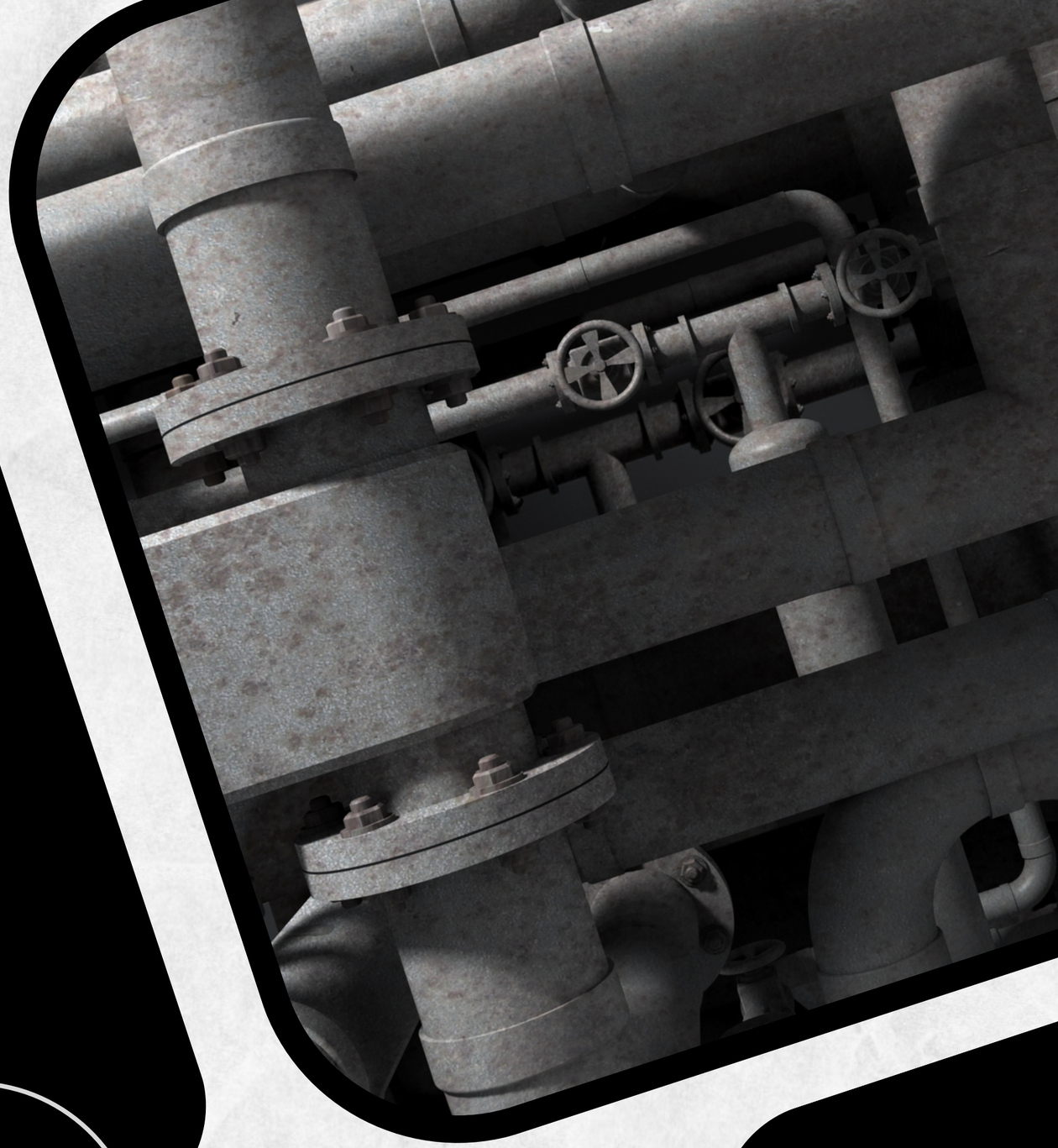
ENHANCING NATURAL GAS PIPELINES USING OPERATIONS RESEARCH



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BACKGROUND

In 2018, China National Petroleum Corporation (**CNPC**) faced challenges due to the increasing demand for natural gas. To expand efficiently, they adopted **Operations Research with linear optimization**, leading to higher profits and reduced infrastructure repair costs.

The method optimized complex transportation processes affected by varying temperature and pressure, ensuring a steady gas supply. CNPC's success demonstrates the power of innovation in the natural gas industry.

QUESTIONS ADDRESSED IN THIS CASE

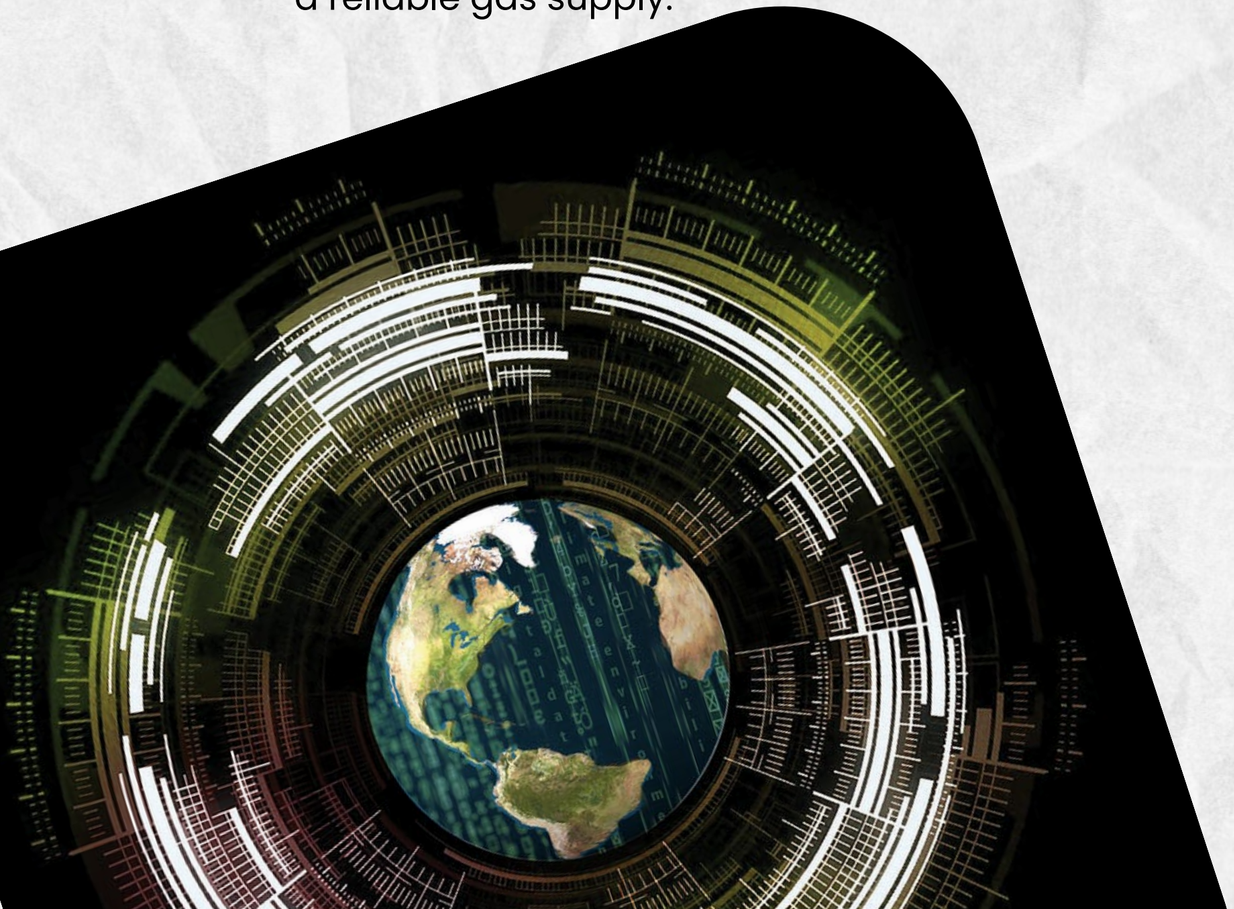
- **What is the capacity of the natural gas transportation network?**

- **What is the optimal transmission plan considering gas production, imports, transportation, storage, and sales, based on available natural gas resources, demand locations, and varying gas prices in the network?**

Stakeholders

CHINA NATIONAL PETROLEUM CORPORATION (CNPC)

The leading player driving pipeline expansion and optimization, aiming to maximize profits and ensure a reliable gas supply.



GOVERNMENT AND REGULATORY BODIES

Overseeing the energy sector, with a stake in policy and regulations impacting CNPC's operations.

LOCAL COMMUNITIES AND ENVIRONMENTAL GROUPS

Concerned about safety, environmental effects, and community engagement.

NATURAL GAS PRODUCERS AND SUPPLIERS

Other companies in the industry, aligning or competing with CNPC's goals.

Customers

INDUSTRIAL AND COMMERCIAL ENTITIES

Rely on gas for energy needs, requiring a stable supply.

RESIDENTIAL CONSUMERS

Depend on gas for heating and household use, seeking affordability and reliability.

POWER GENERATION SECTOR

Gas serves as a crucial energy source for power plants.

IMPORTERS AND EXPORTERS

Foreign entities involved in gas import/export may also be customers or stakeholders.

Traditional Method Using Spreadsheets

1. Divide the system into multiple subsystems.

2. Use **Microsoft Excel** to establish internal balance for production, imports, transmission, storage, and sales within each subsystem.

3. Adjust decisions based on the management team's experience and feedback.

4. Seek a preliminary balance for the entire system by adjusting interflows between subsystems.

5. Check and iterate if necessary to ensure balanced natural gas amounts in each subsystem.

Limitations of Using Excel for Operations Research

1. Limited Solver Capabilities

- Excel's built-in Solver tool is useful for basic optimization problems.
- Struggles with complex or large-scale OR models.
- Lacks the efficiency and robustness of specialized OR solvers.

2. Model Size Constraints

- Excel has limitations on the number of variables and constraints it can handle in a Solver model. Large-scale OR problems may exceed Excel's capacity.

3. Performance Issues

- As the problem size grows, Excel's performance may degrade.
- Slower calculations and increased computation time can be problematic.

4. Lack of Support for Advanced Modeling Features

- Excel lacks some advanced features required for certain types of OR problems.
- Not suitable for handling complex constraints and scenarios.

5. Difficulty with Integer Variables

- Excel can handle integer variables in the Solver, but it might not be as efficient as specialized OR solvers. Integer programming problems may require more sophisticated techniques

Hence, It became very difficult for CNPC to solve their Optimization problems using Excel. They needed a new robust optimization algorithms.

Model

Objective Function: Optimize natural gas flow rates, pressure, and temperature in a fixed network topology.

Decision Variables: Nodes - Net supply, pressure, and temperature, Arcs - Flow rates.

Objective: Maximize total profit (revenue minus purchasing cost) or minimize total cost.

Constraints: Flow balance, flow range (min and max), pressure range, and physical laws in components (e.g., compressor, regulator valve, pipeline).

Algorithms Used

Mixed Integer Linear Programming: is a mathematical optimization technique used to solve problems with both continuous and discrete variables

Piecewise Linear Approximation: is a method of approximating a complex curve or function by breaking it into smaller linear segments, simplifying the representation while retaining accuracy.

Non- convex optimization Problems: are complex mathematical challenges where the objective function and constraints may have multiple local minima or maxima, making it difficult to find the global optimal solution.

Convex relaxation: is a technique used to simplify and solve non-convex optimization problems by transforming them into convex ones, facilitating efficient solutions.

3SCR Algorithm: is a Three-Step Consecutive Refinement approach used to improve the accuracy and efficiency of optimization problems by iteratively refining the solution in three stages.

Model (Approach 1)

- Model natural gas transmission as a mixed-integer linear programming problem with piecewise linear approximation for small-sized networks.
- Satisfactory results for small problems, but issues arose for large-scale problems.
- Inconsistent optimal values between algorithms in IBM ILOG CPLEX.
- Computation time exceeded the set criterion for large problems.

Model (Approach 2)

- Developed an iterative two-stage framework for solution optimality and accuracy.

- Convex relaxation of nonconvex problem for fast iterations and highly accurate solutions.

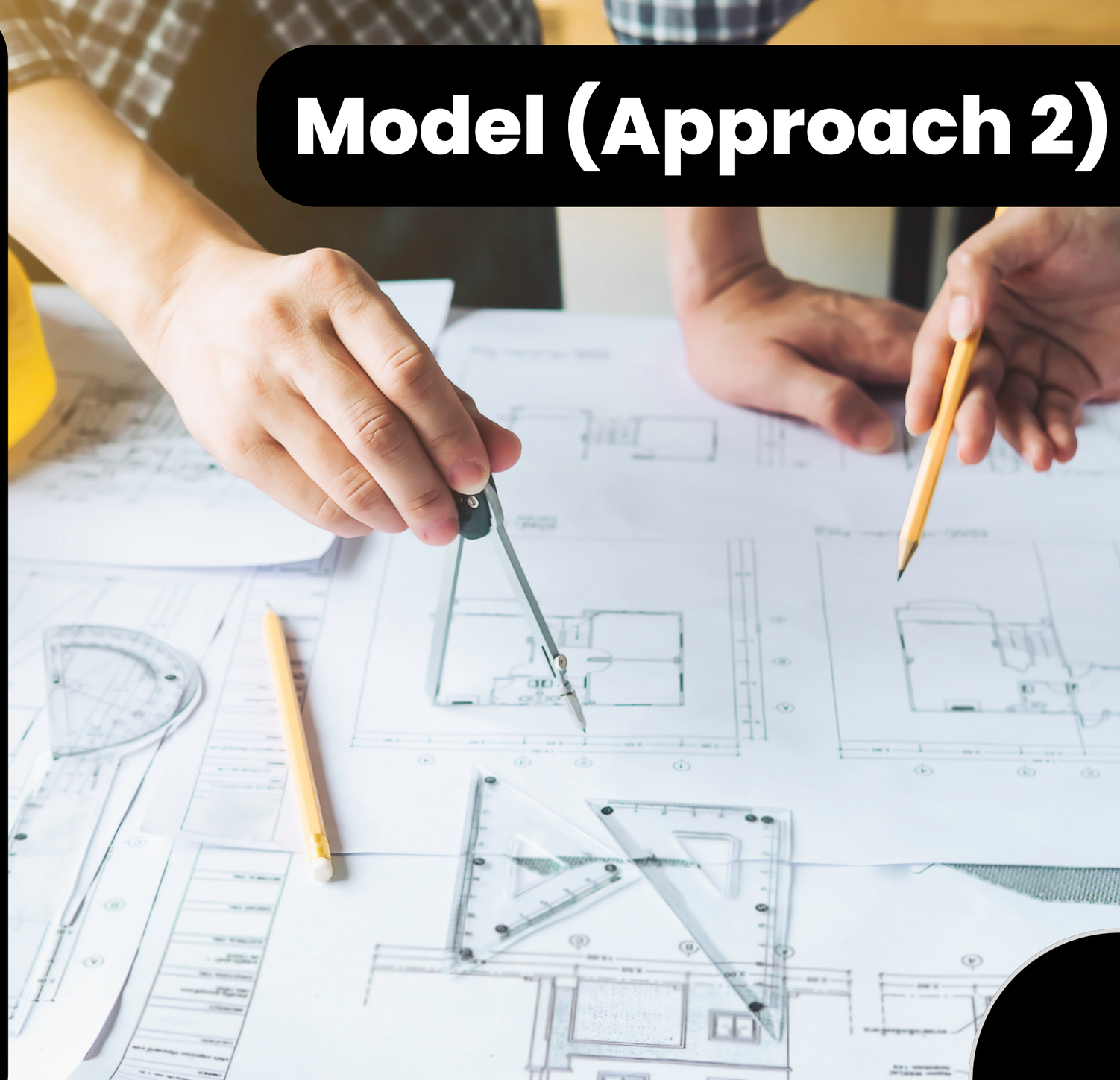
- Achieved convergence error within 2% in one second for a Chinese network with 20+ nodes.

- Verified optimal solutions for small-scale networks (up to 100 nodes).

- Challenges in networks with many cycles, leading to potentially long computation times.

$$z^* = \sum_{i \in \mathcal{I}_s} c_i^s \cdot s_i^{1*} - \sum_{i \in \mathcal{I}_d} c_i^d \cdot (-s_i^{1*}).$$

Minimizing Energy



Improved Approach (3SCR Algorithm)

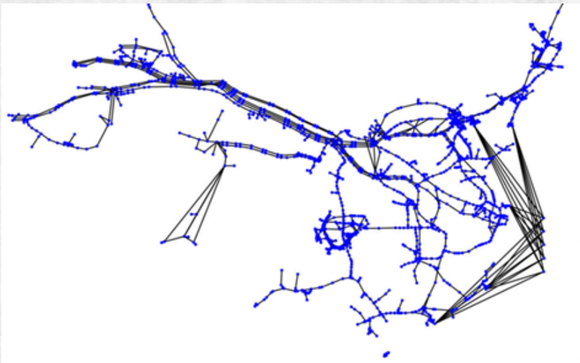
•Proposed 3SCR algorithm as an enhancement to the iterative method.

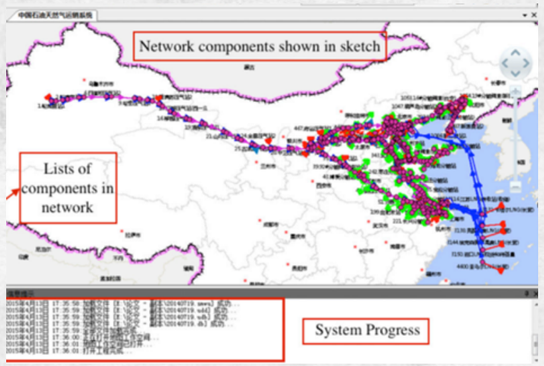
•Extended convex relaxation to constraints on interconnected pipelines.

•Identified conditions where convex relaxation preserves optimality.

•Three-stage process:
- Solve a convex relaxed model.
- If feasible, the process concludes; otherwise, minimize energy in pipelines and update flow rates.
- Determine node pressure and temperature based on updated flows.

• Achieves satisfactory accuracy for the largest Chinese network (1,285 nodes) when other methods fail to generate feasible solutions.





Software Components

1. Data Input: Importing data from the database and storing it in the system's memory.

2. Data Check: Verifying the correctness of the input data.

3. Unit Conversion: Converting arbitrary numerical data into standard units.

4. Optimization: Solving the natural gas pipeline planning problem using the user-selected algorithm (3SCR or piecewise linear approximation) for efficiency and accuracy.

5. Data Output: Converting and generating the calculation results into the required output formats.

Effect (Advantages)

- Substantial economic impact with increased revenue and budget savings for CNPC.

- Generated over $530 million in additional profits for CNPC's natural gas transmission (2015-2017).

- Optimized allocation of natural gas sales led to increased revenue of $340.3 million.

- Significant improvement in work efficiency, reducing planning time from days to minutes.

- Environmental benefits by providing more accurate customer demand estimates based on improved production and transmission capacities.

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THANK YOU