ETM
ENGINEERING & TECHNOLOGY MANAGEMENT

# Municipal Wastewater Asset Prioritization Using Hierarchical Decision Modeling

**ETM 530-Management of Engineering and Technology**
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**Team #2**
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# Table of Contents

## 1. Abstract

Hierarchical Decision Modeling (HDM) has been developed as a decision making tool across multiple industries in wide variety of applications. This paper presents the development of HDM as a tool to be used as an asset prioritization tool in the municipal wastewater industry. Converting an admittedly poorly developed risk-impact matrix, integrating expert feedback across two teams and a manager, and following the guidance of the established problem statement, an effective asset prioritization tool was developed as a means to accurately and consistently score and rank assets according to their priority for consideration for repair or replacement. Following development, a simulation was performed to validate the effectiveness of the tool by comparing it to against the experience and expertise of the current decision maker.

## 2. Introduction

In wastewater systems, assets make up the components of a facility with an independent physical and functional identity and age. These assets are made up of pumps, motors, pipes and other essential pieces that facilitate the movement of wastewater through the system. Many municipalities have used asset management as the way to ensure that these assets are properly maintained and at the lowest life-cycle cost possible. Asset management takes into account factors such as age, condition, criticality, costing, operations and maintenance and capital replacement plans. These factor help municipalities set their annual budgets but may not necessarily help with the prioritization the projects to be performed in the asset management plan.

This report will propose a new asset management tool for use within the city of Gresham wastewater division. The City of Gresham is a community that is just east of Portland, Oregon. Gresham covers 23 square miles and has a population of about 106,000. Within the city there are 300 miles of sanitary sewer mains, 8,150 pipes, and 30,000 sewer services.

The current method used by Gresham for prioritizing asset repairs is through a risk-impact table. Table 1 shows the impact elements currently in use. This table was put together by the wastewater group in quick fashion with little input and feedback from all levels.

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Pipe Size | <=10 | <=15 | <=24 | <=36 | >36 |
| Street type | Neighborhood | Community | Collector | Arterial | Freeway |
| Recently Paved | | | | | Yes |
| Close to creek | >800ft | <=600ft | <=400ft | <=200ft | <=100ft |
| In wetland | | | <=100ft | | Yes |
| High Groundwater | Sumps | | Some | No Sumps | Problem Area |
| Close to Hospital | | | 1000ft | | 100ft |
| Close to School | | | 1000ft | | 100ft |
| Close to Fire Station | | | 1000ft | | 100ft |
| Critical Path | <=10in | <=12in | <=15in | <=18in | >20in |

**Table 1: Impact table currently in use**

The items listed in Table 1 are known as the impact factors and are weighted equally in this model. The risk factor in this model is the NASSCO rating. The NASSCO rating is a score provided by the National Association of Sewer Services Companies that gives a value to the extent of defects in a pipe [1]. The proposed tool was developed using the guidance of the problem statement set forth by the City of Gresham:

***To develop an accurate method by which to assign a consistent prioritization scoring model for the repair and replacement of competing wastewater assets in order to manage the state of the infrastructure more efficiently***

## 3. Proposed Framework

The process of decision-making is based on a complex process where a person places relative weights on criteria for making a decision. The proposed framework of this report uses the hierarchical decision modeling (HDM) method, which elicits multi-level decisions under multiple criteria [2].

In developing an HDM model one must know what is to be the overall object. Next a set of evaluation criteria is determined for which relative weights will be applied that determine which criteria hold greater power in the decision process. This evaluation criteria, is then submitted to a group of subject matter experts (SME's) who complete pairwise evaluations of these criteria. These pairwise comparisons are then converted into relative weights through a series of three matrices [2]. With the use of these relative weights and a utility score that is given to each evaluation criteria for each asset in the wastewater system a prioritization can be determined.

## 4. Evaluation Criteria

As shown in Figure 1, the hierarchical decision model consists of two attributes.

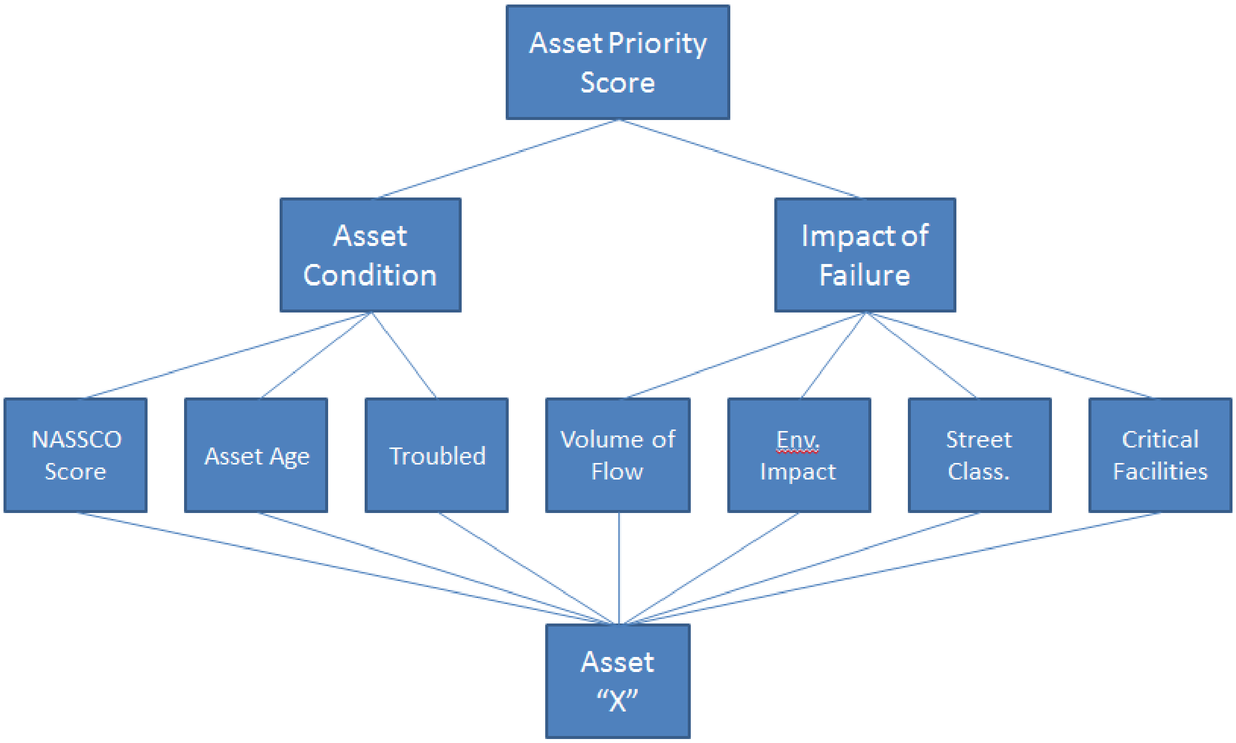


**Figure 1: Hierarchical decision model**

These attributes and their sub-attributes are explained in detail in the following sections.

### *4.1 Asset Condition Attributes*

The asset condition attribute is divided into three sub-attribute categories: NASSCO Score, Asset Age, and Troubled. The NASSCO score is developed through inspections of assets and is designated by a PACP certified inspector. The asset age is the age of the pipe relative to its useful age. For example, a pipe may have been slated to last 30 years but its current age is 45. Having increased age over the estimated life of the asset, therefore, is considered as risk factor. Lastly, a troubled designation is defined by the frequency in which operations crews need to service a particular asset. The more often a crew has to repair an asset the higher the troubled designation becomes for that asset.

### *4.2 Impact of Failure Attributes*

The impact of failure is divided into four sub-attribute categories: Volume of Flow, Environmental Impact, Street Classification, and Critical Facilities. The volume of flow is the amount of wastewater that flows through a particular pipe. This is calculated by measuring the volume of fluid flowing past a section per unit of time. For the purposes of this application, volume of flow will be simplified by using pipe sizes as the City's flow data is in the process of being calibrated. The environmental impact sub-attribute is based on the assets proximity to environmentally sensitive areas such as wetlands, creeks, and other natural water sources. Street classification of an asset is the measure of impact on traffic and danger to the maintenance crews an asset poses. For instance, a pipe that is placed at a major intersection on four-lane highway will have more of an impact on traffic than one located under a road in a more rural area. Lastly, the sub-attribute critical facilities relates to an assets proximity and resulting impact to hospitals, police and fire stations.

## 5. SME Pairwise Evaluation

### *5.1Expert Selection*

To acquire an accurate pairwise evaluation of the HDM criteria, the pool of experts must be carefully selected. The City of Gresham's Wastewater Services Division is broken up into three teams as shown in Figure 2, Engineering, Operations, Treatment Plant, and Pretreatment. The Treatment Plant team is overseen by a Senior Engineer and this team is responsible for the City's wastewater treatment plant in addition to the handful of pump stations located around the City and the assets immediately associated with these facilities such as force mains and power supplies. The Pretreatment team is led by a Program Manager and this team is responsible for managing Significant Industrial Users (SIUs), grease traps, and public education. Many of the heavy industrial users pretreat their wastewater as part of their permit requirements. Furthermore, most restaurants are required to implement grease traps as coagulated grease waste is a major contributor to sewer upsets. Finally, this team performs outreach for the general public regarding the steps individuals can take in contributing to healthy sewers such as keeping grease, pharmaceuticals, and garbage out of the wastewater system. Although both of these teams play a critical role in maintaining a municipal wastewater system, this tool is focused on the specific assets managed by the remaining two teams: Engineering and Operations.

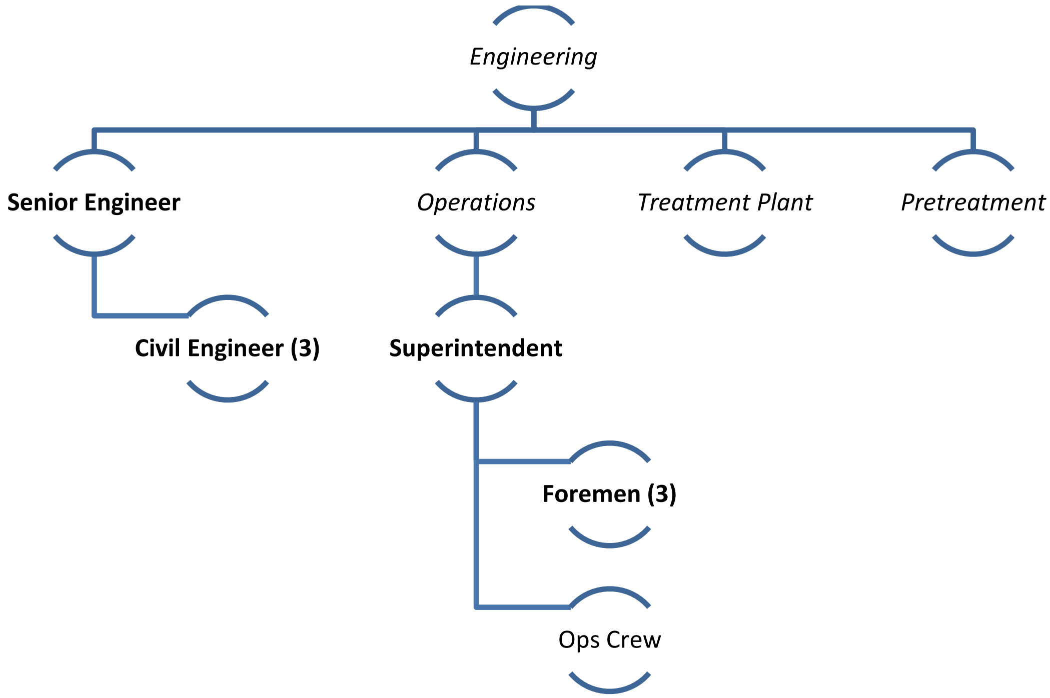


**Figure 2: The city of Gresham's Wastewater Services Division**

The Operations Team is managed by a Superintendent and three Foremen who oversee a collection of crewmen. This team performs the fieldwork necessary to maintain the conveyance system on a daily basis. This team does field repairs, routing cleaning and inspection, along with various other tasks. In the event of a sewer failure, this team would likely be the first onsite to repair or mitigate the damage. As such, this team has a critical stake in the condition of conveyance assets and provides a unique perspective of the system. It was determined that that Superintendent and the three Foremen would provide valuable feedback as experts.

The Engineering Team is managed by a Senior Engineer and this team is responsible for all Capital Improvement Projects (CIPs) associated with the conveyance system. The Senior Engineer of this team acts as the final decision maker regarding which assets will be repaired or replaced as CIPs. The primary difference between these decisions and those made by the Superintendent is that the Operations Team is performing with an annual operating budget which heavily restricts what projects they can undertake. For projects that exceed the capacity of the operations crew, or the low threshold of operating costs available, the Senior Engineer will place these projects under consideration for a CIP budget. An engineering staff of two Civil Engineers and an Engineering Technician report directly to the Senior Engineer. This staff has a responsibility for the conveyance system and maintains a perspective that is unique from those of the Operations Team. For this reason, the three engineers and the Senior Engineer were included as experts. Furthermore, the Senior Engineer serves as the ultimate decision maker for the purposes of testing the validity of the tool through simulation. Finally, the Division Manager was included as an expert given his unique perspective from a higher up management position. All of the experts approached willingly participated for a total of nine experts.

## *5.2Results*

The expert feedback yielded the pairwise comparison results shown below in Table 2.

| Asset Priority Score | NASSCO Score | Asset Age | "Troubled" Designation | Volume of Flow | Environmental Impact | Street Classification | Critical Facilities | Inconsistency |
|---|---|---|---|---|---|---|---|---|
| AJ Thorne | 0.44 | 0.11 | 0.15 | 0.16 | 0.06 | 0.04 | 0.04 | 0.00 |
| Brian Ott | 0.29 | 0.07 | 0.14 | 0.07 | 0.11 | 0.18 | 0.14 | 0.02 |
| Jeff Loftin | 0.46 | 0.11 | 0.23 | 0.03 | 0.07 | 0.02 | 0.07 | 0.01 |
| Jeremy Provenzola | 0.34 | 0.11 | 0.34 | 0.1 | 0.04 | 0.03 | 0.03 | 0.00 |
| Jim Montgomery | 0.45 | 0.13 | 0.22 | 0.11 | 0.05 | 0.02 | 0.02 | 0.01 |
| Joe Ford | 0.16 | 0.08 | 0.26 | 0.11 | 0.07 | 0.16 | 0.15 | 0.01 |
| Paul Eckley | 0.27 | 0.05 | 0.17 | 0.1 | 0.25 | 0.1 | 0.06 | 0.01 |
| Tom Wattenbarger | 0.38 | 0.09 | 0.28 | 0.07 | 0.09 | 0.02 | 0.07 | 0.09 |
| Vance Hardy | 0.21 | 0.1 | 0.44 | 0.07 | 0.04 | 0.03 | 0.12 | 0.02 |
| **Mean** | **0.33** | **0.09** | **0.25** | **0.09** | **0.09** | **0.07** | **0.08** | |
| **Minimum** | **0.16** | **0.05** | **0.14** | **0.03** | **0.04** | **0.02** | **0.02** | |
| **Maximum** | **0.46** | **0.13** | **0.44** | **0.16** | **0.25** | **0.18** | **0.15** | |
| **Std. Deviation** | **0.1** | **0.02** | **0.09** | **0.03** | **0.06** | **0.06** | **0.05** | |
| **Disagreement** | | | | | | | | **0.06** |

**Table 2: Pairwise Comparison yielded from the expert feedback.**

Before pursing application, it is important to review and validate the results. The first indicator is the internal inconsistency. This is the measure of each individual's consistency in scoring between elements. For example, perfect consistency would suggest that if A=2B and B=3C, then A=6C. Only one expert, Tom, had an inconsistency above 0.02. Tom's inconsistency was 0.09; which although is significantly higher than the rest of the experts, is still under 0.10 which is generally regarded as the threshold for reliability. This allows us to accept each of the experts' input as reliable.

The next indicator for reliability is the measure of standard deviation for each element of the HDM across all of the experts' scores. For example, there was a standard deviation of .02 for the total results from each expert with regards to Asset Age. The standard deviations across all HDM elements are then averaged for the final disagreement factor of 0.06. The same value of 0.10 is used as the threshold of reliability, which suggests that the disagreement between experts is low enough to accept the collective expert opinion as consistent.

As a brief exercise to add a level of insight into the varying expert feedbacks, disagreement was isolated between work groups. As expected, the Operations crew shared a disagreement of 0.05 and the Engineering team dropped to a disagreement of 0.03. This information suggests that in addition to having an acceptable level of disagreement across all of the experts, but that the disagreement is healthy. Both the Engineering and Operations experts provide unique, yet equally valuable, perceptions regarding asset prioritization. For example, some of the disagreement between the groups is found in the operations feedback that found the level 2 nodes as more equal than the Engineering team which heavily favored the Asset Condition node. Anecdotally, this could be an effect of the fact that the Operations crew would be the most likely to be directly impacted in the event of a failure as they are the on-site personnel responsible for mitigation.

To statistically validate the results, an F-test is applied to the data. Figure 3 shows the F probability density function assuming degrees of freedom 6 and 48. The critical F-values are captured and shown in Table 3.

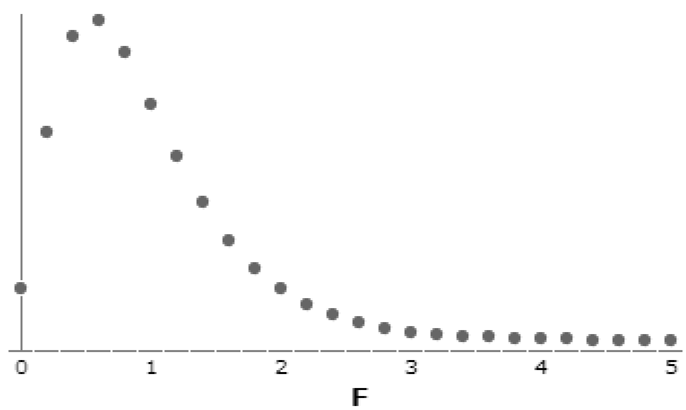


**Figure 3: The F probability density function assuming degree of freedom 6 and 48**

| Source of Variation | Sum of Square | Deg. of Freedom | Mean Square | F-test Value |
|---|---|---|---|---|
| Between Subjects: | 0.59 | 6 | 0.098 | **17.48** |
| Between Conditions: | 0 | 8 | 0 | |
| Residual: | 0.27 | 48 | 0.006 | |
| **Total:** | **0.86** | **62** | | |
| **Critical F-value with degrees of freedom 6 & 48 at 0.01 level:** | | | | **3.2** |
| **Critical F-value with degrees of freedom 6 & 48 at 0.025 level:** | | | | **2.69** |
| **Critical F-value with degrees of freedom 6 & 48 at 0.05 level:** | | | | **2.29** |
| **Critical F-value with degrees of freedom 6 & 48 at 0.1 level:** | | | | **1.9** |

**Table 3: The critical F-values**

As shown in Table 3, the data yielded an F-test value of 17.48, which is well above 3.2, the critical F-value at a 0.01 level of confidence suggesting the data produces a level of confidence exceeding 99%. This indicates that scores are statistically reliable. In fact, the cumulative distribution function (Figure 4) shows that the F-test value of 17.48 yields a 99.999999987% confidence.

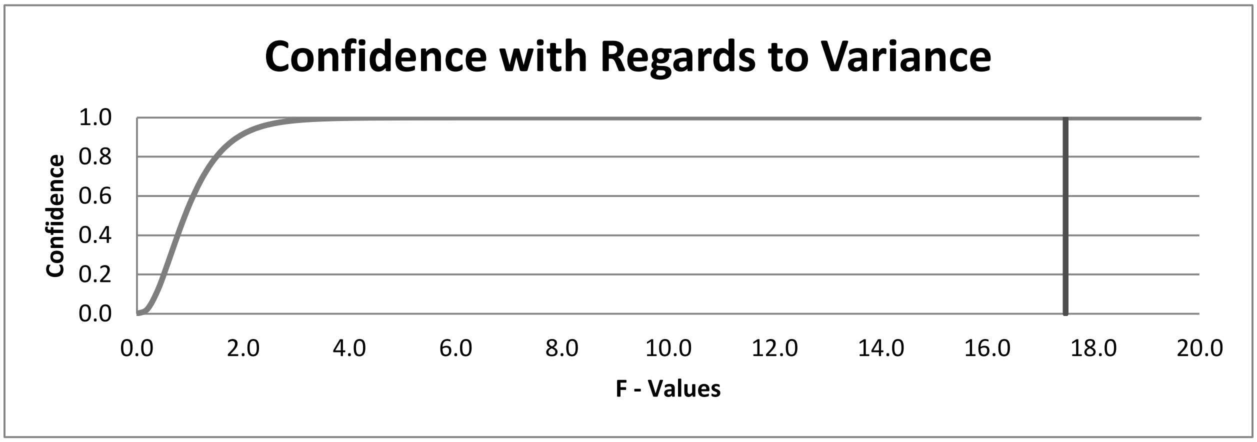


**Figure 4: The cumulative distribution function**

## *5.3HDM Solution*

Following statistical validation of the HDM results, the final Asset Prioritization Tool is presented as shown in Figure 5. The normalized weight for each of the Level 3 HDM elements is shown under each respective box.

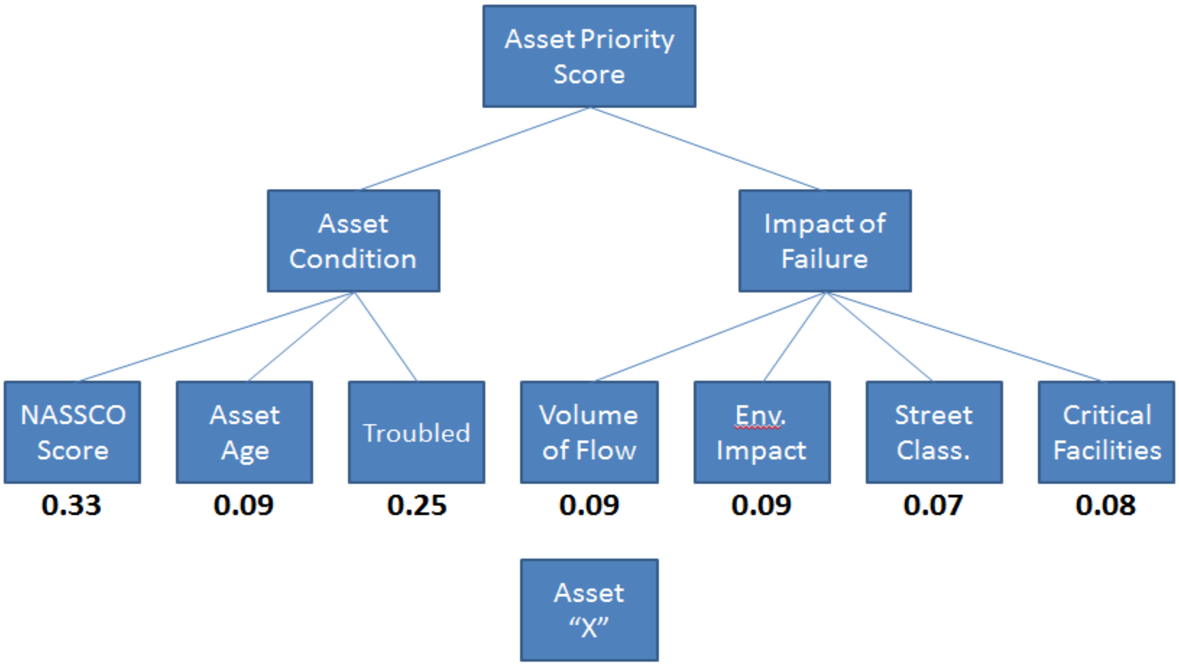


**Figure 5: The Final Asset Prioritization Tool**

Each asset will have an initial score for each of the HDM elements which is then multiplied by its respective weight and the products are summed for a total Asset Priority Score. Coming up with the initial scores requires a discussion regarding utility.

## 6. Utilities

The discussion of utility theory as it pertains to this particular tool is unique. None of the elements possess an inherent value such as money, processing power, screen size, etc. As such, one cannot necessarily infer one state is necessarily more or less valuable than another state within any given attribute. For example, a pipe size of 6 inches is not inherently better or worse than a pipe size of 36 inches unless it is specifically viewed through the lens of Volume of Flow as it pertains to its respective level 2 element of Impact of Failure. Fortunately, for all Impact of Failure elements, the City had already developed utility tables with which they were generally satisfied. The results of these utilities can be seen in Table 4. Notice that all utilities are being scored on a scale of zero to five. There are a handful of reasons for this. One reason is to match current industry standards for other items such as NASSCO scoring. Another reason this scale is employed is in an effort to place the conveyance assets in a similar scale to those used for treatment plant assets by the Treatment Plant team. For the purpose of this tool, although HDM tools will typically use normalized value, the 0-5 scale is just as effective as long as it is applied consistently.

**Volume of Flow**

| Pipe Size (in) | Initial Score |
|---|---|
| ≤ 6 | 0 |
| ≤ 10 | 1 |
| ≤ 15 | 2 |
| ≤ 24 | 3 |
| ≤ 36 | 4 |
| > 36 | 5 |

**Environmental Impact**

| Proximity (ft) | Initial Score |
|---|---|
| > 1000 | 0 |
| ≤ 1000 | 1 |
| ≤ 600 | 2 |
| ≤ 300 | 3 |
| ≤ 100 | 4 |
| Adjacent | 5 |

**Critical Facilities**

| Proximity (ft) | Initial Score |
|---|---|
| > 2500 | 0 |
| ≤ 2500 | 1 |
| ≤ 1500 | 2 |
| ≤ 800 | 3 |
| ≤ 300 | 4 |
| ≤ 100 | 5 |

**Street Classification**

| Classification | Initial Score |
|---|---|
| Offroad | 0 |
| Neighborhood | 1 |
| Community | 2 |
| Collector | 3 |
| Arterial | 4 |
| Freeway | 5 |

**Table 4: Utility Table for each of " Impact of failure" elements**

For the most part, these values were simply derived from the original risk-impact matrix that the City had already begun to develop. The process for identifying specific utility functions for Asset Condition was not necessarily as convenient.

The NASCCO score is a widely accepted industry standard for assessing the structural condition of a pipe based on observations during inspection such as leaks, cracks, roots, offset joints, etc. This standard is rigorously maintained through a certification and validation process. As such, the actual NASCCO score was used as the initial score for its respective element without any scaling factor. Assigning utility scores to troubled assets required more intuition. All things being equal, all pipes are cleaned in a five to seven year rotation. As such, assets with work orders of this frequency are assigned a zero as there is nothing out of the ordinary with these assets in terms of O&M. The most troubled assets require intervention multiple times each year. Those that require O&M attention more than once every 3 months are assigned a 5. Requiring anything between quarterly and semiannual attention received a 4 and so forth. The results for these two Asset Condition elements are shown in Table 5.

**NASSCO Score**

| NASSCO | Initial Score |
|---|---|
| 0 | 0 |
| 1 | 1 |
| 2 | 2 |
| 3 | 3 |
| 4 | 4 |
| 5 | 5 |

**"Troubled" Designation**

| Frequency (per yr) | Initial Score |
|---|---|
| ≤ 0.2 | 0 |
| ≤ 0.5 | 1 |
| ≤ 1 | 2 |
| ≤ 2 | 3 |
| ≤ 4 | 4 |
| > 4 | 5 |

**Table 5: Asset condition elements**

In order to assign a utility score to Asset Age required more intuition and analysis. To assign a straight-line utility function to age may be the easiest approach; however, the sense that a 10 year old asset is twice as likely to fail as a 5 year old asset at a given point due to age violates both historical experience and intuition, especially considering a typical useful life expectancy on the order of 70 years. However, as an economist would note, one cannot simply inquire directly about utility and yield accurate results. Rather, utility can only be inferred "by the outward phenomena" to which desires give rise [3]. Fortunately, in the case of municipal sewer pipes, desire is not part of the equation. Rather, an effective utility score for asset age would be based on a pipe's likelihood of failure at a given age. To this end, an appropriate tool is the Herz cumulative probability distribution for service lifetime expressed as:

$$F(t) = 1 - \frac{a+1}{a + e^{[b(t-c)]}}$$

where a, b, and c are constants to match empirical data [4]. Values for the constants were derived from simulations performed by P. Davis, et al, in predicting probability of failure in municipal water systems [5] and were adjusted accordingly to account for the corrosive forces at play in municipal wastewater to yield the distribution shown in Figure 6. The lifetime probability distribution function *f(t)* corresponding to the Herz distribution is expressed as the derivative of the distribution with respect to time [4] and is also shown graphically in Figure 6:

$$f(t) = \frac{dF(t)}{dt} = \frac{[(a+1)b]e^{[b(t-c)]}}{\{a + e^{[b(t-c)]}\}^2}$$

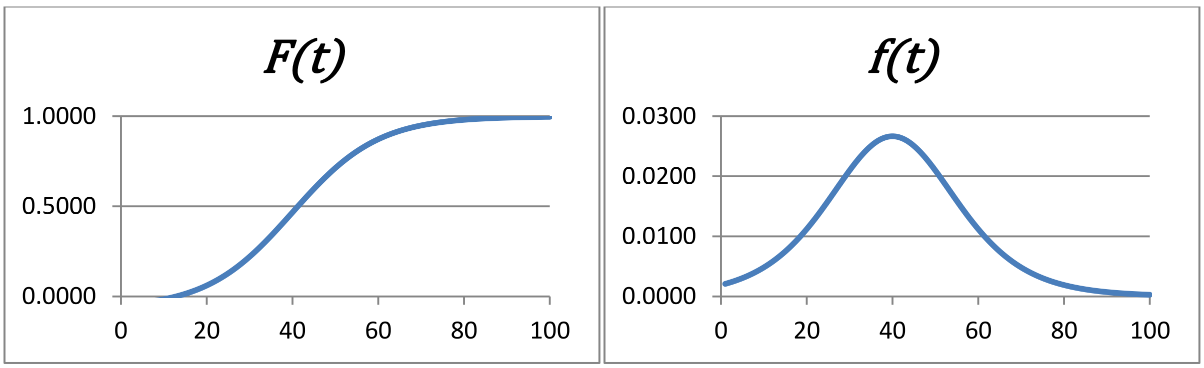


**Figure 6: Herz Cumulative Probability Distribution and Lifetime Probability Density Function**

From the previous functions, one can then derive the hazard function h(t) which is described as an indicator of the "proneness to failure" of an asset at time t [6]. The hazard function is expressed as:

$$\boldsymbol{h(t) = \frac{f(t)}{1 - F(t)}}$$

and is shown graphically in Figure 7. The hazard function is an excellent characterization for an appropriate utility scoring for the age of the pipe as it effectively describes the proneness to failure as a function of age. Therefore, the hazard function simply need be scaled by 50 to accommodate the boundary condition of 0.10 to match the zero to five-scale being implemented for the HDM. The result is shown in Figure 8.

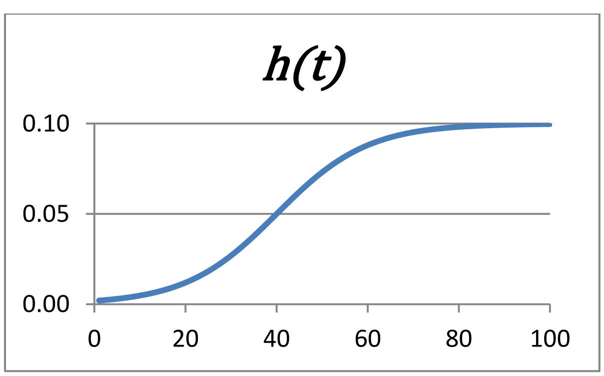


**Figure 7:Hazard Function " Proneness to Failure"**

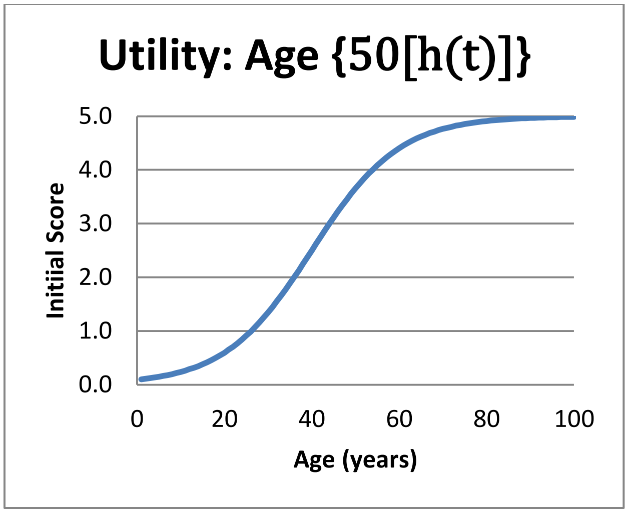


**Figure 8: The Hazard Function scaled by 50.**

## 7. Simulation

As a final effort to verify the effectiveness of the prioritization tool, a simulation was performed using a small sample of assets [7]. To perform the simulation, 10 assets were selected from the system possessing a wide range of attributes. The sample was not selected randomly; rather, assets were generally selected from a smaller pool of pipes that possessed a particular criterion that would suggest it would be in need of replacement over the next decade or so. With no information aside from a description of each asset's characteristics as they pertain to each of the Level 3 elements of the model, Jim Montgomery would rank each of the assets from highest to lowest priority according to his own experience and expertise. Jim Montgomery is the Senior Engineer overseeing the Engineering Team and is the ultimate decision maker for which assets are replaced when. Furthermore, Jim possesses a great deal of experience in wastewater management and is highly respected among his peers for his management of the system. His ranking is then compared to the tool's output for each of the assets. Table 6 shows the results of the simulation with the assets ranked according to the HDM tool with their scores and Jim's respective ranking of each asset.

| NASSCO Score | Asset Age | Troubled | Volume of Flow | Env. Impact | Street Class. | Critical Fac. |
|---|---|---|---|---|---|---|
| 0.33 | 0.09 | 0.25 | 0.09 | 0.09 | 0.07 | 0.08 |

| Asset | Initial Score | | | | | | | Asset Priority Score | Manager Ranking |
|---|---|---|---|---|---|---|---|---|---|
| 5880 | 5.0 | 0.2 | 2 | 3 | 2 | 5 | 0 | 2.97 | 1 |
| 10260 | 3.0 | 4.0 | 3 | 1 | 2 | 2 | 0 | 2.51 | 2 |
| 2863 | 3.9 | 2.9 | 1 | 1 | 5 | 2 | 0 | 2.48 | 4 |
| 6608 | 3.0 | 3.6 | 3 | 2 | 0 | 2 | 1 | 2.46 | 3 |
| 6625 | 2.5 | 3.3 | 3 | 2 | 3 | 0 | 1 | 2.41 | 6 |
| 544 | 2.5 | 3.3 | 2 | 1 | 3 | 5 | 0 | 2.34 | 5 |
| 4404 | 4.0 | 4.5 | 0 | 1 | 0 | 2 | 0 | 1.96 | 7 |
| 1598 | 2.5 | 4.2 | 1 | 2 | 0 | 2 | 2 | 1.93 | 8 |
| 4430 | 2.0 | 4.3 | 0 | 1 | 0 | 4 | 0 | 1.42 | 9 |
| 367 | 1.7 | 2.9 | 0 | 1 | 0 | 4 | 2 | 1.34 | 10 |

**Table 6: Simulation results**

As seen in the results, the Manager's results do not appear to vary significantly from the tool's output. In fact, only four of the assets were not synced up to the tool's results. Those four assets are just two pairs where the assets were swapped. The manager had 3 and 4 swapped, as well as 5 and 6. Although it appears to be a minor discrepancy, it warrants a closer statistical look. The first approach at validating the results is to infer asset scores from the manager's rankings. The first iteration is to infer a straight-line distribution on the manager's behalf. In this case, since the manager matched the tool on the highest and lowest priority assets, the assumption is that the manager would have scored them identically in order to match the spectrum of scores. From here, it is inferred that the manager would have scored each asset according to its rank distributed equally. This is defined as:

$$k = \frac{S_{MAX} - S_{MIN}}{n - 1}$$

where n is the sample size, k is distribution of each score, and S represents asset scores as assigned by the tool. The manager's scores follow the equation:

$$s_r = S_{MAX} - k(R - 1)$$

where R is the rank assigned by the tool and s represents the manager's score for each asset according to his respective ranking, r. The results were then normalized and compared as shown in Table 7.

| Asset | Tool Rank | Tool Score | Manager Score | σ |
|---|---|---|---|---|
| 5880 | 1 | 0.500 | 0.500 | 0.0000 |
| 10260 | 2 | 0.474 | 0.526 | 0.0263 |
| 2863 | 3 | 0.505 | 0.495 | 0.0051 |
| 6608 | 4 | 0.485 | 0.515 | 0.0148 |
| 6625 | 5 | 0.538 | 0.462 | 0.0379 |
| 544 | 6 | 0.510 | 0.490 | 0.0098 |
| 4404 | 7 | 0.510 | 0.490 | 0.0104 |
| 1598 | 8 | 0.532 | 0.468 | 0.0317 |
| 4430 | 9 | 0.483 | 0.517 | 0.0170 |
| 367 | 10 | 0.500 | 0.500 | 0.0000 |
| | | | Inconsistency: | **0.0153** |

**Table 7: Inferred straight line distribution**

The resulting inconsistency again falls well within the acceptable range under 0.10 with a value of 0.0153. A look at the graphical results provides additional insight into the scores, ranks, and distributions in Figure 9.

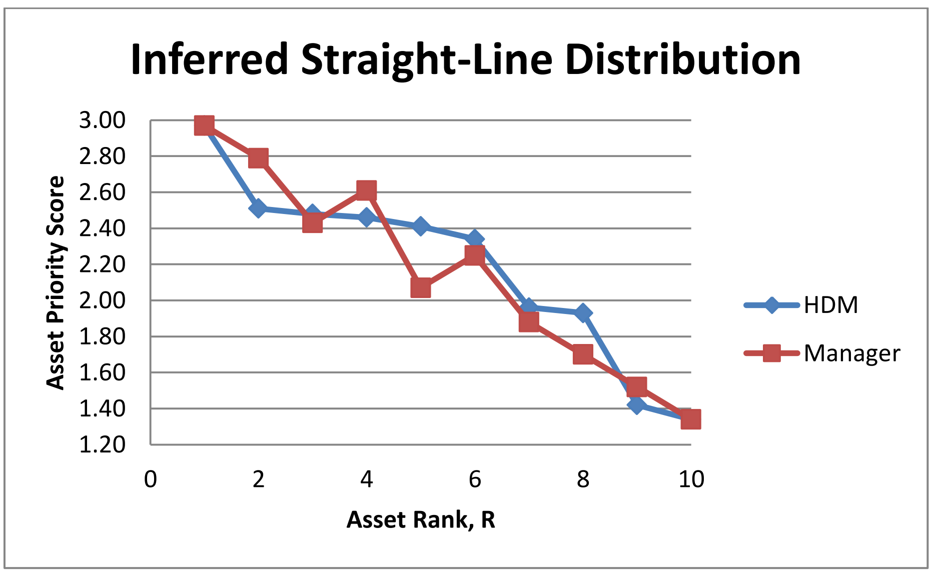


**Figure 9: Inferred straight line distribution "Graphical result"**

Figure 9 shows that aside from the assets ranked three through six, the manager's scoring distribution would have yielded a straight line. However, careful inspection of the results for the tool's output shows that the same range of assets, three through six, is a relatively flat distribution meaning the scored results were relatively tight. The question is whether these four assets are in fact relatively equal in terms of scoring, but create a discrepancy against the manager's results simply by virtue of a forced ranking. In order to address this element, the same test is applied to the manager's ranking but rather than inferring a straight-line distribution, it is assumed that his distribution is similar to that of the tool. As the inconsistency is a measure of the standard deviations of the score, this approach will remedy the inherent penalties for the remaining six assets in which they were ranked identically. This function is defined by the simple equality that:

$$S_R = s_r \; where \; R = r$$

This simply means that whatever score the tool assigned to asset ranked R will equal the inferred score for an asset from his ranking, r. This will result in a standard deviation of zero for all assets in which the tool and the manager were in agreement. Furthermore, the standard deviations for the scores in which their rankings were not equal, the penalty will be reduced to the level of significance inferred from the tool's distribution. The results are then similarly normalized and compared as shown in Table 8.

| Asset | Rank | Tool Score | Manager Score | σ |
|---|---|---|---|---|
| 5880 | 1 | 0.500 | 0.500 | 0.0000 |
| 10260 | 2 | 0.500 | 0.500 | 0.0000 |
| 2863 | 3 | 0.502 | 0.498 | 0.0020 |
| 6608 | 4 | 0.498 | 0.502 | 0.0020 |
| 6625 | 5 | 0.507 | 0.493 | 0.0074 |
| 544 | 6 | 0.493 | 0.507 | 0.0074 |
| 4404 | 7 | 0.500 | 0.500 | 0.0000 |
| 1598 | 8 | 0.500 | 0.500 | 0.0000 |
| 4430 | 9 | 0.500 | 0.500 | 0.0000 |
| 367 | 10 | 0.500 | 0.500 | 0.0000 |
| | | | Inconsistency: | **0.0019** |

**Table 8: Inferred Matching distribution**

The level of inconsistency decreased significantly to 0.0019. Furthermore, the graphical results in Figure 10 show how minor the discrepancy truly was between assets ranked three and four, and five and six between the asset prioritization tool and the lead decision maker.

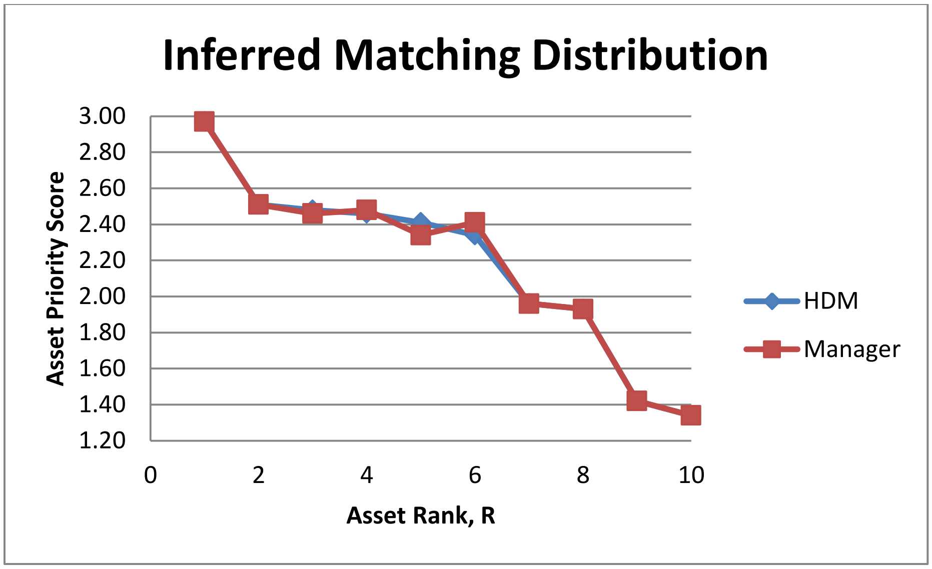


**Figure 10: Inferred Matching Distribution " Graphical result"**

Between the tests, it can be assumed that the rankings were statistically similar and therefore the effectiveness of the tool is verified.

## 8. Conclusion

Following the simulation of the tool, it is determined that the asset prioritization tool effectively satisfies the problem statement as an accurate, consistent, and scalable tool that can be used in the future of wastewater asset management within the City of Gresham. The model and utilities were developed in such a way that the City could integrate them flawlessly into the existing work order management system. This would allow for all assets within the system to be assigned a priority score simultaneously that could be indexed or queried. Furthermore, the asset prioritization tool improves upon the current tool by addressing each of its explicit weaknesses. The proposed tool incorporates expert feedback from multiple sources. Additionally, the proposed tool incorporates weight factors across the board whereas the current tool neither weights any of the "impact" factors, nor does it differentiate between the weights for "risk" or "impact" factors. Finally, the proposed tool has withstood statistical analysis at each step leading to statistical validation of the final product.

# 9. References


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