A LRT Operation & Maintenance (O & M) Cost Model to Perform Sensitivity Analysis

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ABSTRACT

A Light Rail Transit (LRT) Operation and Maintenance (O & M) cost model was developed using various system attributes namely Route Miles, Train Revenue-Hours, Car Revenue-Miles and Peak LRT Cars. System attributes and cost data of twelve peer LRT facilities from 2004-2008 were collected in this context. Using a regression technique, five sets of Power Factor Models (PFM) representing Total O & M cost, Vehicle operation cost, Vehicle maintenance cost, Non-vehicle cost and Administrative cost were derived. The Total O & M cost computed by PFM as well as by the weighted Fully Allocated Cost (FAC) method were compared. It was observed that Total O & M cost computed using PFM is closer to the actual cost. Distribution of predicted Vehicle operating cost, Vehicle maintenance cost, Non-vehicle cost and Administrative cost closely matched the observed distribution. Also, as a part of this study, a set of computation tools (three Nomo-graphs and utility cost calculator) were established to serve as a quick response instrument to estimate Total O & M cost, Vehicle operation cost and Non-vehicle maintenance cost as well as to perform sensitivity analysis.
BACKGROUND

The projection of operating and maintenance (O & M) cost is an important component of the planning of any new Light Rail Transit (LRT) system. According to Federal Transit Administration (FTA), determination of O & M costs of any planned LRT system is significant for two reasons (1).

- The design year O & M costs estimate is a critical factor while determining cost effectiveness of a LRT system.
- The projection of yearly planned O & M costs are crucial to the development of financial plans that cover the multi-year process of construction and operation.

LRT O & M cost has four components 1) Vehicle operation cost 2) Vehicle maintenance cost 3) Non-vehicle maintenance cost and 4) Administrative cost. Typical distribution of Total yearly O & M costs among those components is presented in Figure 1. Vehicle operation cost represents over 40 percent of the yearly O & M costs, followed by Vehicle maintenance cost at 23 percent and Administrative and Non-vehicle maintenance at close to 17 percent each (2).

O & M costs are related to or are driven by different system variables. These system variables play a significant role in influencing O & M costs and its components. FTA stated that for a typical LRT facility

- Annual Route Miles drives some maintenance cost.
- Number of maintenance yards drives facilities maintenance and some supervision cost.
- Annual Train Revenue-Hours drives operator cost.
- Annual Car Revenue-Miles drives vehicle maintenance.
- Number of Peak LRT Cars drives facilities maintenance and some vehicle maintenance cost.

It is to be noted that as a part of the FTA New Starts application process, O & M cost of the planned system must be included. At the planning stage, it is very hard to determine the Total O & M costs of any planned system. One approach to estimate operating and maintenance costs of any planned transit system is to examine the data from other cities which operate LRT. The United States Transit Database (NTD) collects the capital, operating and maintenance costs for all LRT operators in the country. According to FTA (3) guidelines, costs incurred by a transit system are driven by a set of supply variables such as Car Revenue-Miles, Train Revenue-Hours and Peak LRT Cars for a given level of service. Current literature related to O & M models have some common attributes (4). They are

- All models used NTD database as their primary source of data
- All or some of these service variables (Supply variables) such as Peak LRT Cars, terminal stations, Train Revenue-Hours, Car Revenue-Miles, Route Miles and number of maintenance and storage yards were used to compute O & M cost
- A unit cost was developed for each supply variable by collecting NTD operating expense data and assigning cost drivers to each expense item
- The Total O & M cost is estimated by the sum of the unit cost for each supply variable multiplied by the projected yearly units of service (this approach is known as Fully Allocated Cost Model) (5)
OBJECTIVES
One of the challenges of the above mentioned approach is the determination of the unit cost of supply variables. At present, to develop unit cost, the expenses assigned to each supply variable are summed and divided by the annual quantity supplied. Such an approach tends to over-estimate, because there is no reasonable way of determining the expense allocated to each supply variable. To the best of our knowledge, no analytical model is available that can compute vehicle operation, vehicle maintenance, non-vehicle maintenance and administrative cost. Based on the literature review, we strongly believe that there is a need to develop a Total O & M cost and other types of models by only considering some supply variables and not unit costs (6,7,8).

In order to establish a relationship among various LRT system variables and Total Yearly O & M costs and its components, a study was conducted at the University of Detroit Mercy. The objective of this study was to develop a standard O & M model by analyzing system data of twelve LRT facilities. Attempts were also made to derive relationships among cost components and various system variables. Finally, a set of prediction Nomo-graphs and a calculation tool were established to facilitate the cost estimation process. The main focus of this work is to develop a tool that can quickly produce a rough estimate of light rail annual operation and maintenance costs based on a set of system attributes. The tool has the capability to perform sensitivity analysis under various system parameters.

Definition of System Variables
In this section system variables cited before are defined and also approaches used to compute those variables are presented.

Annual Route Miles (Route Miles)
Total number of directional route miles. This value can be calculated as two times the one-way system route length:
Route miles (D) = 2 * Route length (one-way)

Yards
Total number of maintenance and storage facilities.

Annual Train Revenue-Hours (Train-Hours)
Total hours of revenue service operated by all trains in one year. This value can be derived as follows:

- Compute time required by each Light Rail Transit Vehicle (LRTV) to complete one cycle (directional route miles).
- Based on headway (peak and off-peak), number of cycles per peak or off-peak period can be determined. For example, at peak headway of ten minutes, for each peak hour, six cycles will be completed by each LRTV.
- Compute total cycles during peak and off-peak hours. For example, for a transit facility of six hours of peak periods (i.e., AM and PM peak periods, each with three-hour duration), a total of 36 cycles will be completed (6 cycles, times 6 hours equals 36 total cycles). During the 12 hours of off-peak periods (i.e., MID-DAY and OFF-PEAK periods, each with a six-hour duration), at a 20 minute headway, a total of 36 cycles will be completed.
- Determine total number of cycles over an operation day. For example if total operating hours in a given day is 18, of which 6 are peak and 12 are off-peak hours, total cycles during peak and off-peak hours are added to find total cycles during an operating day.
- Total annual revenue Train-Hours is equal to:
  
  \[
  \text{Train Hours} = \text{Total Cycles during an operating day} \times \text{number of operating days in a year} \times \text{time required to complete one cycle in hours.}
  \]

A typical system has 300 operating days during a year,

Annual Car Revenue-Miles (Car-Miles)
Total miles of revenue service operated by all trains in one year.

\[
\text{Car-Miles} = \text{Number of cycles during one operating day} \times \text{number of operating days in a year} \times \text{route miles per cycles} \times \text{number of cars per train.}
\]

Number of Peak LRT Cars
Determine the number of LRTV unit vehicles required to provide peak headways. Then add a spare factor of 30 percent to determine the number trains during peak hours. In order to find the number of peak vehicles, trains used during peak hour must be multiplied by the number of vehicles per train.

Data Collection
Information regarding number of yards, Route-Miles, Train-Hours, Car-Miles, number of Peak LRT Cars along with their unit costs, Total O & M costs, Vehicle operation cost, Vehicle maintenance cost, Non-vehicle maintenance cost and Administrative cost of twelve peer system
from 2004 to 2008 were collected from the FTA database. The twelve peer LRT systems selected are:

- Baltimore: Maryland Transit Administration (MTA)
- Dallas: Dallas Area Rapid Transit (DART)
- Denver: Regional Transportation District (RTD)
- Houston: Metropolitan Transit Authority of Harris County (METRO)
- Minneapolis: Metro Transit (METRO)
- New Orleans: New Orleans Regional Transit Authority (NORTA)
- Portland: Tri-County Metropolitan District of Portland (TriMet)
- Philadelphia: Southeastern Pennsylvania Transportation Authority (SEPTA)
- Sacramento: Regional Transportation District (RT)
- Salt Lake City: Utah Transit Authority (UTA)
- San Jose: Santa Clara Valley Transportation Authority (VTA)
- St. Louis: Bi-State Development Agency (METRO)

### Methodology

A total yearly O&M cost model for LRT systems was developed by using regression analysis. Once the O&M model was developed, an attempt was made to establish a relationship between different components of cost and system variables to determine their dominance using step-wise regression. Also the Total Yearly O&M cost derived in this effort was compared with the previously developed weighted Fully Allocated O&M cost model output (9).

### Development of Total Yearly O&M Cost Model using Regression Approach

A series of step-wise regression analyses were conducted to establish a relationship between yearly cost and four attributes of the system. Variables were excluded by using a backward elimination approach. When the P-value of a variable was more than 0.05, it was removed from further consideration. The non-linear model resulted in the highest $R^2$ and F values:

\[
\text{Total Yearly O&M cost} = 223462.7 \times (\text{Route Miles})^{0.744} \times (\text{Car-Miles})^{0.144}
\]

\[
R^2 = 0.864 \quad \text{and} \quad F = 172.137
\]

Since the model is a product of power functions of dependent variables, the derived model was called the Power Factor Model (PFM). It is to be noted that step-wise regression has identified Route Miles and Car-Miles as the significant independent system variable among the four variables considered. Even though, the power factor of Route Miles is five times larger than the Car-Miles factor, the value of Car-Miles is significantly bigger than Route Miles. This implies Car-Miles is the dominant factor in driving the Total Yearly O&M cost.

### Establishment of Relationship among Cost Components and System Variables

To establish a relationship (if any) among cost components and system variables, the step-wise regression approach was again used. This effort resulted in following set of relationships.

\[
\text{Yearly Vehicle Operation Cost} = 63831.4 \times (\text{Route Miles})^{0.782} \times (\text{Train-Hours})^{0.2}
\]

\[
R^2 = 0.83 \quad \text{and} \quad F = 127.183
\]
Yearly Vehicle Maintenance Cost = $23,155.8 \times (\text{Route Miles})^{0.844} \times (\text{Train-Hours})^{0.211} \quad (3)

R^2 = 0.844 \quad \text{and} \quad F = 140.72

Yearly non-vehicle maintenance Cost = $11,579.6 \times (\text{Route Miles})^{0.831} \times (\text{Car-Miles})^{0.345} \times (\text{Peak LRT Cars})^{-0.530} \quad (4)

R^2 = 0.65 \quad \text{and} \quad F = 31

Yearly General Administrative Cost = $63,767.6 \times (\text{Route Miles})^{0.592} \times (\text{Peak LRT Cars})^{0.556} \quad (5)

R^2 = 0.52 \quad \text{and} \quad F = 28

Equations 2, 3, 4, and 5 reveal the following:

- Besides Route Miles, Train-Hours drives Vehicle Operation cost and Vehicle maintenance cost. Even though the power factor for Route Miles is a few times larger than the power factor of Train-Hours, the value of Train-hour is few times bigger than Route miles. Usually, when a system is built, the Route miles is fixed, thus the impact of Train-Hours on operation and maintenance cost is significant.

- Route Miles factor is related to all four cost components, namely, operation, maintenance, non-maintenance, and administrative. Since Route Miles is fixed for a system within a certain period, the effect of Route Miles on each system can be viewed as a weight/coefficient on the other factor(s) that are driving that part of the cost.

- Route Miles and Car-Miles drive non-maintenance related cost but Peak LRT Cars attempts to drive down the non-vehicle maintenance cost.

- Route Miles and Peak LRT Cars play almost equal roles in driving Administrative cost.

- While Peak LRT Cars within the operation limit seems to drive down the non-vehicle maintenance cost, it actually is proportional to the Administrative cost. It can also be seen from the aggregate model that Peak LRT Cars does little to change the Total Yearly O&M Cost, so increasing the Peak LRT Cars within the operation limit actually shifts the cost from Non-vehicle Maintenance Cost to the Administrative Cost while keeping the total cost at the same level. Such effect is reflected by equation (3) and (4).

**Background of Previously developed Weighted Fully Allocated O & M Cost Model (9)**

A Fully-Allocated Cost (FAC) model was designed to allocate the cost among a larger number of variables. The variables used for the model are those that can conceivably affect transit operation. As a part of another research, Dutta et al developed a weighted FAC O & M cost model by considering the five system variables. The model is represented by equation 6 (For more explanation please consult reference (9)).

The final FAC model for 2008 O & M cost is:

Estimated Yearly O & M cost (2008) =

\[
\$93,111.26 \times \text{Route Miles} + \$3,346,554.4 \times \text{Yards} + \$123.3 \times \text{Train-Hours} \\
+ \$3.16 \times \text{Car-Miles} + \$152,041.14 \times \text{Peak LRT Cars}
\]  

(6)
Case Study

In order to test the validity and sensitivity of the developed FAC and regression models, system attributes data from five existing LRT facilities for the year 2008 were selected as shown in Table 1. These five facilities have Route Miles and other factors that are representative of all the facilities. Total Yearly O & M costs for all five facilities were computed using FAC and PFM models. Results were displayed in Table 3, along with actual O & M cost of the facilities during the year 2008. The FAC estimate was always higher than regression estimates as well as actual costs. In all cases, regression (PFM) estimates were much closer to actual O & M costs than the FAC estimates.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Route-miles</th>
<th>Train-Hours</th>
<th>Car-Miles</th>
<th>Peak LRT Cars</th>
<th>Yard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houston</td>
<td>14.8</td>
<td>62,400</td>
<td>884,171</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td>Baltimore</td>
<td>57.6</td>
<td>78,500</td>
<td>2,789,820</td>
<td>36</td>
<td>2</td>
</tr>
<tr>
<td>Portland</td>
<td>95.9</td>
<td>268,900</td>
<td>6,875,263</td>
<td>85</td>
<td>4</td>
</tr>
<tr>
<td>Denver</td>
<td>70</td>
<td>195,000</td>
<td>9,405,736</td>
<td>101</td>
<td>2</td>
</tr>
<tr>
<td>Salt Lake City</td>
<td>39.4</td>
<td>97,900</td>
<td>2,906,184</td>
<td>46</td>
<td>1</td>
</tr>
</tbody>
</table>

TABLE 2 Total Yearly of O & M Cost

<table>
<thead>
<tr>
<th>Facility</th>
<th>Total Yearly O &amp; M Cost</th>
<th>Predicted by PFM</th>
<th>Predicted by FAC</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houston</td>
<td>15,858,600</td>
<td>17,797,200</td>
<td>11,917,385</td>
<td></td>
</tr>
<tr>
<td>Baltimore</td>
<td>37,452,600</td>
<td>36,049,339</td>
<td>38,647,583</td>
<td></td>
</tr>
<tr>
<td>Portland</td>
<td>84,120,100</td>
<td>90,120,285</td>
<td>64,305,445</td>
<td></td>
</tr>
<tr>
<td>Denver</td>
<td>41,677,200</td>
<td>82,332,677</td>
<td>53,226,333r</td>
<td></td>
</tr>
<tr>
<td>Salt Lake City</td>
<td>27,382,500</td>
<td>35,263,641</td>
<td>29,307,094</td>
<td></td>
</tr>
</tbody>
</table>

Using derived PFM models, Vehicle operation costs, Vehicle maintenance costs, Non-vehicle maintenance costs and Administrative costs for all five facilities were computed and are presented in Table 3. For the purpose of comparison, actual costs are also included in Table 3. Predicted vehicle operation and vehicle maintenance costs are relatively close to the actual costs. A significant variation is observed in the case of predicted non-vehicle and administrative costs. As a reflection of $R^2$, later models have weaker prediction power. Distribution of predicted O & M cost components were also computed and compared with the actual distribution as shown in Table 4. Vehicle operation cost is responsible for 40 percent of total O & M cost. A similar trend is also observed while reviewing the actual data as well as the national trends (Figure 1).
TABLE 3  Predicted and Actual Components of O & M Cost

<table>
<thead>
<tr>
<th>Facility</th>
<th>Vehicle Operation</th>
<th>Vehicle Maintenance</th>
<th>Non-Vehicle maintenance</th>
<th>Administrative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Predicted</td>
<td>Actual</td>
<td>Predicted</td>
<td>Actual</td>
</tr>
<tr>
<td>1</td>
<td>4,777,668</td>
<td>6,487,700</td>
<td>2,312,835</td>
<td>2,182,300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>14,483,706</td>
<td>17,390,500</td>
<td>7,647,281</td>
<td>9,134,800</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>27,588,919</td>
<td>29,277,800</td>
<td>15,239,066</td>
<td>18,663,300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>20,225,905</td>
<td>19,340,300</td>
<td>10,917,415</td>
<td>9,675,800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>11,242,657</td>
<td>8,043,100</td>
<td>5,811,841</td>
<td>7,411,600</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
*1: Houston 2: Baltimore 3: Portland 4: Denver 5: Salt Lake City

TABLE 4  Distribution of Cost Components in Percent

<table>
<thead>
<tr>
<th>Facility</th>
<th>Vehicle Operation</th>
<th>Vehicle Maintenance</th>
<th>Non-Vehicle maintenance</th>
<th>Administrative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Predicted</td>
<td>Actual</td>
<td>Predicted</td>
<td>Actual</td>
</tr>
<tr>
<td>Houston</td>
<td>41</td>
<td>41</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baltimore</td>
<td>39</td>
<td>46</td>
<td>21</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portland</td>
<td>41</td>
<td>35</td>
<td>23</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Denver</td>
<td>39</td>
<td>46</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salt Lake City</td>
<td>40</td>
<td>29</td>
<td>21</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>40</td>
<td>40</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Derivation of O & M Cost Nomo-graph

Once a system is operational, its Route-Miles remains basically unchanged. Thus by keeping Route Miles fixed, a set of Nomo-graphs were prepared to compute Total O & M cost, Vehicle operational cost and Vehicle maintenance cost for various degrees of Train-hours and Car-miles (Figures 2,3 and 4). No attempts were made to derive similar Nomo-graphs for non-vehicle maintenance cost and administrative cost, since R² values of these PMF models are less than 0.80. The rate of change of costs over varying degrees of system variable change became constant over a long range (change of slope is close to zero). The Nomo-graphs can be used to compute the Total Yearly O & M cost, Yearly Operation cost and Yearly Maintenance cost of any LRT facility for any Car-Miles and Train-Hours.

O&M Cost Computation Utility Tool

In order to assist transit agencies in O & M cost computation and to perform sensitivity analysis under various system configurations, a utility calculator was developed as shown in Figures 5 and 6. This tool can be used to compute various system attributes such as Train-Hours, Car-Miles, and Route Miles for a facility based on the system configurations, namely headway, length of segment, boarding/alighting rate, maximum speed etc. In order to compute cost, the users can provide either system attributes information directly or system configuration information as input. Based on the input or calculated values of the system attributes, the Total...
Yearly O&M cost and its components can be calculated with this tool (Figure 6). This tool can be run in any operational platform as an executable module. The tool can be used to study the variation of costs under different system configurations or attributes.

CONCLUSIONS

In this study Yearly O&M costs along with their component data of the twelve existing LRT facilities from 2004-2008 were analyzed to derive a relationship with a number of attributes namely Route Miles, Train-Hours, Car-Miles and Peak LRT Cars. Five cost models were developed in this context using a regression technique. These five models are Total O&M cost, Vehicle operating cost, Vehicle maintenance cost, Non-vehicle maintenance cost and Administrative cost models. A case study was performed using actual data of five LRT facilities for the year 2008. The Total O&M cost computed by PFM was compared with the output of a previously developed weighted FAC model. The findings of this study are summarized below.

- Using the regression approach, Power Factor Models (PFM) of Total O&M cost, Vehicle operation cost, Vehicle maintenance cost, Non-vehicle maintenance cost and Administrative cost were developed.
- A weighted FAC model was also presented using five system variables and their unit cost for comparison purposes.
- The overall result of PFM estimates is closer to the actual values than that of the weighted FAC estimates.
- Route Miles variable is the driving factor of all five models and its impact is significant in all five models.
- Vehicle operation and maintenance cost models are influenced by both Route Miles and Train-Hours equally.
- The Total Yearly O&M cost of a system is primarily driven by Route miles and Car-Miles factors. However, the PFM of each component of the O&M reveals that each component has different driving factors in addition to Route Miles.
- The Non-vehicle cost model is the only model with three independent variables namely Route Miles, Car-Miles and Peak LRT Cars.
- Administrative cost is driven by Route Miles and Peak LRT Cars attributes.
- Total Yearly O&M cost predicted by PFM is closer to actual cost in comparison to the weighted FAC derived O&M cost model.
- Aggregate distribution of Total Yearly O&M cost among Vehicle operation, maintenance, Non-vehicle and Administrative cost follow closely to national as well as actual trends of five selected facilities considered as a part of case study.
- Vehicle operation cost is the dominant cost component, followed by either Vehicle maintenance or Non-vehicle maintenance cost.
- The Nomo-graphs and utility calculator developed as a part of this study can be used to quickly compute Yearly O&M, Vehicle operation and Vehicle maintenance costs as well as to perform sensitivity analysis.
- Transit authorities applying for the New Starts program should be able to use the cost calculator to come up with a reasonable operation and maintenance cost estimate rather than guessing.
FIGURE 2 Nomo-graph to determine Yearly O & M Cost for a particular number of Car-Miles (Note: D= Route Miles of the System).

FIGURE 3 Nomo-graph to determine Yearly Vehicle Operating Cost for a particular number of Train-Hours (Note: D= Route Miles of the System).
FIGURE 4 Nomo-graph to determine yearly Vehicle Maintenance Cost for a particular number of Train-Hours.

Note: D = Route Miles of the system
FIGURE 5 O & M cost Calculator Input Screen.
LRT Operation and Maintenance Cost Calculator

**input:**

<table>
<thead>
<tr>
<th>System Variables (must input all values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Route Miles : 39.7</td>
</tr>
<tr>
<td>2. Annual Train Hours : 97908</td>
</tr>
<tr>
<td>3. Annual Car Miles : 2006104</td>
</tr>
<tr>
<td>4. Number of Peak LRT Vehicles : 48</td>
</tr>
<tr>
<td>5. Year of Planned Operation : 2020</td>
</tr>
</tbody>
</table>

**Calculate**

**output:**

<table>
<thead>
<tr>
<th>Year : 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly Operation and Maintenance Cost : $42021389</td>
</tr>
<tr>
<td>Yearly Vehicle Operation Cost : $16124705</td>
</tr>
<tr>
<td>Yearly Vehicle Maintenance Cost : $8399516</td>
</tr>
</tbody>
</table>

*Do you want to calculate another system cost or exit?*

[Another] [Exit] [Save]

---

**REFERENCES**


