Optimization of Routing a Pipeline Between a Reservoir and a Water Treatment Plant

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Abstract

This project investigates the optimization of routing a pipeline between a reservoir and a water treatment plant using a mixed integer programming method in GAMS. The model incorporates flow, diameter, capacity, and mass balance constraints to minimize the total construction cost. The model identified a route passing from the Reservoir through nodes B and D and to the Water Treatment Plant as the lowest cost route. The total cost of the route was $105. While GAMS is able to effectively use mixed integer programming to optimize pipeline routing, the practical use in the engineering consulting industry is limited. Implementing this problem in ArcGIS Pro would provide clearer visual representation of solutions, and use of widely known software within the engineering industry.

Introduction

The objective of this project is to determine the optimal route a pipeline would take to connect a reservoir and a water treatment plant (WTP). A depiction of the project layout can be found in Figure 1. The optimization was carried out using mixed integer programming in GAMS software. A more effective application of this problem could be done using more visual software like ArcGIS Pro.

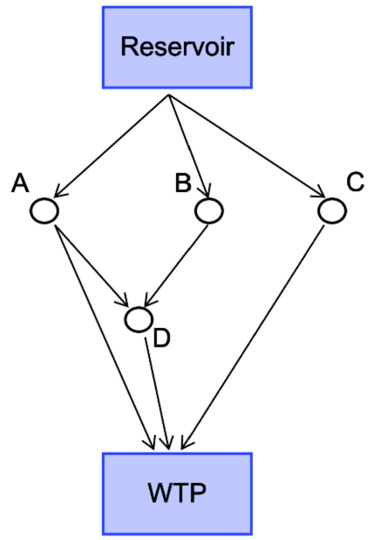

Figure 1. Project Layout

Literature Review

Pipeline routing and network optimization have been a research focus for many engineering disciplines. Recent studies highlight the integration of using advanced techniques like machine learning, or mixed integer optimization, to solve complex problems.

Alavi et al. (2025) developed a GIS-based model to optimize routing selection considering geotechnical, seismic, and cost considerations. An algorithm that models the social behavior and movement patterns of organisms was used to explore routing alternatives. The method was applied to two case studies in Iran to demonstrate effectiveness. In both cases, the routes created by the model had lower project cost, and a reduced seismic risk.

Armin et al. (2021) reviewed machine learning techniques used for routing optimization in software-defined networking (SDN). They organized existing studies into supervised, unsupervised, and reinforcement learning categories and found that the best approach depends on the size and type of the dataset and the problem being addressed. The authors also noted that most research relies on simplified test scenarios, limiting the conclusions that can be drawn.

Guirardello and Swaney (2005) investigated pipeline routing within process plants by dividing the layout problem into manageable subproblems. Process Plants were divided into smaller modules, each with a limited number of components. Routing optimization was first performed on the layout of components in each module, followed by the optimization of the arrangement of all the modules. The authors formatted this problem as a mixed integer linear programming (MILP) model and showed that this approach is effective for improving plant layout designs.

He et al. (2019) presented two mixed integer non-linear programming (MINLP) models focused on optimizing the topological structure of a pipe network and the routing of pipelines across 3D terrain to minimize land development costs. Their method combined the Floyd algorithm with a weighted grid (FAWG). Their approach produced faster computation times and was more innovative compared to existing models.

Skretas et al. (2022) emphasized that selecting optimal pipeline routes should consider design, construction, and maintenance and operation costs across all considered alternatives. They developed a computer-based optimization tool with an environmental cost function. The model was applied to an oil pipeline project in Greece. The optimized routes from the model compared well with a route proposed by the pipeline company.

Methods

This model followed the steps outlined below:

Step 1: Define dimensions, decision variables, and identify constraints.

- Dimensions:
  - Space: where to construct pipe segments (from one source location to one demand location)
- Decision Variables:
  - Flow (volume): What flow is used in each pipe segment.
  - Diam (length): What diameter is used in each segment.
- Constraints:
  - No negative decision variables
  - Flow in each pipe segment must be less than or equal to capacity
  - If a pipe segment is chosen, its diameter must be greater than or equal to the minimum diameter
  - Flow into each node must equal flow out of each node
  - Flow into the water treatment plant must be greater than or equal to the demand.

Step 2: Determine the objective function.

- Min Z = $\sum_{\text{UsedPipelineSegments}}$(Cost Coefficient * Diameter)
  - Minimize the total cost ($) of pipeline construction for all possible routes.

Step 3: Create a process in GAMS to solve this problem.

A mixed integer programming method in GAMS was developed to solve this problem. Cost per unit length of each pipe segment was created to consider the cost of the slope and diameter used in the segment. A table with the unit costs is shown below, where R, A, B, C, D, and W, represent the Reservoir, nodes A, B, C, and D, and the Water Treatment Plant Respectively.

Table 1. Cost Coefficient

Segment	R to A	R to B	R to C	A to D	A to W	B to D	D to W	C to W
Cost	10	8	9	7	15	8	5	20

Results

After following the methods listed above, it was determined that a minimum construction cost that could be generated was $105. The best possible route for this problem was to go from the Reservoir through nodes B and D, and then to the Water Treatment Plant with a diameter of 95. Figure 2 shows a depiction of the optimized route in yellow.

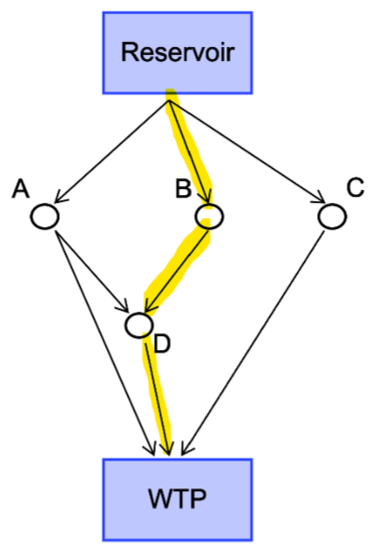

Figure 2. Optimized Route

Practical Applications for the Consulting Industry

While mixed integer programming using GAMS is an effective way of solving this optimization problem, it has limited applicability within the engineering industry. GAMS software requires costly licensing and is not widely used by practicing engineers. Additionally, GAMS output is not visual, which limits its usefulness for easy visual communication. Implementing this optimization problem in ArcGIS Pro would have a better practical value. Most engineering consulting firms already have ArcGIS Pro licenses and are familiar with the software. ArcGIS Pro also offers tools to produce clear and comprehensive visual figures, making it well suited for presenting routing results in the consulting industry. An example of a figure for routing analysis that can be created using ArcGIS Pro is shown in Figure 3.

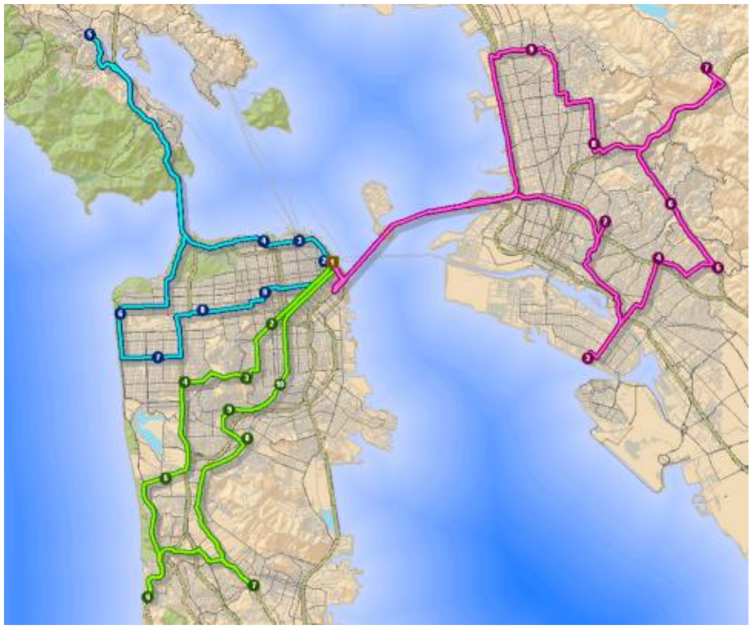

Figure 3. Using ArcGIS for Network Visualization (ESRI)

Conclusion

In conclusion, this project identified an optimal pipeline route between the reservoir and water treatment plant. Using linear programming in GAMS produced an optimal route of Reservoir to Node B to Node D to the WTP for a cost of $105. Although the GAMS based approach is effective for optimization, it could be applied more effectively in the engineering consulting industry through visual, industry standard software like ArcGIS Pro.

References

Alavi, Sayyed Hadi, et al. “Optimized seismic risk mitigation in pipeline routing using a metaheuristic GIS based approach.” Scientific Reports, vol. 15, no. 1, 25 Sept. 2025, https://doi.org/10.1038/s41598-025-17525-w.

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Appendix A – GitHub Link

https://github.com/tmindrum/CEE6410-Mindrum-Project/tree/main

Appendix B – Answers to Canvas Submission Questions:

I added figures to better illustrate the problem, as well as added units to decision variables and the objective function. I also turned all the information that I had previously into a report format so that the information flows nicely and is more easily digested.

Category (Possible Score)	No Evidence	Does not Meet Standard	Nearly Meets Standard	Meets Standard	Exceeds Standard	Self-Score	Instructor Score
Title (2)	Absent $\boxed{0}$	Evidence of one. $\boxed{0}$	Evidence of two. $\boxed{1}$	Evidence of three. $\boxed{1}$	Title, author name and contact info. Neatly finished with no errors. $\boxed{2}$	2	
Introduction (10)	Absent, no evidence $\boxed{0}$	There is no clear introduction, main topic, or outline of content. $\boxed{1 - 5}$	The introduction is either: 1. Too sketchy. Gives an inadequate overview, Or: 2. Too detailed, info later repeated $\boxed{6 – 7}$	The introduction overviews the project and previews the wiki page(s) structure $\boxed{8}$	The introduction overviews the project, work done, and organization of the wiki page(s). An effective summary. Gives enough detail to motivate the reader to continue reading. $\boxed{9 - 10}$	8	
Technical Content (43)	No content provided or analysis evident. $\boxed{0 - 10}$	Little content provided. The reader has no idea about the problem, solution method, results, or what was done for the project. $\boxed{11 – 20}$	Sketchy: may have left out 2 or more content areas; flimsy or incomplete methods; results have errors; and/or recommendations do not derive from the results. No tables, figures, or pictures presented. $\boxed{21 – 33}$	Wiki lacks adequate detail, but content for 4 of the 5 areas is provided and includes one or more tables, figures, or pictures. Most prior work referenced and hyperlinked. $\boxed{34 – 38}$	Defines problem, provides background information, describes solution method(s) used, and presents the results and recommendations that derive from the results. Uses tables, figures, and pictures to illustrate the above. Prior work referred to through references and hyperlinks. $\boxed{39 - 43}$	36	
Organization and Development (15)	No evidence of structure.	Little evidence of structure or organization. $\boxed{1 – 8}$	Organization of ideas not fully developed. Two or more pages, sections, or sub-sections missing or out of order. $\boxed{9 – 11}$	Sub-pages, sections, sub-sections, and/or lists present, but their use not perfected. $\boxed{12-13}$	Logical sequencing of ideas. Uses sub-pages, sections, sub-sections, and/or lists to order, present, and develop ideas. In each section, one or more paragraphs develop each idea. $\boxed{14 - 15}$	13	

Category (Possible Score)	No Evidence	Does not Meet Standard	Nearly Meets Standard	Meets Standard	Exceeds Standard	Self-Score	Instructor Score
Word Usage and Format (15)	Not applicable	Many, distracting errors in grammar, spelling, sentence structure, word usage, significant figures, tables, and figures. Unacceptable at the graduate level. 1 – 8	With some grammatical errors. Figures are too small and/or under-labeled, although they are usually of acceptable quality and focus. Incoherent tables. Inconsistent fonts and headings. Could be improved by being more meticulous. 9 – 11	Almost no errors in punctuation, capitalization, spelling, sentence structure, word usage, significant figures, and presentation of figures and tables. No broken hyperlinks. 12 – 13	Punctuation, capitalization, spelling, sentence structure, word usage, and significant figures all correct. Clear, consistent fonts and headings. Good wiki processing skills. Figures and tables presented in correct format. No broken or empty hyperlinks. 14 - 15	15	
Conclusions (10)	Absent 0	Incomplete and/or not focused. 4 - 6	The conclusion does not adequately restate the main findings. 7	The conclusion restates the main findings. 8	Effectively restates the main findings and recommendations to solve the problem. 9 - 10	8	
Hyperlinks and References (5)	Absent 0	With many errors or only 1 hyperlink provided. 1 – 2	With some errors and only 2 hyperlinks provided. 3	With few errors, at least 3 hyperlinks to content outside the USU domain 4	All citations and references listed in ASCE format with no errors. Include at least 4 hyperlinks to content or work outside the USU domain. 5	5	
TOTAL (100)						87	