**Case Study 2**

**Industrial level selection of control technologies**

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**Problem statement:**

Total Maximum Daily Load (TMDL) of 32.8 kilograms/year for mercury has been established by the USEPA for five contiguous segments of the Savannah River in the state of Georgia, US, leading to the applicable water quality standard (WQS) of 2.8 ng/l (parts per trillion) in the watershed. 29 major industries (point sources) need to comply with this water quality standard. The U.S. Environmental Protection Agency (EPA) defines point source pollution as “any single identifiable source of pollution from which pollutants are discharged, such as a pipe, ditch, ship or factory smokestack”. Three different mercury control technologies, namely, activated carbon adsorption, coagulation and filtration, and ion exchange, are available for installation. Each of these technologies has a different cost and mercury reduction capability.

The specific goal is to formulate an optimization model to determine the optimal selection of the mercury control technology for each of the 29 point sources so that the compliance targets are achieved.

**Specific activities for optimization model formulation**

1. Identify and list the model parameters for which data are given
2. Identify the decision variables in the model
3. Formulate the model constraints
4. Formulate the economic objective function (cost minimization)
5. Program the model in a software tool (GAMS)
6. Exercise: Solve the model and analyse the results

**Solution**

We will first formulate a generic optimization model and then apply it to the specific case of the Savannah River basin.

The TMDL (Total Maximum Daily Load) regulation has already been developed by the state in consultation with USEPA. This translates into a specific load allocation for each point source. Consider a set of point sources (PS*i*), *i* = 1,…,*N*, disposing pollutant containing waste water to a common water body or a watershed. The various point source specific parameters are:

*Di* = Discharge quantity of polluted water from PS*i* [volume/year]

*ci* = Current pollutant concentration in discharge water from PS*i* [mass/volume]

*redi* = Desired pollutant quantity reduction in discharge of PS*i* [mass/year]

Let *j* = 1,…,*M* be the set of waste reduction technologies available to the point sources. The technology specific parameters are:

*fj*(*θj, Di*) = Cost function for total plant cost for technology *j* [$]

*qj* = Pollution reduction possible from the implementation of technology *j* [mass/volume]

where, *θj* is the set of design parameters of technology *j*.

The decision variables are:

* *bij*: Binary variable representing point source-technology correlation. The variable is 1 when PS *i* installs technology *j*, and 0 otherwise.

All the parameters are on annual basis.

Once the model parameters and decision variables have been identified, we then need to formulate the model constraints and the objective function. Constraints in an optimization model are conditions such as mass balance and energy balance that must be satisfied by the solution. Objective function provides the target for the optimization problem solution. The constraints and objective function are modelled here:

1. **Constraint 1:** It needs to be ensured that the prescribed regulatory limits are satisfied for each industry. We, therefore, need a constraint that ensures that the desired pollutant quantity reduction for a point source (*redi*) is met. The constraint is modelled as follows:

Here, the left hand side is the total reduction target for point source *i*. The RHS is the amount of reduction achieved by installing a waste reduction technology *j* at point source *i*. When the model is solved, the binary decision variable *bij* will govern which reduction amount is selected for point source *i*.

It must be noted that we can also formulate a different constraint such that the cumulative reduction targets for all the point sources in the watershed are lower than the cumulative reduction achieved by installation of mercury control technologies at all point sources. Such as constraint will be written as follows:

However, such as constraint may lead to a situation where the some of the point sources individually are not achieving the reduction targets given to them. From a total watershed mercury accounting standpoint, it may not make much of a difference. However, non-compliance by some of the point sources may lead to high mercury concentration at their waste discharge locations. These are known as localized hot-spots and are not desirable. Therefore, the first constraint, which ensures that all point sources must meet the reduction targets, is preferred.

1. **Constraint 2:** One can also put a constraint on the number of mercury control technologies an industry can select. In a realistic scenario, an industry will prefer to select a single more technology rather than two or more different technologies. This is because the operating constraints and the technical knowhow for two different technologies might be vastly different. The model can therefore be modified to include such as constraint as follows:

This constraint ensures that only one of the binary variables is non-zero for each industry. The right hand side may be changed to 2 or 3 depending on how many different technologies are permitted for the same point source. Note that multiple installations of the same technology, such as two ion exchange processes connected in series, are not considered. The model can be extended to model multiple such installations by considering another set of integer variables. This is left as an exercise for students to solve.

1. **Objective function:** The objective of pollutant trading, as stated earlier, is to reduce the overall compliance cost for the set of point sources. Therefore, the objective function for this optimization problem is:

The objective function is the sum of the waste reduction technologies installed across all the point sources in the considered region. A simple cost function is linear with respect to the amount of waste being treated. For such cases, the cost function can be written as:

Here, represents the treatment cost per unit volume for technology *j* ($/volume)*.*

**Programming of the model in GAMS**

The case study provides a separate tutorial for programming an optimization model in GAMS (General Algebraic Modeling System). Screenshots for the programming of mercury trading problem in GAMS are provided (Figures 1-4). The GAMS editor along with the educational version of the license can be freely downloaded from the GAMS website ([www.gams.com](http://www.gams.com)). The free educational version can solve problems up to a maximum of 300 constraints and 300 variables. For larger problems, a solver specific to the problem being solved needs to be purchased. Students can also use the NEOS server (<http://www.neos-server.org/neos/>) hosted by the Wisconsin Institutes for Discovery at the University of Wisconsin in Madison and provides access to several solvers free of charge. The user has to formulate and code the model in GAMS on the local machine. The problem can then be submitted to the NEOS Server (please see the NEOS guide on the website), where it is solved and the results are reported.

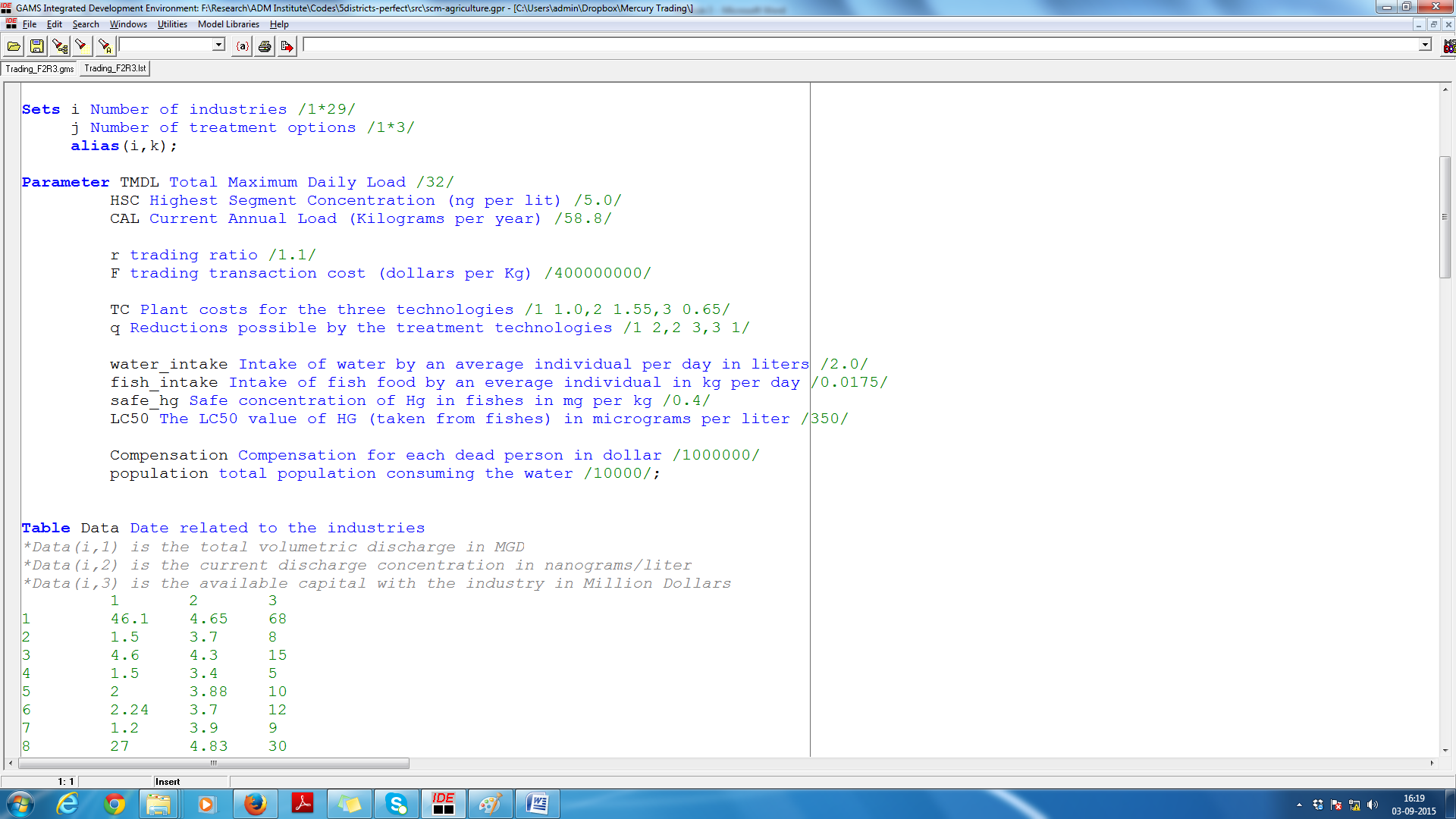


Figure 1: Declaration of sets and parameter values for model formulation

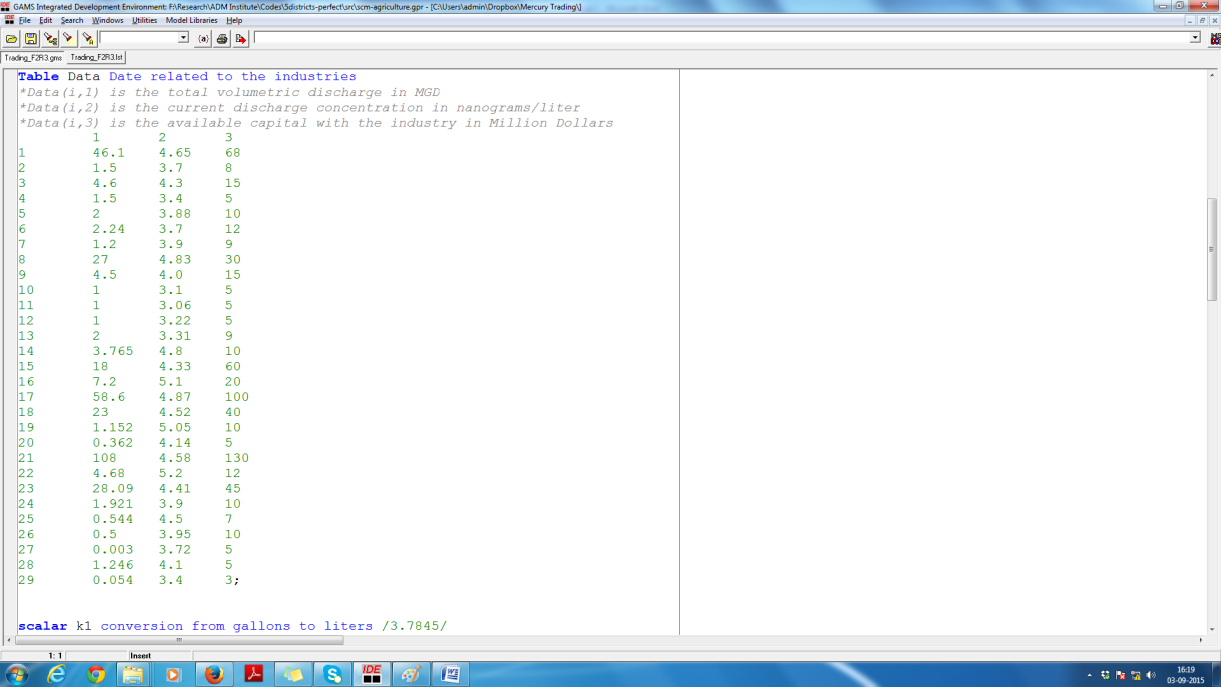


Figure 2: Declaration of data table for 29 point source industries

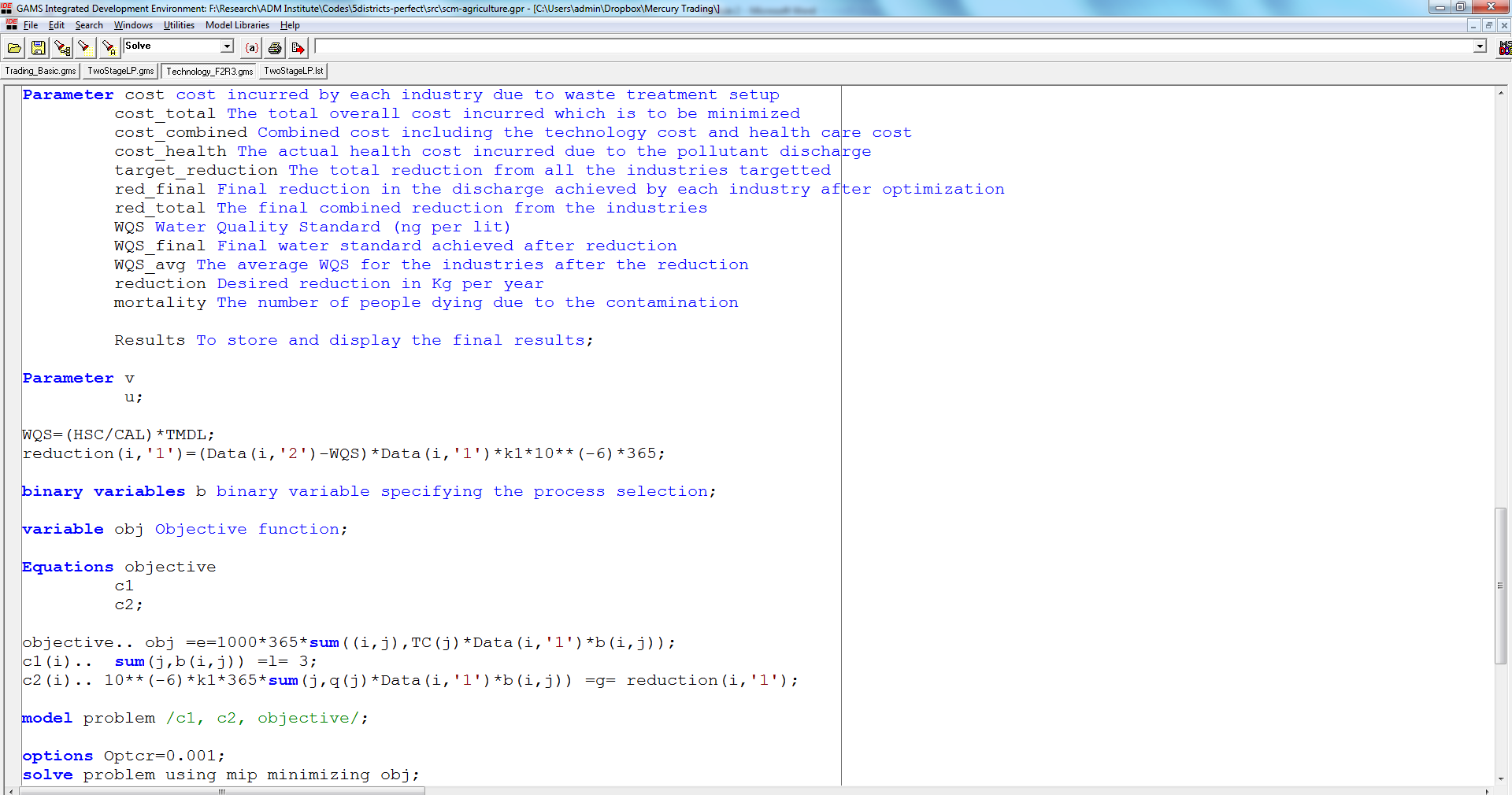


Figure 3: Declaration of equations, model and solve statement

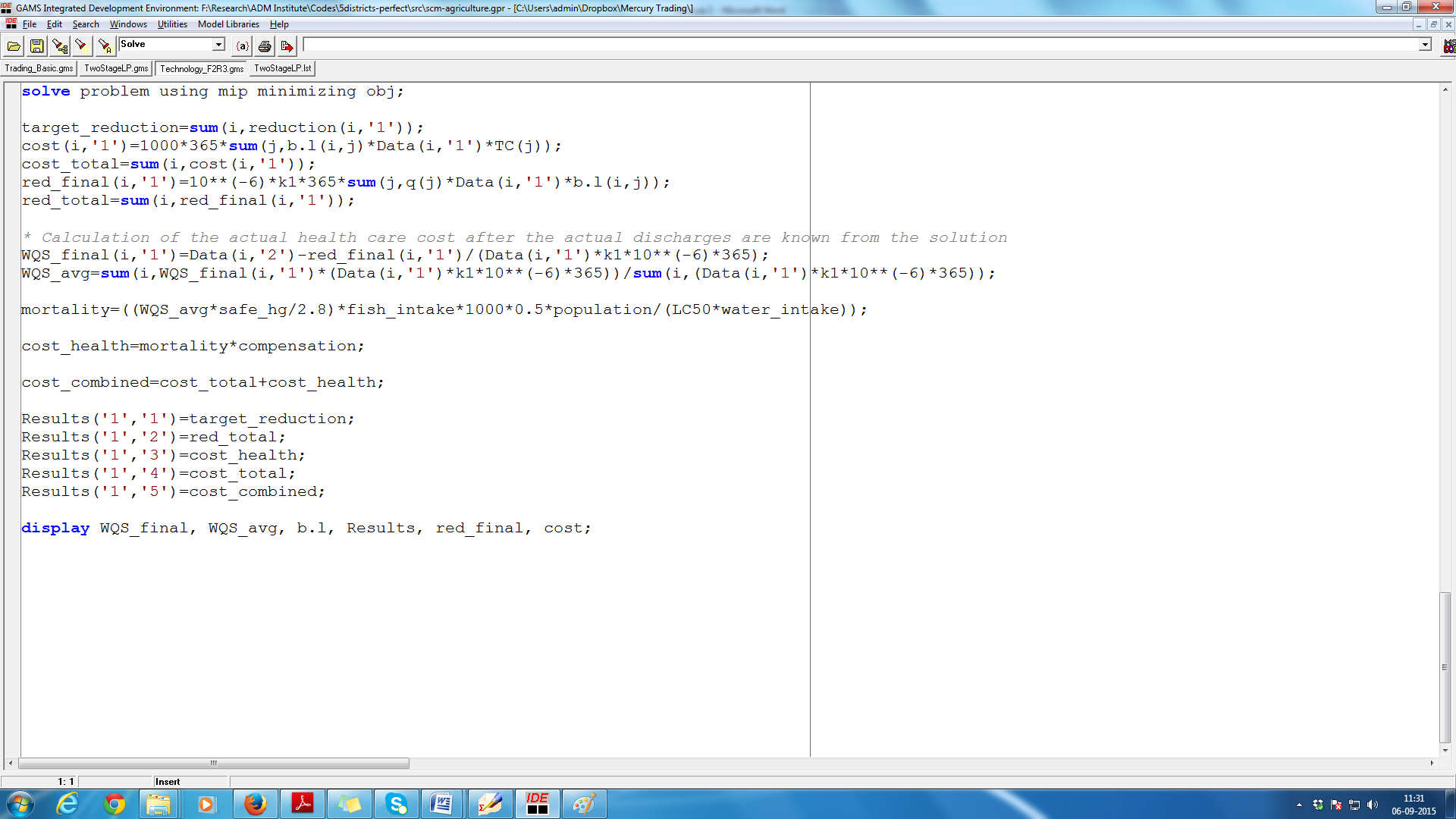


Figure 4: Post optimization calculation of health care cost for the model simulation result

**Exercise: Model solution and analysis of results**

The model that we have formulated and programmed in GAMS is to be used to solve the given case study. In particular, the important questions of interest that need to be answered are:

1. What is the total cost of compliance and the individual cost of compliance for the 29 point sources?
2. What are the preferences for the selection of technology among the three options?
3. Is there any correlation between the type of technology and the volume of the waste stream to be treated?
4. How do these results change if the value of the TMDL is changed? The model can be solved for values of 26 kg/y to 36 kg/y (base case value is 32 kg/y).

**References for further reading**

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