# APPENDIX A

# IN ESSENCE

Inland Navigation Excel Spreadsheet Spatial Equilibrium Nascent Concept Execution

## 1. Introduction

Accomplishing a scientific analysis requires an underlying theoretical concept. In fact, this is what separates science from merely a collection of facts and observations. During the course of this study it became clear that Spatial Price Equilibrium Theory, a well developed economic concept, provided the appropriate framework for analyzing the UMR-IW navigation system, hence, the Spatial Equilibrium Model (SEM) was adopted as the *conceptual model* for conducting this analysis.

Modeling real world problems we must be concerned not only with the theoretical but also the pragmatic. These pragmatic concerns include, but are not limited to, availability of data, mathematical tractability, and limited study resources. To avoid equivocation, this *practical model* is referred to as ESSENCE. This appendix details the construction, calibration, and execution of the ESSENCE model. It is intended to be of sufficient detail to inform the reader what is contained in every cell of the spreadsheet as well as to detail which cells are critical to the operation of the model. The experience analyst, using this documentation as a guide, should be able to understand, use, modify and calibrate the model.

## 2. Background

The SEM represents a significant departure in the underlying concept motivating the economic evaluation of inland navigation infrastructure. The ESSENCE, in contrast, represents the smallest departure from extant navigation systems models (GEM) possible without **blatant inconsistency** with the SEM framework. This is in part due to the fact that the motivation for the analysis remains providing decision support for potential actions involving the navigation infrastructure (locks) and in part due to the fact that the data collection and development of model inputs proceeded in advance and concurrently with model development. Any practical model must make use of the extant inputs.

## 3. ESSENCE in General

As its name implies, ESSENCE was developed and is run in Microsoft Excel 5.0. This software was chosen because the spreadsheet format facilitated model development and also because the solver capabilities available in Excel were suitable for finding the equilibrium conditions. The spreadsheet formulation makes input, output, and the relationships between them readily accessible.

The Excel workbook containing ESSENCE consists of two work sheets. The first sheet contains the model itself while the second sheet contains the traffic forecasts. Embedding the traffic forecasts in the workbook facilitates the automation of traffic updates for out year runs.

There are three essential components to the model. They are 1) calculation of lock congestion (supply), 2) determination of system movements (demand), and 3) calculation of the NED benefit. Since lock congestion is a function of traffic, which in turn is influenced by lock congestion, these two elements must be co-determined. To accomplish this the solver module of Excel is employed. The documentation of ESSENCE proceeds in the following order:

Section 4: Lock Performance
Section 5: Movements
Section 6: Opportunity Cost
Section 7: System Equilibrium
Section 8: Calculation of system NED benefits
Section 9: Forecasts
Section 10: Calibration and Verification
Section 11: Modeling of Potential System Actions

## 4. **Lock Performance**

Modeling the operation of the system locks, specifically, predicting lock transit time is accomplished in the block of cells defined by H5 through BH32. In particular each of the columns I through AS correspond to one of the 37 locks explicitly modeled. The lock site labels are provided in Row 5 and again, for convenience in Row 22. Rows 6 through 20 provide statistics on base year operations, while rows 23 through 31 are concerned with the modeled year. With the exception of locks 26 and 27, locks are modeled as single chamber sites with all data and calculations necessary to accomplish the transit time estimate arrayed in the single column corresponding to the lock. The labels describing the cells in each row are provided in column H. Since data and calculations are similar for all sites (except 26 and 27) we will go through one example in detail.

Because the estimation of lock performance is based largely on Lock Performance Monitoring System (LPMS) data, while traffic is estimated from Waterborne Commerce Statistics Center (WCSC) data, it is important to verify that there is not a disconnect between these two data sources. Referring to Table 1 below rows 6 and 7 of the spreadsheet display the base year (1992) lock tonnage based on these two data sources. As can be noted the WCSC tonnage (cell AI7) is actually calculated from the system movements. These movements will be discussed in a later section. Inspection found that there was good to adequate consistency between these data sources. These rows of cells are not a necessary component of the ESSENCE model.

As described in the following section on movements, traffic data consists of both front-haul and back-haul movements. The movements are arrayed in the spreadsheet so that front-hauls appear first. The front-haul tons is calculated by summing the front-haul movement tons using a particular lock. This parameter, calculated for the base year, appears in row 8. It is used in the calculation of front-haul tons per tow the parameter displayed in row 13. The other parameter used in calculating front-haul tons per tow is number of tows. This is displayed in row 9 and comes directly from 1992 LPMS data.

Rows 10 and 11 contain the mean and standard deviation of Tow Service time as calculated from LPMS data. Since these parameters were originally calculated in days they are converted to hours by multiplying by 24. These parameters are critical to the model. It is (usually) these parameters that that are modified to reflect some system action.

Rows 12 and 13 contain Tons per Tow and Front Haul Tons per Tow, respectively. These parameters are calculated from parameters previously discussed. It is important to note that these parameters are constructed from the combination of WCSC and LPMS data. “Tons per Tow” is provided for information only and is not necessary for executing the model. Front-Haul tons per tow is an important determinant of future lock traffic. Since we do not expect much change in tow configuration over the study horizon, this parameter is assumed to be invariant. The reason Front-Haul Tons per Tow is used (rather than Tons per Tow) is because there is sufficient empty equipment to accommodate increased back-haul movements without requiring additional lockages. In other words, Tons per Tow is not invariant over the study horizon because, depending on the circumstances, back-haul movements may increase or decrease.

Rows 14, 15 and 16 contain the parameters, which describe the demands placed on the lock by recreation traffic. They are number of recreation lockages, mean service time, and standard deviation of service time for recreation lockages, respectively. Since multiple vessel lockages are common for recreation traffic, it is a model assumption that the number of recreation lockages is invariant over the study horizon. That is to say that, even if the number of recreational vessels utilizing the locks increases, there is no clear evidence that this will result in increased lockages. Depending on the measures(s) being modeled the mean and/or standard deviation of the recreational lockage service time may need to be altered to reflect the impacts of the measure.

Rows 17, 18, 19, 20 compute the mean and standard deviation of service time over all traffic along with the expected wait time and total tow transit time. Note that these parameters are provided for use in base year validation only. They are not involved in the actual running of the model. Some of the formulas used in these calculations are interesting and should be discussed. Row 17 is the mean service time. It is computed as the weighted average of the average service times for commercial tows and recreational lockages. The formula in row 18 performs a similar function for the standard deviations. The formula is:

$$\sigma = \sqrt{\left[\frac{\left(\mu_T^2 + \sigma_T^2\right) * N_T + \left(\mu_R^2 + \sigma_R^2\right) * N_R}{N_T + N_R}\right] - \mu}$$

This explains how standard deviation for a population consisting of two sub-populations can be determined from the means and standard deviations as well a the size of the two subgroups.

The estimated lock wait time is found using the following formula from Queuing Theory:

> $Ex(D) = [(:_s{}^2+\Phi_s{}^2)/2(:_a-:_s)][(\Phi_a{}^2+ \Phi_s{}^2)/( :_a{}^2+ \Phi_s{}^2)]$, where $:_s$ represents the mean service time, $\Phi_s$ represents the standard deviation of the service time, $:_a$ represents the mean inter-arrival time at the lock, $\Phi_a$ represents the standard deviation of the inter-arrival times at the lock. As explained in the SEM documentation, this formula provides an approximation that should become increasingly accurate with congestion. Further the interarrival times are assumed to be exponentially distributed, hence the mean interrarival time is equal to the standard deviation of interarrival time, and hence the second term, $[(\Phi_a{}^2+ \Phi_s{}^2)/( :_a{}^2+ \Phi_s{}^2)]$, in the equation is equal to 1. This formula, as it actually appears in the ESSENCE model, can be inspected below in cell AI19. Note that the average interarrival time is computed by dividing the number of lockages by the number of hours in a 270 day navigation season. For locks on the Illinois Waterway, as well as locks 26 and 27, a 365 day navigation season is used. It should be noted that, since this calculation is the expected value of a random variable, we would not expect to see exact replication of wait times actually observed on the navigation system. What we look for is wait times that are consistent with those that we have historically observed. Row 20 contains the expected tow transit time which is simply the sum of the average tow service time and the expected wait time.
>
> Rows 23 through 31 contain the lock specific outputs for the model run. They are, in many cases, analogous to the inputs previously discussed. Tons and front-haul tons are contained in rows 23 and 24. They are calculated by summing the tonnage in the system movements using the lock in the scenario (year & actions) be modeled. Tons locked is provided merely for interest, but front-haul tons are necessary to compute the number of commercial tows found in row 25 of

ESSENCE. Note that number of tows is calculated by dividing the front-haul tons by the "front-haul tons per tow" (row 13) which was assumed to be invariant.

Once the number of tows is determined, the mean interarrival time, mean service time, and standard deviation can be computed in an exactly analogous manner to that previously discussed. Note again that these are the critical inputs used in calculating the wait time.

Rows 29 and 30 show a capacity estimate assuming no recreation lockages and a calculation of lock utilization. These outputs are calculated in a straightforward manner which the reader can determine by inspection of the cells. Note that these outputs are provided purely for interest and are not essential to executing the model.

Finally, row 31 computes the expected value of tow lock transit by adding the mean service time to the wait time computed using the formula discussed above.

Both the Melvin Price Lock and Dam (26) and Lock 27 have 600' and 1200' chambers capable of moving significant quantities of commercial traffic. It was determined that delay estimation for these sites could be accomplished using techniques and formulas similar to the single chamber formulation if traffic could be properly allocated between the two chambers. This allocation is done using Excel's Solver feature.

The portion of the spreadsheet which accomplishes this is contained in the section defined by cells AW1 through BH32. Table two below shows an extract of that section. The allocation is accomplished as follows. First the LPMS data is examined to determine the proportion of the commercial tows which would require a double lockage in the 600' chamber. This proportion is about .75 and is displayed in cell AY4 (cell AY3 displays the proportion requiring only a single lockage). Next LPMS data is used to determine the mean and standard deviation of single, double and recreation service times in the 600' chamber. For the 1200' chamber we identify the mean and standard deviation of service times for Tow lockages and for recreation lockages (since all commercial lockages in the 1200' chamber are accomplished in a single cut). These values are input into rows 16 through 18 (mean) and rows 20 through 22 (standard deviation). Note that for the main (1200') chamber the mean and standard deviation are identical both tow lockage types since, in this chamber, both would require a single lockage. From these parameters the weighted averages of the mean and standard deviation of lock service time over all traffic is computed in a way analogous to that used in the single chamber case. Note that the average is now over three subgroups (single, double, recreation) rather than the two used in the single chamber case. These calculations are accomplished in rows 25, 26 and 27 of the spreadsheet. Interarrival time is computed by dividing the total hours in the year by the number of lockages allocated to the chamber in cell 30. The calculation of average tow transit time for the chamber takes place in cell 32 and is identical to the calculation used for the single chamber site. The lock transit time for tows for the total site is then found (in cell AJ32) by calculating the weighted average of this parameter for each chamber. The solver is employed to minimize this number (total average tow transit time) by adjusting the allocation of single, double and recreation lockages in the auxiliary (600') chamber to any non-negative number. These "floating cells" are AZ10, AZ11, and AZ12. The allocation of lockages to the main chamber is done in cell AY10, AY11, AY12 and is simply the difference between the total number of lockages of a given type and those allocated to the auxiliary chamber.

In the ESSENCE model, since we must perform this process for two sites (possibly more if we choose to model the addition of 2nd chambers), we actually use the solver to minimize the sum to the transit times across all two-chamber sites. Since these parameters are independent and non-negative, minimizing the sum is equivalent to minimizing each separately.

Those familiar with queuing theory may recognize that this algorithm will theoretically overestimate transit time. This is because the allocation is done a priori rather than in real time. This is only a minor problem since there are factors, such a vessel interference and bias towards a particular chamber, that would tend to increase observed delays. Further, in the limit of large queues, the formulation described above becomes theoretically correct.

Also, it should be noted, that while 2nd chambers exist at locks 14 and 15, due to their small sizes and locations it is not expected that these auxiliary chambers will move significant commercial traffic, therefore, in order to save computational overhead, we modeled these as single chamber sites.

## TABLE A-1. SPREADSHEET EXCERPT – CALCULATION OF LOCK TRANSIT TIME

| ROW | COLUMN G | COLUMN AI WITH FORMULAS DISPLAYED | COLUMN AI WITH VALUES DISPLAYED |
|---|---|---|---|
| 5 | | UM 25 | UM 25 |
| 6 | 1992 PMS Tons | 39379000 | 39,379,000 |
| 7 | 1992 WCSC Tons | =SUMPRODUCT($F$48:$F$818,AI48:AI818) | 39,082,581 |
| 8 | 1992 WCSC Front Haul Tons | =SUMPRODUCT($F$48:$F$586,AI48:AI586) | 32,557,840 |
| 9 | 1992 PMS Tows | 3454 | 3,454 |
| 10 | Mean Service Tows (hrs) | =0.0577*24 | 1.3848 |
| 11 | Stnd Dev Service Tows (hrs) | =0.0295*24 | 0.708 |
| 12 | Tons/Tow | =AI7/AI9 | 11,315 |
| 13 | Front Haul Tons/Tow | =AI8/AI9 | 9,426 |
| 14 | 1996 Rec Lockages | 687 | 687 |
| 15 | Mean Service Rec (hrs) | 0.1842 | 0.1842 |
| 16 | Stnd Dev Service Rec (hrs) | 0.1 | 0.1000 |
| 17 | Mean Service All (hrs) | =(AI9*AI10+AI14*AI15)/(AI9+AI14) | 1.1856 |
| 18 | Stnd Dev Service All (hrs) | =(((AI10^2+AI11^2)*AI9+(AI15^2+AI16^2)*AI14)/(AI14+AI9)-AI17^2)^0.5 | 0.7869 |
| 19 | Estimated Lock Wait Time 1992 (hrs) | =(0.5*(AI17^2+AI18^2)/((270*24)/(AI9+AI14)-AI17)) | 2.67 |
| 20 | Estimated Total Tow Transit Time 1992 (hrs) | =AI10+AI19 | 4.05 |
| 21 | | | |
| 22 | LOCK | UM 25 | UM 25 |
| 23 | Tons | =SUMPRODUCT($G$48:$G$818,AI48:AI818) | 39,082,581 |
| 24 | Front Haul Tons | =SUMPRODUCT($G$48:$G$586,AI48:AI586) | 32,557,840 |
| 25 | Tows | =AI24/AI13 | 3,454 |
| 26 | Mean Interarrival Time All (hrs) | =270*24/(AI14+AI25) | 1.56 |
| 27 | Mean Service Time All (hrs) | =(AI25*AI10+AI14*AI15)/(AI25+AI14) | 1.19 |
| 28 | Stnd Dev Service Time All (hrs) | =(((AI10^2+AI11^2)*AI25+(AI15^2+AI16^2)*AI14)/(AI25+AI14)-AI27^2)^0.5 | 0.7869 |
| 29 | Main Chamber Capacity with no Rec Lockages (tons) | =(270*24/AI10)*(AI12) | 52,947,914 |
| 30 | Utilization | =AI27/AI26 | 75.8% |
| 31 | Total Tow Transit Time from Lock Data (hrs) | =AI10+(0.5*(AI27^2+AI28^2)/(AI26-AI27)) | 4.05 |

# Table A-2. A Two Chamber Lock

| Row | AW | AX | AY | AZ | BA |
|---|---|---|---|---|---|
| 1 | | LOCK 26 DETAIL | | | |
| 2 | | | | | |
| 3 | | PERC 1 | 0.25 | | |
| 4 | | PERC 2 | 0.75 | | |
| 5 | | | | | |
| 6 | | | MAIN | AUX | TOTAL |
| 7 | TOWS | | 7924.62 | 2641.54 | 10566.16 |
| 8 | | | | | |
| 9 | | | | | |
| 10 | TOWS1 | | 0.00 | 2641.54 | 2641.54 |
| 11 | TOWS2 | | 7924.62 | 0.00 | 7924.62 |
| 12 | REC | | 0.00 | 1722.00 | 1722.00 |
| 13 | | | | | |
| 14 | TOTAL VESSELS | | 7924.62 | 4363.54 | 12288.16 |
| 15 | | | | | |
| 16 | Mean Service Tows (hrs) 1 | | 0.63 | 0.56 | 0.56 |
| 17 | Mean Service Tows (hrs) 2 | | 0.63 | 1.54 | 0.63 |
| 18 | Mean Service Rec (hrs) | | 0.23 | 0.24 | 0.24 |
| 19 | | | | | |
| 20 | Stnd Dev Service Tows (hrs) | | 0.29 | 0.20 | |
| 21 | Stnd Dev Service Tows (hrs) | | 0.29 | 0.30 | |
| 22 | Stnd Dev Service Rec (hrs) | | 0.10 | 0.10 | |
| 23 | | | | | |
| 24 | | | | | |
| 25 | Mean Service All (hrs) | | 0.63 | 0.43 | 0.56 |
| 26 | Mean Service All Tows (hrs) | | 0.63 | 0.56 | 0.61 |
| 27 | | | | | |
| 28 | Stnd Dev Service All (hrs) | | 0.29 | 0.23 | |
| 29 | | | | | |
| 30 | Mean Interarrival Time All (hrs) | | 1.11 | 2.01 | 0.71 |
| 31 | | | | | |
| 32 | Total Tow Transit Time All (hrs) | | 1.13 | 0.64 | 1.00 |

# Table A-2 (continued)

| ROW | AW | AX | AY | AZ | BA |
|---|---|---|---|---|---|
| 1 | | LOCK 26 DETAIL | | | |
| 2 | | | | | |
| 3 | | PERC1 | 0.25 | | |
| 4 | | PERC2 | =1-AY3 | | |
| 5 | | | | | |
| 6 | | | MAIN | AUX | TOTAL |
| 7 | TOWS | | =AY10+AY11 | =AZ10+AZ11 | =AJ25 |
| 8 | | | | | |
| 9 | | | | | |
| 10 | TOWS1 | | =BA10-AZ10 | 2641.53998992027 | =BA7*AY3 |
| 11 | TOWS2 | | =BA11-AZ11 | 0.00001 | =BA7*AY4 |
| 12 | REC | | =BA12-AZ12 | 1721.99999 | =AJ14 |
| 13 | | | | | |
| 14 | TOTAL VESSELS | | =SUM(AY10:AY12) | =SUM(AZ10:AZ12) | =SUM(BA10:BA12) |
| 15 | | | | | |
| 16 | Mean Service Tows (hrs) 1 | | 0.6264 | =33.7/60 | =(AY16*AY10+AZ16*AZ10)/(AY10+AZ10) |
| 17 | Mean Service Tows (hrs) 2 | | 0.6264 | =92.4/60 | =(AY17*AY11+AZ17*AZ11)/(AY11+AZ11) |
| 18 | Mean Service Rec (hrs) | | 0.2323 | 0.2358 | =(AY18*AY12+AZ18*AZ12)/(AY12+AZ12) |
| 19 | | | | | |
| 20 | Stnd Dev Service Tows (hrs) | | 0.2928 | 0.2 | |
| 21 | Stnd Dev Service Tows (hrs) | | 0.2928 | 0.3 | |
| 22 | Stnd Dev Service Rec (hrs) | | 0.1 | 0.1 | |
| 23 | | | | | |
| 24 | | | | | |
| 25 | Mean Service All (hrs) | | =(AY10*AY16+AY11*AY17+AY12*AY18)/(AY10+AY11+AY12) | =(AZ10*AZ16+AZ11*AZ17+AZ12*AZ18)/(AZ10+AZ11+AZ12) | =(AY25*AY14+AZ25*AZ14)/BA14 |
| 26 | Mean Service All Tows (hrs) | | =(AY10*AY16+AY11*AY17)/(AY10+AY11) | =(AZ10*AZ16+AZ11*AZ17)/(AZ10+AZ11) | =(BA10*BA16+BA11*BA17)/(BA10+BA11) |
| 27 | | | | | |
| 28 | Stnd Dev Service All (hrs) | | =(((AY16^2+AY20^2)*AY10+(AY17^2+AY21^2)*AY11+(AY18^2+AY22^2)*AY12)/(AY14)-AY25^2)^0.5 | =(((AZ16^2+AZ20^2)*AZ10+(AZ17^2+AZ21^2)*AZ11+(AZ18^2+AZ22^2)*AZ12)/(AZ14)-AZ25^2)^0.5 | |
| 29 | | | | | |
| 30 | Mean Interarrival Time All (hrs) | | =(365*24)/AY14 | =(365*24)/AZ14 | =(365*24)/BA14 |
| 31 | | | | | |
| 32 | Total Tow Transit Time All (hrs) | | =AY26+(0.5*(AY25^2+AY28^2))/(AY30-AY25) | =AZ26+(0.5*(AZ25^2+AZ28^2))/(AZ30-AZ25) | =(AY7*AY32+AZ7*AZ32)/(AY7+AZ7) |

5. **Movements**

After aggregation by origin, destination, and commodity group 771 movements, accounting for almost 135 million tons in the base year were identified. The parameters defining these movements, along with the movement specific calculations are contained in rows 48 through 818 of the ESSENCE model. An important distinction between movements occurring on the system are those whose water transportation prices will be sensitive to lock congestion and those whose water prices will be insensitive. These are referred to as elastic and inelastic movements, respectively. It should be noted, however, that we consider (almost) all movements to be price elastic, but the focus of this model is the impact of lock congestion. Movements that are considered inelastic are: 1)movements that do not use any system locks (41,000,000 tons) and 2)back-haul movements (16,000,000 tons). Back-haul movements are defined as movements that utilize resources (barges, tows) which, in the absence of the movement would transit the locks empty. Generally back-haul movements are long-haul northbound movements of commodities utilizing hopper barges. Since, for back-haul movements, the opportunity cost of production foregone is incurred in either case, lock congestion should not impact the back-haul rate and therefore these movements should be inelastic with respect to lock congestion. Conversely, front-haul movements incur congestion on both the trip and return, hence their prices are doubly sensitive to the opportunity foregone while awaiting lockage. There were a small number of movements (less than a million tons) where the existing transportation cost analysis indicated no economic incentive to use the waterway. Since these movements are observed the conclusion must be that their reasons for using the waterway, economic or otherwise, are not fully understood. This led to the decision to model these movements as inelastic (in volume) to lock congestion, even through their water prices increase with increasing congestion. The following table illustrates the breakdown of the movements:

Elastic: 507 Movements, 76642077 tons

Inelastic: 264 Movements, 58085096 tons
- Negative Rate Savings: 32 movements, 992990 tons
- Do Not Use Locks: 51 movements, 41113268 tons
- Backhauls: 181 movements, 15978838 tons

Note the extract of the first 8 cells of the first 3 movements below.

| A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|
| | | | | 2020 | | | |
| | | | | Faucett | | | |
| | | | | Tons | 1992 | 2020 | |
| Originating | Terminating | Com | | with | WCSC | Water | NED |
| Pool | Pool | Grp | Rvr | 1994 Costs | TONS | Tons | 2020 |
| BLACKRIV | 99 | 1 | M | 20,627 | 10,988 | 13,896 | 1.88 |
| CALUMETR | 99 | 1 | I | 682,113 | 332,998 | 639,477 | 2.41 |
| CHIRIVER | 99 | 1 | I | 3,355 | 1,638 | 3,148 | 2.44 |

The first four cells of the movement are straightforward. They are movement origin, destination, commodity group, and River. Code 99 in the destination indicates a movement leaving the UMR-IW system. The commodity groups are listed on the 2nd sheet of the workbook with the forecasts. Column D indicates whether the movement takes place primarily on the Mississippi River or the Illinois Waterway.

The calculation that applies the forecast to the individual movement takes place in column D. The formula is:

For the Illinois Waterway
F49*VLOOKUP(C49,Forecasts!$B$21:$K$31,$A$12+1)/VLOOKUP(C49,Forecasts!$B$21:$K$31,2)
or For the Mississippi River
=F48*VLOOKUP(C48,Forecasts!$B$7:$K$17,$A$12+1)/VLOOKUP(C48,Forecasts!$B$7:$K$17,2)

These formulas look up, in sheet two of the model, the forecast tonnage for the proper river system and commodity group, and calculate the ratio of it to the base year traffic. This proportional increase is then multiplied by the base year (1992) traffic found in column F to produce the movement specific forecast. The model year is input into the cell A6, which in turn updates the appearance of the year in the column labels as well as affecting cell A12 the lookup column. Note that this tonnage is that which is forecast to move on the river system if prices remain at existing levels.

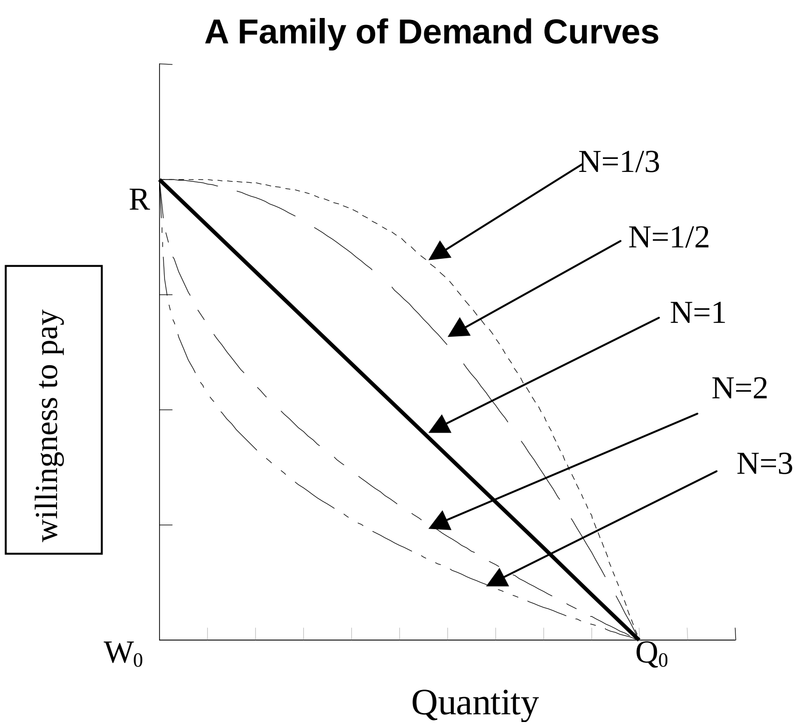
The base year (1992) for model movements is the actual movements as reported by WCSC while the forecast base is actually an average of 1991-1993 traffic. This creates a small discrepancy between total traffic as measured in the model and that which appears on the forecast sheet. Given that there exists a large uncertainty in the forecasts, this discrepancy is not considered important.

Column G performs the calculation that estimates the quantity of forecast tonnage which actually will have the economic incentive to use the system. This is one of the ESSENTIAL features of the model and the key feature in terms of making the model consistent with the SEM framework so will be explored in some detail. The formula in this cell is the demand curve for the aggregate (origin, destination, commodity group) movement.

As noted in the body of this documentation the demand for waterway transportation service is a derived demand with the willingness to pay for the final increment of output equal to the observed rate for each (aggregate) waterway movement. Further, spatial economic theory suggests that the willingness to pay cannot exceed the rate of accomplishing the same movement by an alternative mode. Note that the rate for the alternative mode for each movement is found in column AZ. These prices were estimated based upon a study performed by the Tennessee Valley Authority (TVA). Further conditions that we wish to impose on the demand curves is that 1) they be non-increasing functions, 2) be continuos, 3) at least piecewise differentiable, and 4) integrable in closed form. The reason for this last condition will become evident when we discuss the evaluation of NED benefits.

An important family of curves that satisfy the above mathematical properties is illustrated below:

**FIGURE A-1**



$$Q = \left( \frac{R - y}{R - W_0} \right)^N * Q_0 \quad ; 0<=y<R$$

$$Q = 0 \qquad ; y>=R$$

Q = quantity of water transportation for O-D-Commodity triple
R = Upper Bound on water transportation rate
y = water rate of O-D-Commodity triple
$W_0$ = Observe water rate for movement at quantity $Q_0$

Note that N>0. For large values of N the curve is more elastic at the margin, while for small values of N the curve is less elastic at the margin.

In the absence of evidence to the contrary, ESSENCE uses the demand curve with N=1 (linear) for all movements except for agricultural products (commodity groups 1-4). For agricultural products, the distributed nature of the production process, and the need to collect grain at a river terminal suggests that a quadratic formulation (N=2) should be used. This argument is presented below.

The maximum distance of the grain from the river, x, is proportional to the price paid, at the river elevator, P. The volume of grain shipped from a given origin is proportional to the land-side area the river terminal draws from which in turn is proportional to the square of the drawing distance ($x^2$). Therefore, since x is proportional to P, the volume of grain is proportional to the square of the price offered. This implies that the quadratic form of the above curve (N=2) should be used.

In summary for the front-haul movements of agriculture products (commodity groups 1-4) the calculation of tonnage on the system in column G is determined by the formula (the movement in row 48 is used as an example):

=MAX(((AZ48-AY48)/(AZ48-AW48)),0)^2*E48

where AZ48 is the rate on the alternative mode, AY48 is the estimated water rate, and AW48 is the 1994 (base) water rate and E48 is the movement tonnage forecast at the 94 rate. Note that this formulation has the desired property that if the estimated water rate is equal to the 1994 water rate the system tonnage will be the forecast tonnage. Also, if the estimated water rate exceeds the alternative mode rate, the estimated system tonnage for the movement will be zero.

For the other movements the demand is characterized by (using movement 175 as an example):

=MAX(E175*(AZ175-AY175)/(AZ175-AW175),0)

Note that this demand curve shows the same characteristics as the previously discussed demand curve, but is less elastic at the margin.

Neither of the above curves is used for the 32 movements that showed negative rate savings. These movements are simply assumed to traverse the system independent of water rate.

The NED contribution of the movement to the system is calculated in Row H. This is discussed in detail in a later section.

Columns I through AS contain the lock use indicators and correspond directly to the 37 locks in the modeled system. A "1" in the cell indicates that lock is used by the movement a "0" indicates that it is not used. The lock use indicators are blank for movements that use no system locks. The use of this scheme allows for the efficient calculation of predicted lock tonnage by multiplying movement tonnage by the appropriate indicator then summing across all movements. See the above discussion of lock tonnage in Section 4 for an example computation.

Column AT contains the opportunity cost of net revenues foregone due to congestion. For convenience it is expressed on a per-ton hour basis. The values of this cell are $.026 for front-haul movements utilizing hopper barges, $.069 for movements utilizing tank barges, and 0 for back-haul movement, or movements not utilizing system locks. More will be said about the construction of these numbers in a later section.

**TABLE A-3. MOVEMENT WATER RATE CALCULATION**

| AT | AU | AV | AW | AX | AY | AZ |
|---|---|---|---|---|---|---|
| | | | Exist | | | |
| Hourly | | 1994 | 1994 | | =A6 | 1994 |
| Unit | Total | No Lock | Total | =A6 | Total | Maximum |
| Opptnty | Opp | Water | Water | Cost | Water | Alternative |
| Cost | Cost | Cost | Cost | Increase | Cost | Cost |
| =$C$16 | =AT48*SUMPRODUCT($I$32:$AS$32,I48:AS48) | 14.92 | 16.37 | =AY48-AW48 | =AU48+AV48 | 23.24 |
| =$C$16 | =AT49*SUMPRODUCT($I$32:$AS$32,I49:AS49) | 16.66 | 17.11 | =AY49-AW49 | =AU49+AV49 | 24.58 |
| =$C$16 | =AT50*SUMPRODUCT($I$32:$AS$32,I50:AS50) | 16.68 | 17.12 | =AY50-AW50 | =AU50+AV50 | 24.67 |
| =$C$16 | =AT51*SUMPRODUCT($I$32:$AS$32,I51:AS51) | 16.14 | 16.58 | =AY51-AW51 | =AU51+AV51 | 24.09 |
| =$C$16 | =AT52*SUMPRODUCT($I$32:$AS$32,I52:AS52) | 3.74 | 3.76 | =AY52-AW52 | =AU52+AV52 | 6.87 |
| =$C$16 | =AT53*SUMPRODUCT($I$32:$AS$32,I53:AS53) | 12.99 | 13.04 | =AY53-AW53 | =AU53+AV53 | 17.01 |
| =$C$16 | =AT54*SUMPRODUCT($I$32:$AS$32,I54:AS54) | 15.54 | 15.65 | =AY54-AW54 | =AU54+AV54 | 19.62 |

Column AU is used to determine total (per ton) net revenues foregone due to all of the movements lock transits. In is done by summing the product of the lock indicators with the lock transit times and multiplying this by the per hourly costs presented in column AT.

Note that the lock transit times come from cells I32 through AS32. The purpose of this distinction between the transit times (delay + service) used in the movement calculation and those computed via lock usage will be explained in the section on equilibrium.

Column AV contains the adjusted water rate of the movement if no loss is incurred at the locks. This column contains numeric entries that are generated in the model calibration.

The existing base (1994) water costs, developed by TVA are contained in column AW. The next column (AX) shows the difference in water rate for the modeled year and/or action and the 1994 base. This is provided for interest only and is not essential to the model.

Column AY shows the constructed water rate for the year and/or action being modeled. It is constructed by adding the opportunity cost (AU) to the no congestion base rate (AV). As mentioned previously, column AZ contains the alternative mode transportation cost.

The final item of interest in the movement specification is located in column BH. This is the indicator of whether the movement is elastic with respect to lock congestion. A “1” in the cell indicates the movement is elastic, a “2” indicates that the movement is one of the “negative rate savers” and hence the water rate will increase in response to congestion but the tonnage volume will not respond, a blank in this field indicates that the movements water rate is inelastic with respect to congestion at the locks.

There are several cells in the movement string that have not yet been discussed. These cells have no impact on the execution of the model or the calculation of NED benefits so, for now, suffice it to say that these cells can be ignored.

## 6. **Opportunity Cost**

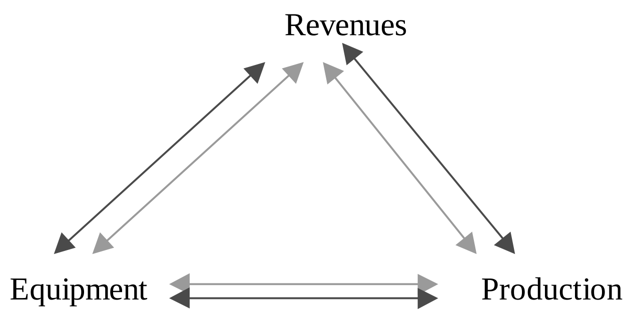
Opportunity Cost is located in column AT and is the estimate of the value of production foregone due to lock congestion. The calculation of this parameter utilizes the fact that, in equilibrium, the marginal value of a unit of production is equal to the cost of providing an additional unit of productive capacity (i.e. towboats, barges, labor, etc.). These costs are constructed based upon guidance received in EC 1105-5-144 which collects data on towboat and barge operating costs. Applying these data to typical equipment and configurations found on the UMR-IW system hourly per ton operating costs are identified on the for dry and liquid cargoes. The only discrimination made in computing this number is by dry and liquid cargo since the spatial equilibrium framework enforces that similar equipment face similar opportunities regardless of the particular movement being examined.

As noted previously, the opportunity cost of back-hauls is zero. For the front-haul movements the estimated opportunity cost is doubled to reflect both the northbound and southbound congestion incurred. It should be noted that a significant portion of the estimated opportunity cost consists of return to capital on floating equipment. We used a rate of 7.5 % to compute this return. It may be that a larger or smaller return may be required by private agents to induce investment in floating equipment. This will be part of the sensitivity analysis.

7. Definition of Equilibrium and Solving the Model

Before proceeding further it is useful to discuss what is meant by equilibrium. In a general sense the graphic below illustrates what is meant by system equilibrium.

FIGURE A-2




where:

Production = movements accomplished on the waterway
Revenues = payments received for movements
Equipment = Towboats + Barges + Labor + Fuel + etc. (Privately owned resources)

A formal definition states:

For each movement on the system, the willingness to pay for the final increment of output is equal to the observed rate which in turn is equal to the (per unit) economic cost of providing the privately owned resources to accomplish that production.

This definition is put into operation by recognizing that it allows us to consider delay at system locks in two distinct ways. First, delay is an operational characteristic of the lock determined as a function of traffic. Second, delay represents the increase in the private costs of producing a movement, hence a change in the observed rate that the shippers are willing to incur to produce movements. For example, if we observe X tons of traffic at a particular lock with Y hours of delay we can say that those X tons produced those Y hours of delay **OR** that the Y hours of delay permitted only the X tons of traffic willing to incur the costs associated with that delay. This is the essence of the ESSENCE model.

This concept is specifically modeled by specifying lock transit time twice in the spreadsheet. As explained in section 4 it appears in cells I31 through AS31 where it is computed based upon the traffic traversing the locks. It appears again in cells I32 through AS32 where it impacts the rate of water transportation.

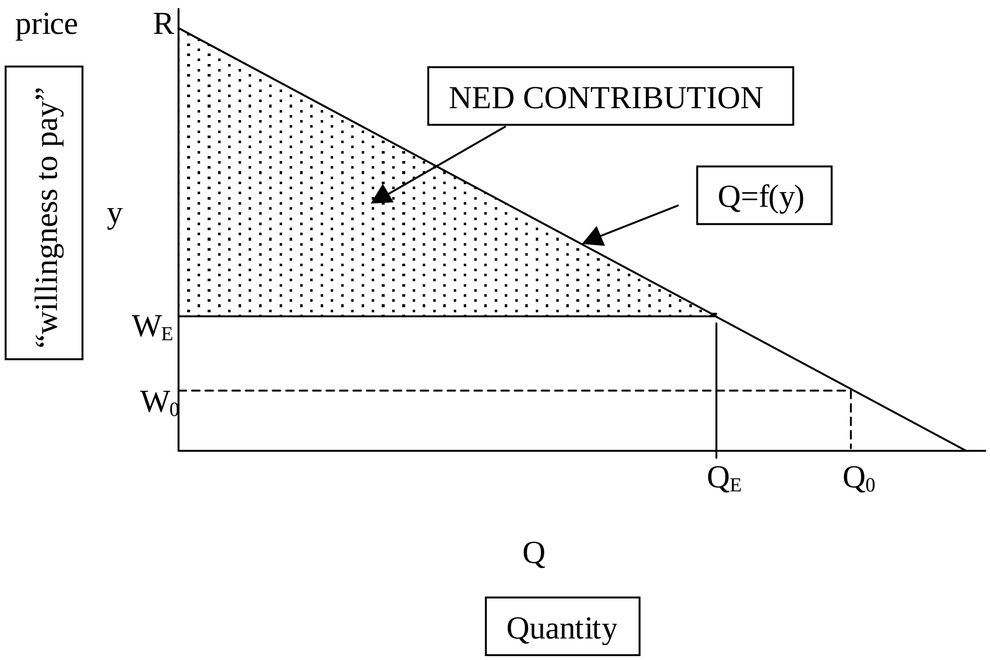
The equilibrium solution is found by specifying in the Excel Solver Module that these corresponding times must be equal and that cells I32 through AS32 may be adjusted to create this equality. Note how this works, if the time as specified in row 32 is larger than that in row 31, solver will adjust cell 32 downward. This will in turn decrease water prices and hence increase system traffic. This change in traffic will then cause a new delay to be computed in row 31. Solver iterates to a solution.

One note of caution, before starting solver the model user must ensure that a feasible starting point is in effect. This is done by placing enough time in the cells in row 32 to ensure that lock traffic does not exceed the capability of the lock(s) to process it. If this happens negative numbers will appear in some of the cells in row 31 and the solver will not be able to iterate to a solution. Once any feasible solution is specified the model can be solved simply by clicking tools, solver, solve.

8. **Calculation of system NED benefits.**

In the discussion of movements it was mentioned that it is useful to specify a demand function which is integrable in closed form. This is because operationally the NED system benefits may be defined as the area between the demand function and the water price from 0 to the equilibrium level of tonnage. For the family of functions previously discussed this area can be found as follows:

**FIGURE A-3**
**Calculation of NED contribution per movement.**




where:

R – Rail Rate
$W_E$ – Equilibrium Water Rate
$Q_E$ – Quantity Moved at Equilibrium Water Rate
$W_0$ – '94' Water Rate
$Q_0$ – Quantity Moved (forecast) at '94' Water Rate

If the demand curve is described by the function:

$$Q = \left( \frac{R - y}{R - W_0} \right)^N Q_0$$

where Q is quantity and y is willingness to pay, then we can write the inverse demand function as:

$$y = R - \left[ \sqrt[N]{\frac{Q}{Q_0}} * (R - W_0) \right]$$

the average (per ton) NED contribution is given by:

**AVERAGE NED =** $$\frac{1}{Q_E} \int_0^{Q_E} (y - W_E) dQ$$

Which we rewrite as:

$$\frac{1}{Q_E} \int_0^{Q_E} \left\{ (R - W_E) - \sqrt[N]{\frac{Q}{Q_0}} * (R - W_0) \right\} dQ$$

$$= \frac{1}{Q_E} \left\{ (R - W_E) * Q - \frac{N}{N+1} * Q * \sqrt[N]{\frac{Q}{Q_0}} * (R - W_0) \Big|_0^{Q_E} \right\}$$

$$= \left\{ (R - W_E) - \frac{N}{N+1} * \sqrt[N]{\frac{Q_E}{Q_0}} * (R - W_0) \right\}$$

and since $\sqrt[N]{\frac{Q_E}{Q_0}} = \frac{R - W_E}{R - W_0}$ we have:

$$= \left\{ (R - W_E) - \frac{N}{N+1} * \frac{(R - W_E)}{(R - W_0)} * (R - W_0) \right\}$$

which simplifies to:

$$= \left\{ 1 - \frac{N}{N+1} \right\} * \left( R - W_E \right) = \frac{1}{N+1} * \left( R - W_E \right)$$

Hence we see that, for N=1 the per ton benefit is $(R-W_E)/2$ and for N=2 the per ton benefit is specified as $(R-W_E)/3$. These formulas are located in column H of the spreadsheet as appropriate for the particular demand curve used. For the 32 movements with negative rate savings the per-ton contribution to the NED benefits is calculated as $(R-W_E)$ and is likely to be a negative number.

The total system NED benefits are then found by multiplying the movement tonnage (column G) by the per-ton benefit (column H) and then summing across all system movements. The results of this calculation are displayed in the model in cell D12.

## 9. **Calibration and Validation of the ESSENCE Model**

Calibrating the ESSENCE Model is a straightforward procedure. First the modeler must ensure that the base year (1992) is entered in cell A6 and that the cells reflecting lock performance in rows 10, 11, 14, 15, and 16 reflect the base year operating conditions.

After the above is verified, the cell in column AV is replaced by the formula AWxx-Auxx (where xx represents the appropriate row number) for each movement. The Excel Solver is then invoked to solve the model. This procedure calculates the “no congestion” water price. The AV column is the copied and pasted onto itself using Excel’s “paste special values” option. The AV column now contains numeric values and the model is now calibrated.

Validation of the model consists of inspecting the congestion level (lock transit time in row 31) and ensuring that these numbers correspond to observed values. Again it should be noted that these numbers represent the expected value of a random variable so an exact match is neither expected nor desired. Further validation is accomplished by running the model for future years and comparing congestion levels with historically congested locks. It is in this test where the ESSENCE model, in a purely empirical manner, outperforms previous Navigation System models.

**10. Forecasts of Potential Traffic Demands**

The second worksheet of the Excel workbook contains the forecasts of future traffic demands for the UMR-IW navigation system. These forecasts of potential system demands for transportation were completed by Jack Faucett Associates as a work item of the system feasibility study. The Jack Faucett Associates report is entitled "Waterway Traffic Forecasts for the Upper Mississippi River Basin" and presents detailed forecasts of potential system movement demands at five year intervals beginning in the year 200 and ending in the year 2050. The potential movement demands are forecast based on the analytical assumption that transportation costs remain at 1994 levels for all modes of transportation. Consequently, these demands serve to increment the quantity demanded at existing (1994) water transportation prices dependent on the year of analysis.

Table A-4 below displays the forecast worksheet data.

# Table A-4

| | | Mississippi River | | | | Year | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Comm Group | Group | 1992 | 2000 | 2005 | 2010 | 2015 | 2020 | 2030 | 2040 | 2050 |
| Corn | 1 | 27611 | 38664 | 42939 | 46221 | 49092 | 51832 | 57874 | 64851 | 71970 |
| Soybeans | 2 | 9131 | 9501 | 10630 | 11327 | 12040 | 12737 | 14242 | 15920 | 17632 |
| Wheat | 3 | 1567 | 2892 | 3122 | 3315 | 3512 | 3709 | 4120 | 4557 | 5002 |
| Farm NEC | 4 | 3480 | 3393 | 3568 | 3703 | 3866 | 4023 | 4323 | 4607 | 4875 |
| Coal | 5 | 9200 | 9700 | 9900 | 9900 | 9600 | 9900 | 10300 | 10800 | 11400 |
| Petroleum | 6 | 5917 | 5972 | 5983 | 5976 | 5952 | 5927 | 5878 | 5746 | 5502 |
| Ind. Chems. | 7 | 3356 | 3440 | 3717 | 3989 | 4252 | 4503 | 5129 | 5879 | 6629 |
| Agg. Chems. | 8 | 4567 | 3998 | 4002 | 4008 | 4014 | 4018 | 4027 | 4034 | 4041 |
| Iron & Steel | 9 | 2421 | 2831 | 2957 | 3100 | 3265 | 3435 | 3749 | 4038 | 4336 |
| Aggregates | 10 | 5884 | 5628 | 5888 | 6144 | 6350 | 6531 | 7100 | 7943 | 8908 |
| Miscellaneous | 11 | 7665 | 9016 | 9717 | 10238 | 10685 | 11174 | 12236 | 13455 | 14704 |
| | | | | | | | | | | |
| | | Illinois Waterway | | | | Year | | | | |
| Comm Group | Group | 1992 | 2000 | 2005 | 2010 | 2015 | 2020 | 2030 | 2040 | 2050 |
| Corn | 1 | 11591 | 17711 | 19670 | 21173 | 22488 | 23743 | 26511 | 29707 | 32968 |
| Soybeans | 2 | 3806 | 3891 | 4354 | 4639 | 4931 | 5216 | 5833 | 6520 | 7221 |
| Wheat | 3 | 288 | 510 | 550 | 584 | 619 | 654 | 726 | 803 | 881 |
| Farm NEC | 4 | 1939 | 1868 | 1964 | 2038 | 2128 | 2214 | 2380 | 2536 | 2683 |
| Coal | 5 | 7800 | 7000 | 6900 | 7000 | 7000 | 7100 | 7400 | 7700 | 8000 |
| Petroleum | 6 | 5526 | 6008 | 6293 | 6481 | 6597 | 6698 | 6842 | 6864 | 6789 |
| Ind. Chems. | 7 | 3990 | 4167 | 4514 | 4854 | 5181 | 5494 | 6273 | 7205 | 8138 |
| Agg. Chems. | 8 | 1620 | 1379 | 1377 | 1372 | 1371 | 1370 | 1367 | 1366 | 1363 |
| Iron & Steel | 9 | 2233 | 2582 | 2709 | 2853 | 3018 | 3188 | 3503 | 3793 | 4092 |
| Aggregates | 10 | 2134 | 2234 | 2371 | 2506 | 2615 | 2712 | 3019 | 3481 | 4018 |
| Miscellaneous | 11 | 2882 | 3335 | 3571 | 3768 | 3940 | 4112 | 4497 | 4928 | 5363 |

The Faucett analysis used the average of the 1991, 1992, and 1993 historic system traffic commodity flows as the base for their forecast demands. The equilibrium worksheet of this model uses 1992 historic commodity flows as the basis for forecasting future demands. Consequently, the 1992 flows in the equilibrium worksheet are increased by the ratio of the origin, destination, commodity, specific Faucett projected tonnage to the same Faucett base tonnage to estimate traffic demands with existing (1994) transportation costs for the various years of analysis.

**11. Modeling of Potential System Actions**

Potential actions at system locks are modeled at a point in time in the spreadsheet by altering one of the parameters that describe the operation of the lock or locks being acted upon. Then the equilibrium spreadsheet is re-solved for the new resultant equilibrium and subsequent new system NED benefits.

For example, an action that reduces the mean and standard deviation of the time required to complete a recreation lockage at a lock is modeled by changing the mean and standard deviation of the recreation lockage service time distribution at the lock in question. The change in service parameters at the lock will then alter the system equilibrium. The model is then solved for the new system equilibrium, which in turn yields a new estimate of system NED benefits.

A set of potential system actions is modeled in the same manner. First, the relevant parameters are changed at the locations where actions are taken. For example, 1200 foot extended chambers at UMR Locks 20 through 25 in the year 2020 are modeled by changing the service distributions at those five chambers to the values associated with 1200 extensions. Then the year of analysis is set to 2020 in the spreadsheet to reflect forecast traffic demands at that time and the resulting equilibrium is estimated by solving the model with the altered lock performance parameters. The new equilibrium will then reflect the altered performance of the lock chambers and the impact those changes have on supply and demand for water transportation at that time.