  while( x>=p[i].v )
    {
      result += p[i].p;
      ++i;
    }
  result=1.0-result;
  return (result);
}
```

```
float inv_prob(P,p)
struct prob_s p[P_VALUES];
float P;
{
int i=0;
while(p[i].p<P)
  {
    P -= p[i].p;
    ++i;
  }
return (p[i].v);
}

float radius(loc1,loc2)
struct location_s loc1,loc2;
{
  float r,dx,dy,rsq;
  dx=loc2.x-loc1.x;
  dy=loc2.y-loc1.y;
  rsq=dx*dx+dy*dy;
  r=sqrt(rsq);
  return (r);
}

float f_w (sloc,loc)
     struct location_s sloc,loc;
{
  float factor,r;
  float base=3.0;
  r=radius(sloc,loc);
  if (r<0.001) return(1.0);
  factor=(loc.x-sloc.x)/r;
  factor=(base+factor)/base;
  return (factor);
}

struct i_pair i_region(loc)
struct location_s loc;
{
  struct i_pair I;

  I.i=I.j=0;
  while(region[I.i][I.j].xmax<loc.x) ++I.i;
  while(region[I.i][I.j].ymax<loc.y) ++I.j;
  return I;
}
```

```
float risk_to_point_from_source(loc,s)
      struct location_s loc;
      struct source_s s;
{
  struct i_pair reg;
  struct region_s pt;
  float result,inv_attn,ru,fw;
  reg=i_region(loc);
  pt=region[reg.i][reg.j];
  ru=radius(loc,s.location) * pt.u;
  fw=f_w(s.location,loc);
  inv_attn=exp(ru)*pt.p/(pt.v*fw*s.hazard);
  result=one_cdf(D_*inv_attn,s.prob);
  return result;
}

float point_risk(loc)
struct location_s loc;
{
float sum=0;
int i;

for (i=0 ; i<N_SOURCES ; ++i )
   sum += risk_to_point_from_source(loc,source[i]);
return sum;
}


int is_in_bounds(x,bound)
      float x;
      float bound;
{
  float u_bound,l_bound;
  u_bound=1.1*bound;
  l_bound=0.9*bound;
  if (l_bound < 0.0001) l_bound = 0.0001;
  if (x<=bound && x>=l_bound) return(1);
  return(0);
}
```

```
void read_inputs (FILE *input_file)
{
int i,j;
int index=0;
struct region_s *r_p=&region[0][0];

for(index=0; index<N_SOURCES ;++index)
  {
/* Proceed in input_file untill first datum is met */
while(getc(input_file) != '-') ;

if (feof(input_file))
fprintf(stderr,"ERROR while reading source data from
<plane_risk.input>");

/* Read Source Data using appropriate structure */
fscanf(input_file,"%f
%f\n",&source[index].location.x,&source[index].location.y);
fscanf(input_file,"%f\n",&source[index].hazard);
for(i=0;i<P_VALUES;++i)
  {
fscanf(input_file,"%f
%f\n",&source[index].prob[i].v,&source[index].prob[i].p);
  }
   }

for(i=0;i<REGIONS_X;++i)
for(j=0;j<REGIONS_Y;++j)
  {
    /* Proceed in input_file untill first datum is met */
    while(getc(input_file) != '-') ;

    /* Read Region Data using appropriate structure */
    fscanf(input_file,"%f %f %f\n",&r_p->v,&r_p->p,&r_p->u);
    fscanf(input_file,
         "%f %f %f %f\n",&r_p->xmin,&r_p->xmax,&r_p->ymin,&r_p-
>ymax);
    ++r_p;
  }

fclose(input_file);
}
```

```
float attn(loc,s)
     struct location_s loc;
     struct source_s s;
{
  struct i_pair reg;
  struct region_s pt;
  float ru,fw;

  reg=i_region(loc);
  pt=region[reg.i][reg.j];
  ru=radius(loc,s.location) * pt.u;
  fw=f_w(s.location,loc);
  return (pt.v*fw*s.hazard)/(exp(ru)*pt.p);
}


float rand_1()
{
  return ((float) random()/rand_range);
}


float point_corr_risk(struct location_s loc)
{
  int i,j;
  float sum,est,a[N_SOURCES];

  for(i=0;i<N_SOURCES;++i)
    {
      a[i]=attn(loc,source[i]);
    }

  for(j=0,est=0;j<50;++j)
    {
      for(i=0,sum=0.;i<N_SOURCES;++i)
      {
        sum += a[i]*inv_prob(rand_1(),source[i].prob);
      }
      est+=(sum>D_);
    }

  if(est==0) return 0.;
```

```
for(j=0;j<CYCLES;++j)
  {
   for(i=0,sum=0.;i<N_SOURCES;++i)
   {
    sum += a[i]*inv_prob(rand_1(),source[i].prob);
   }
   est+=(sum>D_);
  }
 fprintf(stderr,".");
 return (est/((float) CYCLES+50));
}

float point_corr_risk_cv(struct location_s loc)
{
 int i,j,k,N_big_a,N_nonzero_a,flag;
 float sum,max,est,est_av,Li;
 float a[N_SOURCES];
 float threshold=.01 * D_ / ((float) N_SOURCES);
 struct index_s
  {
   int pos;
   int big;
  } I[N_SOURCES];


 for(i=0,j=0,k=0,max=0;i<N_SOURCES;++i)
  {
   a[i]=attn(loc,source[i]);
   if(a[i]>max) max=a[i];
   if(a[i]>D_) I[k++].big=i;
   else if (a[i]>threshold) I[j++].pos=i;
  }

 if(max< (D_ / ((float) N_SOURCES))) return 0.0 ;

 N_nonzero_a=j;
 N_big_a=k;
```

```
  for(j=0,est=0;j<200;++j)
    {
      for(i=0,sum=0.;i<N_nonzero_a;++i)
      sum += a[I[i].pos]*inv_prob(rand_1(),source[I[i].pos].prob);

      for(i=0,flag=0;i<N_big_a;++i)
      {
        Li = a[I[i].big]*inv_prob(rand_1(),source[I[i].big].prob);
        sum += Li;
        flag += (Li>D_);
      }
      est+=(sum>D_)-flag;
    }
  if(est==0)
    {
      for(i=0,est_av=0.;i<N_big_a;++i)
      est_av += one_cdf(D_/a[I[i].big],source[I[i].big].prob);

      return est_av;
    }

  for(;j<CYCLES_MC;++j)
    {
      for(i=0,sum=0.;i<N_nonzero_a;++i)
      sum += a[I[i].pos]*inv_prob(rand_1(),source[I[i].pos].prob);

      for(i=0,flag=0;i<N_big_a;++i)
      {
        Li = a[I[i].big]*inv_prob(rand_1(),source[I[i].big].prob);
        sum += Li;
      flag += (Li>D_);
      }
      est+=(sum>D_)-flag;
    }

  est_av=est/((float) CYCLES_MC);

  for(i=0;i<N_big_a;++i)
    est_av += one_cdf(D_/a[I[i].big],source[I[i].big].prob);

  return est_av;
}
```

```
float risk_profile(FILE *mathcad)
{
int i,j,irisk;
float dx,dy,ave_risk=0.0,row_risk;
float risk[GRID_RESOLUTION] [GRID_RESOLUTION];
struct location_s loc,uploc;

dx=(XMAX-XMIN)/GRID_RESOLUTION;
dy=(YMAX-YMIN)/GRID_RESOLUTION;

/* CALCULATION OF RISK MATRIX */
for (j=0;j<GRID_RESOLUTION;j++)
  {
    for (i=0,row_risk=0.0;i<GRID_RESOLUTION;i++)
      {
      loc.x=(float)i*dx;
      loc.y=(float)j*dy;
      risk[i] [j]=(*risk_at)(loc);
      row_risk+=risk[i] [j];
      }
    ave_risk+=row_risk/GRID_RESOLUTION;
  }
ave_risk=ave_risk/GRID_RESOLUTION;


/* SMOOTHING OF RISK MATRIX */
/* GENERATION OF OUTPUT FILE */
/* First Row */
j=0;

i=0;
irisk=(int)(100*
          (0.5*risk[i] [j]+0.5*
           0.5*(risk[i+1] [j]+risk[i] [j+1]))
           /ave_risk);
fprintf(mathcad,"%d\t",irisk);

for (i=1;i<GRID_RESOLUTION-1;i++)
  {
    irisk=(int)(100*
           (0.5*risk[i] [j]+
            0.5*0.333*(risk[i-1] [j]+risk[i] [j+1]+risk[i+1] [j]))
           /ave_risk);
    fprintf(mathcad,"%d\t",irisk);
  }
```

```
irisk=(int)(100*
          (0.5*risk[i][j]+
           0.5*0.5*(risk[i-1][j]+risk[i][j+1]))
          /ave_risk);
fprintf(mathcad,"%d\n",irisk);

/* Main Rows */
for (j=1;j<GRID_RESOLUTION-1;j++)
  {
    i=0;
    irisk=(int)(100*
            (0.5*risk[i][j]+
             0.5*0.333*(risk[i][j-1]+risk[i][j+1]+risk[i+1][j]))
            /ave_risk);
    fprintf(mathcad,"%d\t",irisk);

    for (i=1;i<GRID_RESOLUTION-1;i++)
      {
      irisk=(int)(100*
            (0.5*risk[i][j]+
                 0.5*0.25*(risk[i][j-1]+risk[i][j+1]+
                 risk[i+1][j])+risk[i-1][j])/ave_risk);
      fprintf(mathcad,"%d\t",irisk);
      }

    irisk=(int)(100*
            (0.5*risk[i][j]+
             0.5*0.333*(risk[i][j-1]+risk[i][j+1]+risk[i-1][j]))
            /ave_risk);
    fprintf(mathcad,"%d\n",irisk);
  }

/* Last Row */
i=0;
irisk=(int)(100*
          (0.5*risk[i][j]+
           0.5*0.5*(risk[i+1][j]+risk[i][j-1]))
           /ave_risk);
fprintf(mathcad,"%d\t",irisk);
```

```
for (i=1;i<GRID_RESOLUTION-1;i++)
  {
    irisk=(int)(100*
            (0.5*risk[i][j]+
             0.5*0.333*(risk[i-1][j]+risk[i][j-1]+risk[i+1][j]))
            /ave_risk);
    fprintf(mathcad,"%d\t",irisk);
  }
irisk=(int)(100*
          (0.5*risk[i][j]+
           0.5*0.5*(risk[i-1][j]+risk[i][j-1]))
          /ave_risk);
fprintf(mathcad,"%d\n",irisk);


fclose(mathcad);
return ave_risk;
}


main()
{
  float average;

  srandom(RAND_START);

  /* UNCORRELATED SOURCES */
  read_inputs(fopen("plane_risk_uncorr.input","r"));
  risk_at=point_risk;
  average=risk_profile(fopen("Uncorr.prn","w"));
  printf("UNCORRELATED SOURCES: Average Risk = %5f\n",average);

  /* CORRELATED SOURCES */
  read_inputs(fopen("plane_risk.input","r"));

  risk_at=point_corr_risk_cv;
  average=risk_profile(fopen("Corr.prn","w"));
  printf("CORRELATED SOURCES: Average Risk = %5f\n",average);

  risk_at=point_risk;
  average=risk_profile(fopen("CorrTAU.prn","w"));
  printf("CORRELATED SOURCES TAU: Average Risk = %5f\n",average);
}
```

Algorithm for the contraction of arcs with positive net benefit in pseudocode

```
Input:          G
Output:         $I_m(i)$ $\forall i \in V$
Initialize:     $\forall i \in V$ $m(i) := i;$
                $\forall i \in V$ $I_m(i) = \{i\};$

$\forall (i,j) \in S$   do
begin
    if $b_{ij} > 0$ then
    begin
        for all $k \in I_m(j)$
            $m(k) := m(i);$
        $I_m(m(i)) := I_m(m(i)) \cup I_m(m(j));$
        $I_m(m(j)) := \varnothing;$
    end;
end;
```

Algorithm for the determination of site interlinks in pseudocode

```
Input:           L(i,j),F(m), $V_R$
Output:          {F(m,j) $\forall$m,j$\in V_m$ , m$\neq$j}

for all m$\in V_m$  do
begin
u(m):=0;
T:=$V_R$ -{m};

for all j$\in$T  do
      begin
      u(j):=L(m,j); (cmnt: L(m,j)=INF when (m,j) not in $A_F$)
      end;
label loop_start;
min=INF; (comment: INF is a large enough value)
for all j in T do
      if u(j)<min then do
            begin
            i_min=j;
            min=u(j);
            end;
if(i_min$\in V_m$) F(m,i_min):=min;
T:=T-{i_min};
if (T=$\emptyset$ OR min>F(m)) then goto out_of_loop;
for all j in T do
      if(u(j)>min+L(i_min,j))
            then u(j):= min+L(i_min,j);
goto loop_start;
label out_of_loop;
end;
```

Algorithm for the Augmentation of the Lagrangean

Solution in pseudocode

```
Input:        W, $V_{acc}$, $\beta(\bar{\lambda})$
Output:       $A_{aug}$, f($A_{aug}$), $\beta$($A_{aug}$), optimal($A(\bar{\lambda})$)
Initialize:   $A_{aug}$:= $A(\bar{\lambda})$, f($A_{aug}$):=f($\bar{\lambda}$), $\beta$($A_{aug}$):=$\beta$($\bar{\lambda}$)
              $V_{acc}$:= $V_{acc} \cup \{$Origin$\}$
              optimal($A(\bar{\lambda})$):=0

while($\beta$($A_{aug}$) $\leq 0$) do
begin
ymax:=0;
for all (w,f) in W do
if($i \in V_{acc}$ OR $j \in V_{acc}$ AND ymax $\leq y_{ijk}$) then
      begin
      imax:=i;
      jmax:=j;
      kmax:=k;
      ymax:=$y_{ijk}$;
      c:=$c_{ijk}$; (comment: $c_{ijk} = w_{ijk}/\left(y_{ijk}^{-1} - 1\right)$ )
      end;
      if(ymax<0) then
            begin
            optimal($A(\bar{\lambda})$):=1;
            $V_{acc}$:=$V_{acc}$+$\{$jmax,imax$\}$;
            if(kmax=-1) then imax:=Origin;
            if(kmax=1)  then jmax:=Origin;
            $A_{aug}$:=$A_{aug}$+$\{$(imax,jmax)$\}$;
            $\beta$($A_{aug}$):=$\beta$($A_{aug}$)+c;
            end;
      else stop;
end;
```

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