A09 & A11: Modeling the Taum Sauk Reservoir

Team Project

This project includes (2) milestones.

Purpose of this project	Engineers must analyze large datasets to understand **trends and behavior** of a system. Many times, with the help of a simplified model, they can use these large datasets to perform necessary calculations and present their results in a concise manner. Additionally, understanding fluid mechanics is important to all engineering disciplines. To illustrate applications of conservation principles, engineers use **schematics.** These schematics complement **mathematical models**. These mathematical models range in complexity, with most models requiring certain simplifying **assumptions**. Client memos and **technical briefs** are common in engineering. In their briefs and reports, engineers explain their work and its details to their target audience/client and preserve information for future use. In this assignment, you will explore the **Taum Sauk Reservoir**, a pumped-storage hydroelectric power generation system located in Missouri.

Relevant Course Resources:

Assignment Resources	• The “Ameren Memo” includes information on the expectations of the client • “Excel Spreadsheet” with data on Upper and Lower Reservoirs of Taum Sauk • “Technical Brief template” outlines sections of your technical brief and specific expectations
Video Modules	All modules related to Data Analysis and Modeling

Organizing Your Work
Pay attention to how you format and organize your work in your technical report and Excel spreadsheet. Below are some general instructions:

Technical Brief:
- Follow the "technical brief template".

Excel Spreadsheet:
- Make sure your tables have captions and titles, and your columns have clear labels & units
- Format your cells with reasonable decimal places and data type (In Excel right click, format cells).
- Include details on your calculations using text boxes located near the calculations you are describing. Have detailed explanations in your text boxes so that a user can easily follow along with your work presented in the spreadsheet.
- Follow instructions on how to name each sheet in your Excel document.

Submission Instructions:

- Complete both milestones **as a team.** One member of your team must submit your work on Brightspace, but all team members should review and approve the submission.

  Deliverables from Milestone 1:
  - Technical Brief:
    Name your Word file: **ENGR131_ A09 _teamnum.docx**
    Note: You will not have a complete technical brief document at the end of this milestone. Instead, you will have parts of it completed that pertain to Milestone 1. You will be graded on this incomplete document.
  - Spreadsheet showing model calculations:
    Name your Excel file: **ENGR131_ A09_ teamnum.xlsx**
    Label your Excel sheets as: **Raw Data, TaumSauk, Model 1, and Model 2**

  Deliverables from Milestone 2: (You will start this in a later class)
  - Technical brief:
    Name your Word file: **ENGR131_A11_ teamnum.docx**
    Note: Complete the document you started in Milestone 1 and rename with the above naming convention.
  - Spreadsheet showing data description and calculations:
    Name your Excel file: **ENGR131_ A11_ teamnum.xlsx**
    Label your sheets as: **Q_Upper, HEPower**
    Note: You will continue with the excel file you started in Milestone 1 but rename it with the above naming conventions.

- Submit your work through the designated **Brightspace Assignment Dropbox at** https://purdue.brightspace.com/

Assignment 09:	**Scoping with data and mathematical models**

Goal

The company that manages the reservoir, Ameren Missouri, is asking you to create and evaluate a set of mathematical models for the Taum Sauk Reservoir. These models will help calculate reservoir volume given a specific height (volume as a function of height).

1. **Technical Report:** (Complete Sections I-V and IX in the template provided)
   - Cover Page & Table of Contents (make necessary updates)
   - I. Team Member Roles: Briefly describe contributions of each team member specific to this assignment.
   - II. Problem Statement**:** Present your problem statement followed by your modeling constraints and criteria.
   - III. Background Information:
     - Present information you gathered on hydroelectric power generation in general and the Taum Sauk Reservoir specifically (e.g., its history, location, shape and size).
     - Ameren Missouri regularly publishes data on water levels for the two reservoirs in the Taum Sauk system. Describe the Taum Sauk reservoir based on your analysis of the large dataset given to you. Enrich your descriptions with graph(s) and appropriate descriptive statistics. Describe your observations on the different time intervals of operation of the Upper Taum Sauk reservoir along with interesting findings from your analysis.
   - IV. Two Alternative Mathematical Models:
     - Sketch two visual models that represent the shape of the Upper Reservoir and are useful in guiding your mathematical models. Model 1 should assume that the surface of the reservoir is a single simple shape; Model 2 should assume the reservoir surface is a combination of two or three shapes.
     - Provide illustrations and written descriptions of your models along with assumptions you have made about the shape of the reservoir. Explain how these assumptions would impact the calculations (over estimate, under estimate, etc.).
   - V. Modeling with the Laminar Approach*:
     - Using the laminar approach* and your two models (Model 1 and Model 2), calculate the mathematical relationship between water height and volume for the Upper Taum Sauk Reservoir (note: you will create a Regression Equation in Excel)
     - With an appropriate graph, compare the volume of the full reservoir (in acre-feet) between your Model 1 and Model 2 as well as the actual volume of the Upper Taum Sauk Reservoir (cite your source). Include a short discussion of the differences and the sources of error in your models.
     - Given that the actual Upper Reservoir can hold 4,600 acre-feet when full, compare your two models and determine which one you would use. Explain the reasoning behind your choice.

- IX. Provide a properly formatted list of references.

2. **Excel Spreadsheet**:
   - In an Excel sheet named, TaumSauk, visualize the data and when necessary, if appropriate, use descriptive statistics. The analyses should help you explain how the Taum Sauk reservoir works, its capacity, daily/monthly workings, etc.
   - In an Excel sheet named, Model1, present calculations for your first model
   - In an Excel sheet named, Model2, present calculations for your second model

***** See explanation of laminar approach in "Technical Specifications" section below.

Background/Technical Content:

The Upper Taum Sauk Reservoir is a man-made pumped-storage reservoir on the top of Proffitt Mountain in southwest Missouri. There are two reservoirs in the Taum Sauk system: a lower reservoir created by a simple dam, and the upper reservoir, enclosed on all sides by a dam (see photo).

The system acts to store electrical power: in periods of low electricity demand (night-time), water is pumped from the lower reservoir to the upper. It then returns in periods of high electricity demand (afternoons/evenings). This system allows the true electricity-generating sources (mostly coal and natural gas fired power plants) to run with a constant output through the day, even though the demand varies widely through a typical day.

Figure 1: Upper reservoir – Taum Sauk

Retrieved from: (http://news.stlpublicradio.org/post/rebuilt-taum-sauk-reservoir-operate-soon#stream/0)

Technical Specifications:

While the actual Upper Taum Sauk Reservoir is not a simple geometric shape, it is relatively easy to describe (see the topographic map). However, it is deceptively difficult to turn that description into a mathematical model that will allow you to calculate volume as a function of height.

Here are some characteristics of the reservoir:

- The surface area when full is 55 acres.
- The general shape is shown in the topographic map provided (See Figure 2).
- The bottom of the reservoir is flat, and 92 feet below the maximum water level when the reservoir is full.

- From the top of the reservoir, the first two feet are freeboard. Freeboard is a design requirement and is the vertical distance from the top of the dam to the full supply level. Under normal operation, there is no water in the top two feet of the reservoir.
- The walls are vertical for the first eight feet of water depth, and then slope in at a ratio of 1 : 1.3 (e.g., 1.3 feet horizontally for each additional foot of water depth).

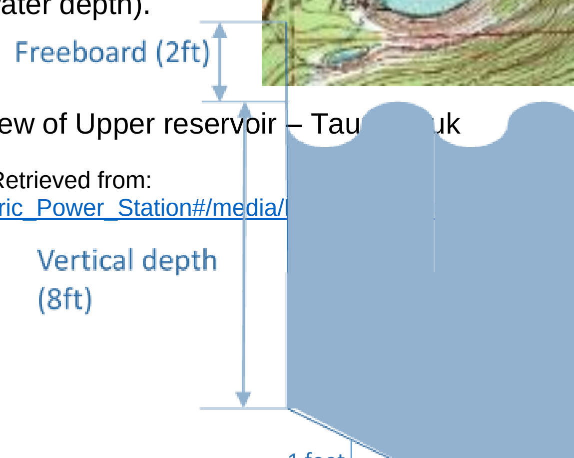

Figure 2: Topographic view of Upper reservoir – Tau uk

Retrieved from:
https://en.wikipedia.org/wiki/Taum_Sauk_Hydroelectric_Power_Station#/media/ Storage.jpg

Figure 3: Schematic of Upper Taum Sauk Reservoir

What is the Laminar Approach?

A typical model of a reservoir would have three-dimensions: height, length, and width. While the actual Upper Taum Sauk Reservoir is not a simple geometric shape, it is relatively easy to describe. Yet, it is deceptively difficult to turn that description into a mathematical model that will allow you to **calculate volume as a function of height**.

One approach that can help deal with the difficulty of modeling a reservoir is called the "laminar" or "layers" approach. For this approach, imagine that the reservoir is a series of stacked layers, each a foot in thickness (so, in this case, there are 92 layers) as shown in Figure 4.

Hence, a mathematical model that uses the laminar approach would:

- remove one dimension from the model (e.g., by converting height into 1 feet sections)
- simplify the other two dimensions (e.g., the kidney bean can be represented as an ellipse).
- reduce unknowns to one dimension by establishing assumed relationships/assumptions (e.g., set a ratio between length and width of the surface shape)

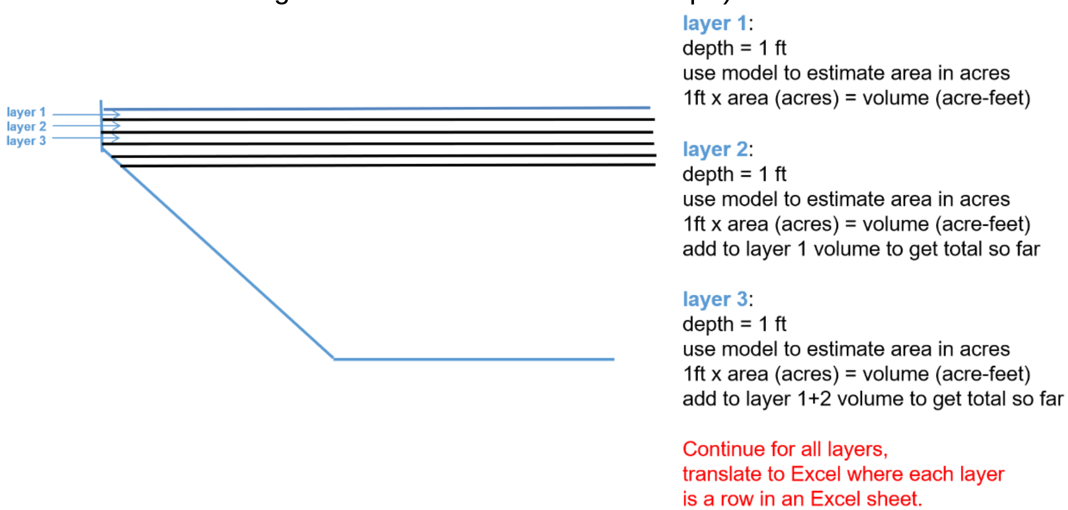

Figure 4: Illustration of laminar approach used to calculate volume

A spreadsheet is well suited for a Laminar Model. Using the equation for area of a two-dimensional shape, and assuming a ratio between the two dimensions of this shape, you can calculate volume for a unit of depth. You can then add together the volumes of each depth layer to get the total volume. This is best done in a spreadsheet where each line represents one foot of depth. It is key to set up spreadsheet to allow easy changing of the assumed length/width ratio, so the assumption can be modified when necessary.

- Determining the volume becomes a task of calculating or estimating the **area** of each of these layers (in acres), and then multiplying by height (1 ft) to get volume of each layer (in acre-feet).
- Adding together the volume of all layers gives you the total volume of the full reservoir.
- Adding together the volume of a subset of layers (up to a certain height) gives you the volume contained in a less-than-full reservoir.
- Excel is particularly well suited for this sort of analysis, because each row of the spreadsheet can represent one 1-ft layer.
- You may find it helpful to assume that the horizontal shape of the reservoir is some simple geometric shape or combination of shapes (this makes relating surface area to depth easier). Consider carefully what shape (or shapes) most closely represents the actual reservoir shape. Use appropriate sources to find equations that relate area to linear dimensions for various simple shapes.
- For the first model, assume that the reservoir is a single simple shape; for the second assume that it is a combination of two or three shapes.

Using a laminar (or layers) approach, you can calculate the volume of each layer in the reservoir, and of the total volume (in acre-feet) of the full reservoir. The total volume of the Taum Sauk reservoir in (in acre-feet) is known. So, you can also compare your calculations with the actual volume of Taum Sauk's Upper reservoir

Regression Analysis

Regression analysis is a statistical process used to estimate the relationships among variables. Typically, a relationship is explained between a dependent variable (predicted value, y-axis values) and one or more independent variables or predictors (x-axis values). A linear regression assumes the relationship is linear.

In Excel, for a simple linear data set, you can insert a trendline to create a best-fit straight line. A linear trendline usually shows that variables are increasing or decreasing at a steady rate. If "Display Equation on chart" option is selected, Excel outputs the following equation, which represents the least squares fit for a line:

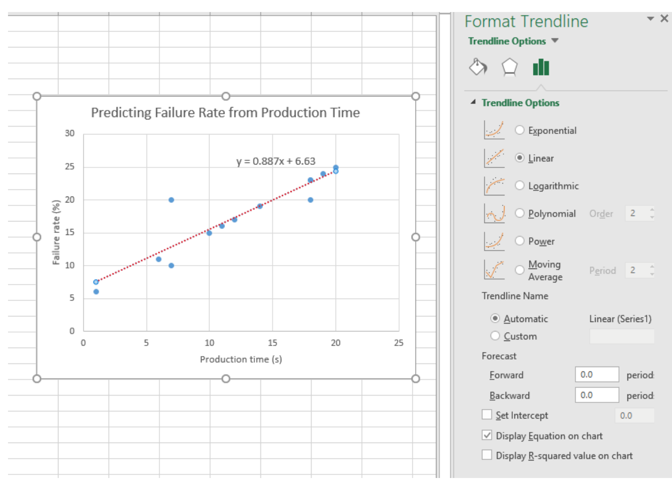

Figure 5. Regression in Excel

$$y = mx + b$$

where m is the slope and b is the intercept.

Check Your Work with the Learning Objectives:

Assignment 09: *Technical Brief*
Learning Objectives
EB02 - Identify assumptions made in cases when there are barriers to accessing information.
EB03 - Clearly articulate reasons for answers with explicit reference to data to justify decisions or to evaluate alternative solutions.
IL01 - Ask questions to determine what new information is needed to scope and solve a problem.
IL02 - Gather information from reliable sources.
IL04 - Include citations within the text (in-text citations) that show how the references at the end of the text are used as evidence to support decisions.
IL05 - Format reference list of used sources that is traceable to original sources (APA).
PC01 - Use professional communication (written, visual, and oral), free of grammatical or spelling mistakes and in a formal tone, appropriate for engineering school and workplace.
PC04 - Professionally present all visuals representations (figures, images, sketches or prototypes) to clearly convey meaning by labeling key components to show their form and function.
PS01 - Explain the problem based on synthesis of client, user, and other stakeholder needs
PS02 - Justify why problem is important to solve by making reference to relevant global, societal, economic, or environmental issues.
TW02 - Document all contributions to the team performance with evidence that these contributions are significant.
UC01- Demonstrate an understanding of conservation principles (mass, energy, momentum, and/or charge) in a boundary system

Assignment 09: Excel Spreadsheet
Learning Objectives
DV01 - Efficient use of engineering tools for basic statistics. Use of automated solutions, such as cell referencing and built in functions.
DV02 - Select appropriate graphical representation of dataset based on data characteristics such as numerical (discrete or continuous) or categorical (ordinal or nominal)
DV04 - Prepare table for technical presentation with proper formatting, including title, row labels, column labels, units and correct decimal places.
DV05 - Prepare a chart for technical presentation with proper formatting, including title, axes labels, appropriately scaled axes, units and appropriate markers.
DV11 - Given data, calculate regression equation (with slope and intercept) and interpret the strength of the correlation in terms of R^2.
SQ01 - Use accurate, scientific, mathematical, and/or technical concepts and data in final solution.

Assignment 11: Calculation of hydroelectric power

Goal

In Milestone 1, you developed a model to estimate the relationship between the height of the upper reservoir and the volume. This relationship will be needed in Milestone 2 to calculate the **pressure head** which will in turn be used to calculate the volumetric flowrate and the hydroelectric power generated by the Taum Sauk reservoir. You will also calculate the daily energy generated and estimate how many houses would be powered by this energy.

1. **Technical Report:** (Complete Sections I through IX in the template provided)
    - Make any necessary updates to
        - Cover Page & Table of Contents
        - I. Team Member Roles: Briefly describe contributions of each team member specific to this assignment.
        - II. Problem Statement
        - III. Background Information
        - IV. Two Alternative Mathematical Models
        - V. Modeling with the Laminar Approach

    New sections
    - VI. Calculating Volumetric Flowrate:
        - Using the distinct time interval method (slopes)
        - Using 15-minute segments
    - VII. Estimating Power Generated:
    - VIII. Lessons Learned: Summarize your project/tasks and describe what you learned about modeling and how you dealt with challenges.
    - IX: References: (expand, update references as necessary)

2. **Excel Spreadsheet:** (continue working on the same document from Milestone 1 and make changes as necessary)

    - In an Excel spreadsheet named, **Q_Upper**, calculate flow from volume on **July 12, 2018** using two different methods:
        - By identifying 5-6 distinct points where the flowrate is noticeably changing. There are at least five distinct time intervals through the day with different flow rates: some time intervals with water entering the upper reservoir, sometime intervals with water leaving the upper reservoir, and some time intervals with no flow. Create appropriate tables and charts that defines these time intervals and calculates an estimate of the volumetric flow rate for each time interval. Calculate the volumetric flow rate in four different sets of units: acre-feet/hr, gallons/hr, m^3/s, and cfs. CFS (cubic feet per second, or ft^3/s) is a common abbreviation used by engineers.
        - By calculating instantaneous flowrate (in m^3/s) **July 12, 2018** in 15-minute segments. Note that Ameren Missouri provided volume in the Upper Taum Sauk reservoir as a function of time. Create appropriate tables and charts. Discuss the accuracy of these results compared to the distinct time interval calculations (based on changes in slope).

- In an Excel spreadsheet named, **HEPower**, calculate hydroelectric power. You will need the regression equation from your first milestone to calculate reservoir height (i.e., the pressure head) at specific volumes. You also will apply the hydroelectric power equation given in the **"Background/Technical Content"** section below, to estimate the power generated as a function of time during all parts of the day on July 12, 2018, where water was flowing from the upper reservoir to the lower reservoir. You will need to calculate the units of power that this equation generates from the units of the five parameters that appear in the hydroelectric power equation. Once you have calculated the power at various points during the day,
    - Calculate the total energy, in MWh (Megawatt-hours), that was generated by the power station over the course of the day on July 12th. State any assumptions made in your calculations.
    - Determine how many "average homes" can be powered by this amount of energy in one day. Cite any sources you use to estimate energy use of an "average home."

Background/Technical Content:

The amount of hydroelectric power generated from a reservoir depends on several factors

- Potential energy due to gravity or height. The scientific term that describes the height of a liquid that corresponds to a pressure exerted by the height of the liquid on the base is known as **pressure head** (To calculate pressure head, refer to the parameters presented in Figure 6).
- Rate of fluid flow. The scientific term here is **volumetric flow rate** which is the volume of fluid which passes through a given cross sectional area per unit time.
- The **efficiency factor** of the turbines. Efficiency factor is a ratio of the work output from the turbine to the net energy input supplied to the turbine.
- The **density** of the water. Temperature affects density.

Interestingly, previously derived empirical or theoretical models indicate a linear relationship among these variables and make is easy to hydroelectric power given the engineering parameters.

Below is a theoretical model that calculates hydroelectric power output as a function of volumetric flow rate and other known parameters.

$$\textbf{Power} = E\ \rho\ Q\ g\ P_h$$

where:

- E = efficiency factor (90% is a commonly used number)
- ρ = the density of water (pure water at 4°C = 1000 kg/m^3)
- Q = volumetric flow rate (in m^3/s)
- g = gravitational acceleration constant (9.81 m/s^2)
- P_h = pressure head (height of water, typically in vertical units of meters, from the power station to the surface of the upper reservoir).

Technical Specifications:

Important parameters of the Taum Sauk system are shown in a diagram below: (drawing modified from Taum Sauk description in *St. Louis Post Dispatch*)

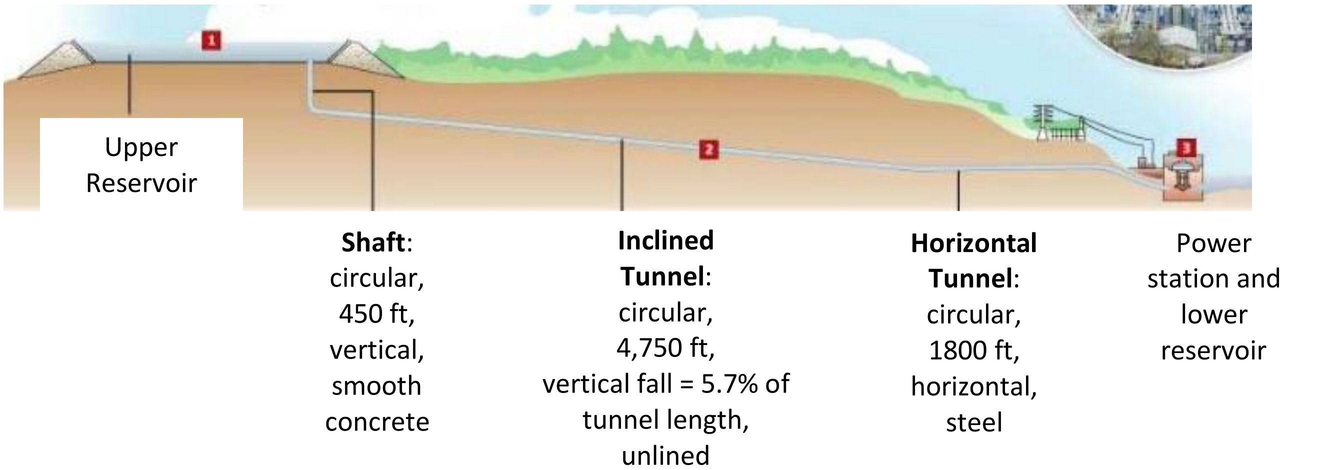

Figure 6. Key parameters of the Taum Sauk system

Note that this is a simplification of the system. The material of the shaft and tunnel have an impact on the water flow. The tunnel should be as smooth as possible to reduce friction and sound enough to minimize erosion.

The data from Ameren Missouri provided volume in the Upper Taum Sauk reservoir is available as a function of time. The slope of this line at each time (you may also consider this the first derivative of the data) gives **the volumetric flow rate through time**.

For reference, the generators at Taum Sauk are rated at 450 MW. Your power, and therefore daily energy, calculation was a product of several numbers that have some uncertainty (for example, the flow rate, the efficiency factor, and the pressure head are all measured or estimated, and the density of water may vary from 1000 kg/m^3, based on temperature).

Check Your Work with the Learning Objectives:

Assignment 11: *Technical Brief*
Learning Objectives
DV08 - Make accurate comparisons across groups with explicit reference to data.
EB02 - Identify assumptions made in cases when there are barriers to accessing information.
EB03 - Clearly articulate reasons for answers with explicit reference to data to justify decisions or to evaluate alternative solutions.
IL02 - Gather information from reliable sources.
IL04 - Include citations within the text (in-text citations) that show how the references at the end of the text are used as evidence to support decisions.
IL05 - Format reference list of used sources that is traceable to original sources (APA).
PA01- Identify strengths in problem solving/design approach.
PA02 - Identify limitations in the approach used.
PA03 - Identify potential behaviors to improve approach in future/current problem solving/design projects.
PC01 - Use professional communication (written, visual, and oral), free of grammatical or spelling mistakes and in a formal tone, appropriate for engineering school and workplace.
PC04 - Professionally present all visuals representations (figures, images, sketches or prototypes) to clearly convey meaning by labeling key components to show their form and function.
PC05 - Fully address all parts of assignment by following instructions and completing all work.
SQ01 - Use accurate, scientific, mathematical, and/or technical concepts and data in final solution.
TW02 - Document all contributions to the team performance with evidence that these contributions are significant.

Assignment 11: Excel Spreadsheet
Learning Objectives
DV01 - Efficient use of engineering tools for basic statistics. Use of automated solutions, such as cell referencing and built in functions.
DV04 - Prepare table for technical presentation with proper formatting, including title, row labels, column labels, units and correct decimal places.
DV05 - Prepare a chart for technical presentation with proper formatting, including title, axes labels, appropriately scaled axes, units and appropriate markers.
SQ01 - Use accurate, scientific, mathematical, and/or technical concepts and data in final solution.