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Pipeline Network Growth Optimisation for CCUS: A Case Study on the North Sea Port Cluster

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ABSTRACT

By 2050 around 12% of cumulative emissions reductions will come from Carbon Capture, Utilisation and Storage (CCUS) making it an essential component in the path towards net zero [1]. Focus will initially be on the retrofitting of fossil fuel power plants, which will shift to hard-to-decarbonise industries such as iron, steel, and concrete [1]. Such industries are often grouped together in industrial clusters. Comprising both large and small point sources concentrated over a defined geographical area, industrial clusters offer an opportunity to maximise the impact of CCUS whilst also improving economic feasibility [2]. The North Sea Port (NSP) cluster an example of this. Within the NSP cluster an initial set of five emitters are to join a capture, conditioning, and transport network by 2030. From there other emitters within the area will be able to join incrementally to 2050 [3]. However, the emitters who join and the timing of their connection will have a significant effect on the evolution the network. The pipeline network design will balance design requirements for initial emitters in a backbone network, with requirements for encouraging and enabling expansion. This study builds on scenarios defined between 2030 and 2050 [3] and applies a multi-period evolutionary-based approach (Steiner tree with Obstacles Genetic Algorithm (StObGA)) to predict pipeline year-on-year network growth in the NSP cluster. This provides a novel approach to the problem. The results are used in an examination of the potential growth of the pipeline network and an investigation of trade-offs necessary in the infrastructure design.

Keywords: Carbon Dioxide Capture, Genetic Algorithm, Modelling and Simulations, Energy, Carbon Capture.

BACKGROUND

Carbon Capture, Utilisation and Storage (CCUS) is a key technology in the pathway to meaningful CO2 abatement. If the application of CCUS is to be successful, the planning of the infrastructure required must be comprehensive and consider several factors. Technical, geographical, political, and social factors all require extensive planning/research if any CCUS infrastructure is to be successfully deployed. If improperly planned and risks/uncertainties are not accounted for there could be serious economic repercussions for emitters, thus dissuading any further uptake [4,5,6].

One way to make CCUS more enticing to emitters is the formation of industrial clusters. Here emitters within a set geographical area are grouped and can share infrastructure, thus increasing the potential for economy of scale and reducing the cost to individual entities [4,5]. However, the cost is influenced by many factors including number and size of emitters, availability of potential transport methods, distance from utilisation/storage sites, upcoming policies and regulations, and social acceptance of CCUS within the area. Subsequently, despite the benefits that industrial clusters offer, the infrastructure must still be properly planned [7].

Figure 1 outlines the major infrastructure elements of the CCUS supply chain. Starting with CO2 sources, the gas is captured and conditioned (usually compressed and purified) then it is transported onward for either utilisation or storage.

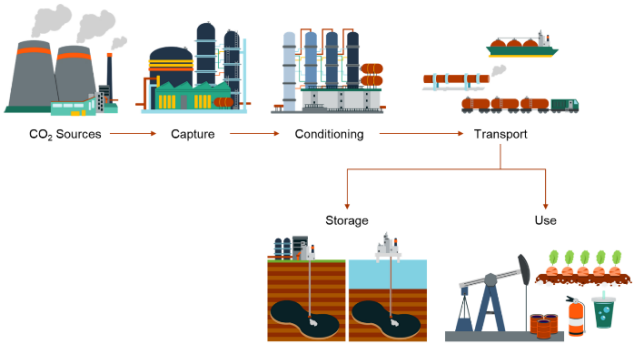

Figure 1. Diagram of the key stages in the CCUS supply chain.

In general, capture occurs at the site of large stationary emitters. The vast majority of which are from power plants, and other industries such as concrete, steel and chemical production [8]. Once captured, CO2 must be conditioned to ensure safe and efficient transport. Whilst often sited with capture, it can be considered as a distinct and vital stage in the CCUS supply chain. Conditioning encompasses several processes including dehydration, purification, and compression.

There are several options when considering CO2 transport infrastructure, each with their own advantages and disadvantages.

For smaller, discontinuous volumes of gas, rail and road are valid options. Shipping, however, is a candidate that can be scaled up to meet these demands, and, geography depending, can also be implemented with minimal infrastructure capital expenditure [4,5]. This is particularly evident in locations of well-established industrial clusters along coastlines and canal networks. As CCUS projects become established, shipping is seen as a viable option for the initial timeframe when pipeline infrastructure has yet to be established, and/or fewer emitters have joined the network.

Pipeline transport is anticipated to be the most economically efficient transportation option for large stationary emitters over industrial clusters [9-11] Pipelines also have the advantage of being able to efficiently transport CO2 over large distances and multiple terrains.

Whilst pipelines do have the potential to be an effective mode of transport, they require extensive infrastructure investment. This can be involved, requiring knowledge on pipeline sizing; locations of emitters and storage sites; specifications for transport and storage; network expansion over time [12]. Fortunately, gaseous phase pipeline infrastructure technologies for are well established, so existing standards on sizing and material can be drawn on when designing networks [12, 13]. However liquid phase pipeline transport requires additional considerations [6].

Extra complexity is added when considering network expansion, as geographic information needs to be combined with predictive models to create the most future-proof network.

Generally, pipeline network designs are modelled using graphs with emitters and offtake sites are taken as nodes with the pipelines themselves as arcs between them. To model both the topology and pipeline sizing simultaneously is computationally expensive so the two are generally modelled separately [14].

For length minimisation, Minimum Spanning Tree algorithms, such as Kruskal's are commonly used. This allows for generalised cost minimisation [15].

However, for any simulation to be truly representative, real-world constraints must be considered. In some cases, this can be circumvented, by utilising existing infrastructure such as road, or gas networks to provide predefined routes [16].

However, these methods are inflexible and do not consider novel routes, thus eliminating many possible optimal solutions.

Graph-based methods, such as Steiner points can also be used to enhance design flexibility, however this can also be limiting due to high computational expense, and inability to consider different geographic obstacles [14].

A more recently developed methodology by Rosenberg et al. (2021), displayed the viability of combining the Steiner tree method with a genetic algorithm to design networks that consider such obstacles [17]. This methodology is built on here, by applying it to CCS networks within an industrial cluster.

Methodology

The methodology used in this work produces an optimised pipeline route for CCUS pipeline networks that connects point sources with offtake locations. Also taken into consideration, is a set of real-world constraints such as urban areas and waterways. These may be regions in which construction cannot occur, or in which a higher cost will be incurred to traverse them, known and solid and soft obstacles respectively. Such obstacles are represented as a graph consisting of polygons, each is assigned a crossing weight representative of the ease of traversal, with those that are un-traversable given an infinite value. An obstacle's crossing weight is multiplied with the length of the pipeline that crosses it.

Topology

To separate the topology from sizing, the necessary assumption that the shortest route will be the most cost-effective is made. To find the minimum length between emitters and offtake, the Euclidean Steiner tree problem with soft and solid obstacles (ESTPO) is applied. To solve this for a set of given constraints, a genetic algorithm for Steiner trees with obstacles (StObGA) can be used. This was developed by Rosenberg et al. (2021) [17].

The genetic algorithm utilises the following chromosome type structure:

$$\{(x_1, y_1), (x_2, y_2), (x_3, y_3), \dots, (x_s, y_s)\} + \{1|0|1|0|0|0|1|1|0|0\} \quad (1)$$

This is split into two distinct parts, the first being the x-y coordinates of s number of Steiner points of variable length, and the second is a fixed length binary list which determines four obstacle corners to be used in the network.

To connect the terminals, Steiner points and obstacle nodes, weighted edges are created using Kruskal's minimum spanning tree [18]. The weighting depends on edge length and whether is traverses any obstacles.

The nodes and edges found this way are then subject to an optimisation regarding given emission and offtake values, with all edges assumed to be unidirectional.

Sizing

Pipeline sizing is determined using a mixed integer nonlinear programming (MINLP) optimisation. With constraints being hydraulic, structural, and commercial. The following objective function minimised the total cost in $, C, for a defined set of arcs A:

$$C = (1 + 0.03) \sum_{i|(i,j)\in A} C_{ij}^{C} \quad (2)$$

Where the total cost is the sum of the capital costs (C^C in the equation below) and the operating costs (assumed to be 3% of C^C.

The capital cost is a function of pipeline length L, outer diameters D^{po}, and considers the material, labour, right-of-way and other miscellaneous costs:

$$C^C = [674(dia)^2 + 11754(dia) + 234085](length) + 405000 \quad (3)$$

Where diameter (*dia*) is in inches, length is in miles, and cost is in dollars.

Additional constraints are material balance, discrete sizing, and erosion velocity as described by Ejeh et al 2023b, and Hammond et al 2025 [19, 20].

An overview of the methodology can be found in Figure 2.

CASE STUDY

The method described above has been applied to the case study illustrated in Figure 3. Here an industrial cluster spread over the North Sea Port region which spans Belgium and The Netherlands.

The emitters have been selected as a selection of the largest in the region with respect to their 2023 verified emissions data [21]. The planned base route is as described in Ejeh et al 2023a. This is predicated to start working in 2030, and will include Zeeland Refinery, Sloe Centrale, DOW Benelux, Yara Sluiskil B.V., and ArcelorMittal. From there the network can then expand to encompass more and more emitters in the cluster.

This will then expand over successive years to 2050 in increments shown in Table 1.

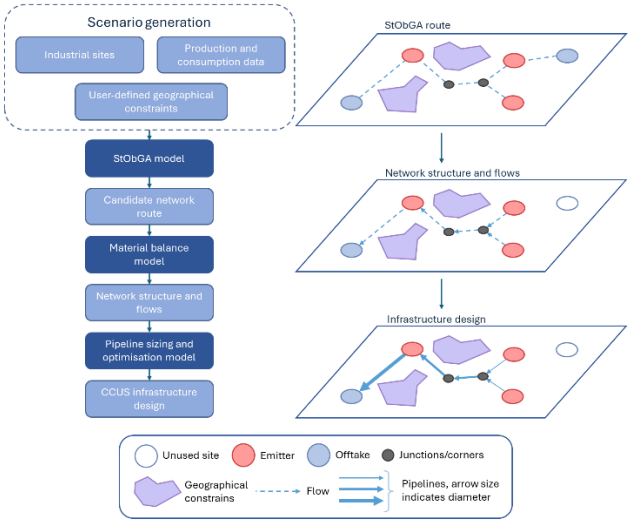

Figure 2. The worflow of the model showing consectutive steps and the final output.

Table 1. The list of point sources within the NSP cluster with the assumed year that they will join the network.

Number of emitters	Assumed Addition year
5	2030
11	2035
17	2040
23	2045
29	2050

A diagram displaying all emitters, obstacles, and the currently planned 2030 route is shown in Figure 3. The route shown in Figure 3 is based work previously conducted by C4U [3].

Compared with previous work [20, 22], the network developed here spans across a much smaller area with a higher density of emitters and industrial/urban areas. Providing a set of scenarios to further refine the network expansion methodology.

The network expansion was divided into Graded increases, with predetermined additions at 5-year intervals. This was further split into two distinct scenarios. The first (Graded Perfect), where the final network was simulated, and the intermediates were then built to match it. The second (Graded), was build piecewise with no knowledge of the final network. This allowed for a comparison of the two levels of implied knowledge.

Figure 3. The NSP cluster showing the location of all point source emitters, built up areas, and the currently planned pipeline route.

RESULTS AND DISCUSSION

A numerical summary of the results is shown in Table 2, with topological results presented in Figure 4. It can be seen in Table 2 Graded Perfect is longer than Graded but is cheaper, this indicates that it routed around areas with higher weighting when compared to the Graded system (Table 2 and Figure 4). The difference in length is 0.71% whereas the difference in costs is 7.9%. Indicating the importance of routing around areas with higher cost weightings. Highlighting the advantages of a predetermined final network when considering known, phased additions.

The difference in routing is clearly visible Figure 4, where the Graded Perfect method has deviated from the original set out in Figure 3. Providing an interesting contrast between partially fixed sections of the infrastructure with that of a fully variable one. The difference between the two networks is most likely due to the prioritisation of cost reduction over pipeline length.

The difference also highlights the potential for many possible routes across the same geographical area.

Here, the cost weightings of the urban and industrial areas have dictated the shape of the routes, specifically the Graded Perfect (Figure 4a) where no pre-existing initial route was enforced. This left the algorithm to find the most cost-effective route across the cluster, leading to a different final network to the Graded results (Figure 4b). To fully assess the impact of the cost weightings on the final network may be altered to bring the Graded Perfect network in line with that of the Graded.

This emphasises inherent uncertainties in pipeline network design, as small changes in decision-making can affect the final network. Such changes can have an impact on overall costs due to differing infrastructure requirements needed to counter pressure drops and cross certain obstacles, so require fully assessing before construction can begin.

Further work will be required to understand the effect of predetermined infrastructures fully.

Table 2. Summary of simulated pipelines, with calculated costs based on pipeline lengths, diameters, and operating costs

Scenario	Total Length (km)	Total cost ($million)
Graded Perfect	115.04	162.20
Graded	114.23	174.94
% Difference	0.71	7.9

CONCLUSIONS

This work has provided an extension to previous work on pipeline network design that considers topological constraints. Here, the decreased length scale and increased density of point source emitters has provided a unique view of this method.

The Authors have successfully demonstrated its applicability in this case, thus increasing the scope of the method to shorter distances and more densely populated areas. The effect of cost weighting on soft obstacles was presented. The Authors also believe that the consideration of known and unknown final infrastructures will facilitate more informed decision making by allowing for consideration of a wide array of possible arrangements.

Future work should focus on further quantifying the impact of the addition of point source emitters over varying time periods. With particular emphasis on prior knowledge of the final infrastructure. The impact of predetermined sections of infrastructure on final outcomes should also be investigated.

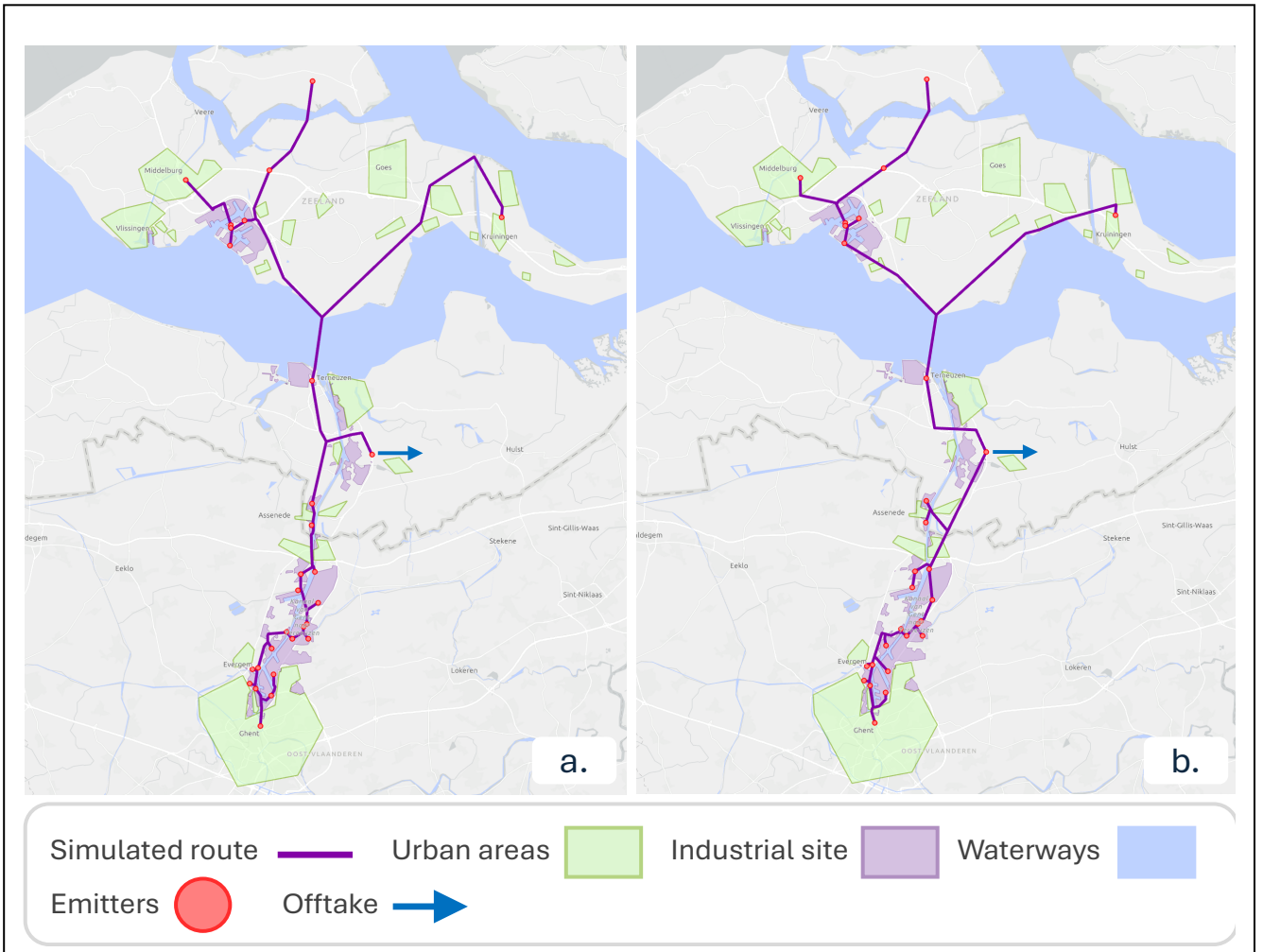

Figure 4: The NSP cluster showing the simulated pipeline infracstructure routes with a. Graded Perfect, and b. Graded.

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REFERENCES

1. The International Energy Agency (IEA). https://www.iea.org/reports/energy-technology-perspectives-2020
2. Realise CCUS. https://realiseccus.eu/ccus-and-refineries/industrial-clusters
3. J. O. Ejeh, S. Brown and D. Roberts. D4.8. Report on Techno-Economic Evaluation of the 2030 North Sea Port cluster. C4U. (2023a)
4. Geske J, Berghout N, van den Broek M. Cost-effective balance between CO2 vessel and pipeline transport - Part 1. Int. J. Greenhouse Gas Control 36:175-188 (2015) https://doi.org/10.1016/j.ijggc.2015.01.026
5. Geske J, Berghout N, van den Broek M. Cost-effective balance between CO2 vessel and pipeline transport - Part 2. Int. J. Greenhouse Gas Control 33:122-134 (2015) https://doi.org/10.1016/j.ijggc.2014.12.005
6. Mechleri E, Brown S, Fennell P, Mac Dowell N. CO2 capture and storage (CCS) cost reduction via infrastructure right sizing. Chemical Engineering Research and Design 119:130-139 https://doi.org/10.1016/j.cherd.2017.01.016
7. D'Amore F, Romano M, Bezzo F, Optimal design of European supply chains for carbon capture and storage from industrial emission sources including pipe and ship transport. Int. J. Greenhouse Gas Control 109, 103372. (2021) https://doi.org/10.1016/j.ijggc.2021.103372
8. Romano M, Anantharaman R, Arasto A, Can Ozcan D, Ahn H, Wilco Dijkstra J, Carbo M, Boavida D. Application of advanced technologies for CO2 capture from industrial sources. Energy Procedia 37: 7176-7185 (2013)

https://doi.org/10.1016/j.egypro.2013.06.655
9. Grant T, Guinan A, Shih C, Lin S, Vikara D, Morgan D, Remson D. Comparative analysis of transport and storage options from a CO2 source perspective. Int. J. Greenhouse Gas Control 72:175–191 (2018) https://doi.org/10.1016/j.ijggc.2018.03.012
10. Knoope M, Ramírez A, Faaij P. A state-of-the-art review of techno-economic models predicting the costs of CO2 pipeline transport. Int. J. Greenhouse Gas Control 16, 241–270 (2013) https://doi.org/10.1016/j.ijggc.2013.01.005
11. Wilkes M, Mukherjee, S, Brown, S. Linking CO2 capture and pipeline transportation: sensitivity analysis and dynamic study of the compression train. Int. J. Greenhouse Gas Control 111: 103449 (2021) https://doi.org/10.1016/j.ijggc.2021.103449
12. BS EN 10208-2 Steel pipes for pipelines for combustible fluids. Technical delivery conditions - Pipes of requirement class B. (2009)
13. ISO 6708:1995(en) Pipework components — Definition and selection of DN (nominal size)
14. Heijnen W, Ligtvoet A, Stikkelman M, Herder M. Maximising the worth of nascent networks. Networks and Spatial Economics: 14, 27-46 (2013) https://doi.org/10.1007/s11067-013-9199-1
15. André J, Auray S, Brac J, Wolf D, Maisonnier G, Ould-Sidi M, Simonnet A. Design and dimensioning of hydrogen transmission pipeline networks: European Journal of Operational Research229, 239-251 (2013) https://doi.org/10.1016/j.ejor.2013.02.036
16. Parolin F, Colbertaldo P, Campanari S. Development of a multi-modality hydrogen delivery infrastructure: An optimization model for design and operation. Energy Conversion and Management: 266 (2022) https://doi.org/10.1016/j.enconman.2022.115650
17. Rosenberg M, French T, Reynolds M, While L. A genetic algorithm approach for the Euclidean Steiner tree problem with soft obstacles. Genetic and Evolutionary Computation Conference 618-626 (2021) https://doi.org/10.1145/3449639.3459397
18. Kruskal J. On the shortest spanning subtree of a graph and the traveling salesman problem. Proceedings of the American Mathematical Society 7:48–50 (1956) https://doi.org/10.2307/2033241
19. Ejeh J, Martynov S, Brown S. An MINLP model for the optimal design of CO2 transportation infrastructure in industrial clusters. Computer Aided Chemical Engineering 52:3085-3090 (2023b) https://doi.org/10.1016/B978-0-443-15274-0.50492-3
20. Hammond J, Rosenburg M, Brown S. Understanding Costs in Hydrogen Infrastructure Networks: A Multi-Stage Approach for Spatially-Aware Pipeline Design. Int. J. Hydrogen Energy 102:430-443 (2025). https://doi.org/10.1016/j.ijhydene.2024.12.273
21. Abrell J. EUETS.INFO
22. Hammond J, Rosenburg M, Brown S. A Genetic Algorithm-Based Design for Hydrogen Pipeline Infrastructure with Real Geographical Constraints. Computer Aided Chemical Engineering 53:631-636 (2024) https://doi.org/10.1016/B978-0-443-28824-1.50106-X