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New York City Bridge Management: Influence of Subjective Elements

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Contents

Introduction

There are 2,027 bridges in New York City. DOT's Division of Bridges owns, operates, and/or maintains 770 structures. While the Division is responsible for the capital rehabilitation, maintenance and inspection responsibilities remain with the New York City Department of Environmental Protection. Of the 770 bridges, 20 connect boroughs. Of the remaining 766, 20% are in the Bronx, 23% are in Brooklyn, 23% are in Manhattan, 26% are in Queens, and 8% are in Staten Island.

It should be sufficient to hear these numbers to understand that the bridge management in New York City is not the very easy. Even if the Department of Transportation (DOT) is a big, well composed and operating institution, they are always looking for new ideas to implement and improve the bridge management system of the Big Apple.

Bojidar S. Yanev, responsable for the bridge management ad the Department of Transportation and Rene B. Testa, Professor at Columbia University have been answering this problem first by proposing a model and after by implementig it in a excell spreadsheets software. With this model and this software parameter in assesing the effectiveness of the maintenance tasks on the overall cost of a bridge or system of bridges are identified and the linkage among maintenance, condition rating and cost is made (as all engineering process should do) by subdividing the subjective process into smaller parts.

The main purpose of this thesis will be to study and explain the model and to show, by using several example, how it works. Moreover, always through exhaustive examples, this thesis will highlight some problems that the software has and that could be easily corretted in order to improve accuracy of the model and the adherence to the reality.

It will be shown the difference between bridge construction material. In fact, as it will be possible to see, a concrete bridge generally requires much cheaper maintenance than an equal dimension bridge made of steel.

Finally the subjectivity that is present during the inspection phases as well as in the definition of the Importance Factor Matrix and the weights of the components are studied. Expecially when the maintenance level is not uniform, for all the different tasks, the Importance Factor Matrix plays an important role in the computation of the Annualized Total Cost per square foot as well as in the determination of the final expected life of the structure.

Bridge Management in New York City: History

The Bridge Management Problem

The New York City Department of Transportation (NYC DOT) is in charge of more than 770 bridges. They have something like 47010 spans and a total deck area larger than 1.43 x 10^6 m^2.Even if there are old bridges, as the famous Brooklyn Bridge (figure 1), that are still used, in 1998 the average age of the bridges was 75 years that means that today is around 85 years. New York City has to allocate every year more than half of billion dollars for bridge rehabilitation, component rehabilitation, maintenance, repairs and hazard mitigation. In general the average expenditure are around $ 500,000,000 for bridge rehabilitation, $30 million for component rehabilitation, $ 20 million for maintenance and $ 25 million for standard repairs and hazards mitigations (Yanev & Testa). This huge annul amount of money spent by the City is far to be sufficient to a complete keep the bridges system in a perfect state. In fact, it is impossible to guarantee a level of maintenance of 100% for every bridge in the city area.

Therefore the Department of Transportation had to find a way to rank the bridge in order to create a model to allocate the annual budget to gain the best level of bridges condition. In order to do that a system to rank the bridges has been created since 1982.

Figure 1 - Brooklyn Bridge

Bridge Inventory and Inspection

Since it was established in 1978 the Federal Bridge inspection program has undergone several modifications. Nonetheless it has been consistent for a period sufficient to create a reliable inventory and condition assessment database. The bridge inventory reflects the structural type and contains reference to all components in all spans. Significant reconstruction data, geometry and traffic volumes are included, although in practice they are lacking in accuracy. In fact, even if there is some lack, this system provides a huge and well done database of information that is difficult to find in other countries. The inspection database includes condition ratings for each span of each bridge. In this way, condition ratings can be generated for the larger components such as the deck, the primary member…. At the end an overall bridge condition rating based on weighted averages of the significant component rating is obtained as a result of every inspection.

Bridge inventory and operating rating are computed independently, specifying the live load the bridge can support in a normal working condition and the maximum ones.

The problem of these inspections and thus of these scales is that they are based on the subjectivity of the operators that go to inspect the bridge. The efforts to compensate for the subjective nature of the condition ratings have led to an evolution of different rating scale. In fact, historically, the Federal System rated bridge elements using a scale from 0 to 9. The New York State System, instead, ratings condition on a scale from 1 to 7. One means failure of the components, 7 perfect state while 3 identifies that the components "is not functioning as designed".

Among all the span and objects observed and inspected the New York City Department of Transportation has chosen 13 main components that will establish the overall bridge rateing.

The thirteen components are the following:

1. Bearings
2. Backwalls
3. Abutments
4. Wingwalls
5. Bridge Seats
6. Primary Members
7. Secondary Members

8. Curbs
9. Sidewalks
10. Deck
11. Wearing Surface
12. Piers
13. Joints

As said before, once that each of these components is rated by a team it's possible to find the overall bridge rating, R, by summing every component rateing multiplied by an importance factor peculiar for each component. In fact, it's easy to understand that not every member has the same importance in the bridge system, for example in order to guarantee that a bridge works the Piers or the Primary Members are more important and useful than Sidewalks or Curbs. This relative importance between the different components is given by assigning number from 1 (not important) to 10 (very important – fundamental) to every component. Once these numbers are given, they are normalized (w_i) and it's possible to find the overall rating R.

$$R = \sum_{i=1}^{13} w_i R_i$$

Where:

- W_i is the "weight" of each component with respect to the others
- R_i is the rating of the i-th component given alter the inspection of the bridge

In the current model, as it will be shown in the next chapter, the relative importance of each component is a parameter assigned deterministically.

In the last 10 years the overall bridge condition, that takes in account all the 770+ bridges in New York City area, has stayed stable close to 4.5. This means that the whole system is closer to be not functioning as designed than to be in a perfect state. Something to improve the allocation of the money or the maintenance in order to raise the overall rating should be done.

Deterioration

For every component is possible to assign, based on experience, an expected life that the component would have if the full maintenance was guaranteed every year (L_{i1}) and an expected life due to a none maintenance (L_{i0}). In the table 1 it's possible to see for each component the importance weight, the shortest life, the longest life, the initial rating R (that means new component) and the R_{ic} that is the rating that, if reached, means the failure of the component.

	COMPONENT	Lio	Li1	Rio	Ric	weight
1	**Bearings**	**20**	**120**	**7**	**1**	**6**
2	**Backwalls**	**35**	**120**	**7**	**1**	**5**
3	**Abutments**	**35**	**120**	**7**	**2**	**8**
4	**Wingwalls**	**50**	**120**	**7**	**1**	**5**
5	**Bridge seats**	**20**	**120**	**7**	**1**	**6**
6	**Primary members**	**30/35**	**120**	**7**	**2**	**10**
7	**Second. Members**	**35**	**120**	**7**	**1**	**5**
8	**Curbs**	**15**	**60**	**7**	**1**	**1**
9	**Sidewalks**	**15**	**60**	**7**	**1**	**2**
10	**Deck**	**20/35**	**60**	**7**	**2**	**8**
11	**Wearing surface**	**10/15**	**20/30**	**7**	**1**	**4**
12	**Piers**	**30**	**120**	**7**	**2**	**8**
13	**Joints**	**10**	**30**	**7**	**1**	**4**

Table 1 Bridge Components and Properties

The rating of each component, R_i, decreases every year. The rate of deterioration of components (r_i) is defined as:

$$r_i = -\frac{dR_i}{dt}$$

And thus the rate of deterioration for the whole bridge is:

$$r = -\frac{dR}{dt}$$

Once that the fastest rate of deterioration (r_{i0}) and the slowest one (r_{i1}) are found it's possible to define the rate of deterioration as a function of the level of maintenance done on every component.

In the model proposed by (Testa & Yanev, 2002) in their article "Bridge Maintenance Level Assessment" it's possible to choose among three kind of trend for the deterioration rate:

- Linear
- Exponential
- Secant

For example, by choosing the linear trend of rate deterioration, the r_{i0} and the r_{i1} are computed, for each component, by dividing the difference between the rate R "at new condition" and the critic rate by, respectively, the shortest expected life or the longest one.

$$r_{i0} = \frac{(R_{i0} - R_{ic})}{L_{i0}}$$

And

$$r_{i1} = \frac{(R_{i0} - R_{ic})}{L_{i1}}$$

In figure 3 it's possible to see the linear rate for the two different rates r_{i1} and r_{i0}. Naturally r_{i1} has a lower slope with respect to the rate with no maintenance and thus the critical rating for the given component is reached in more than the double time.

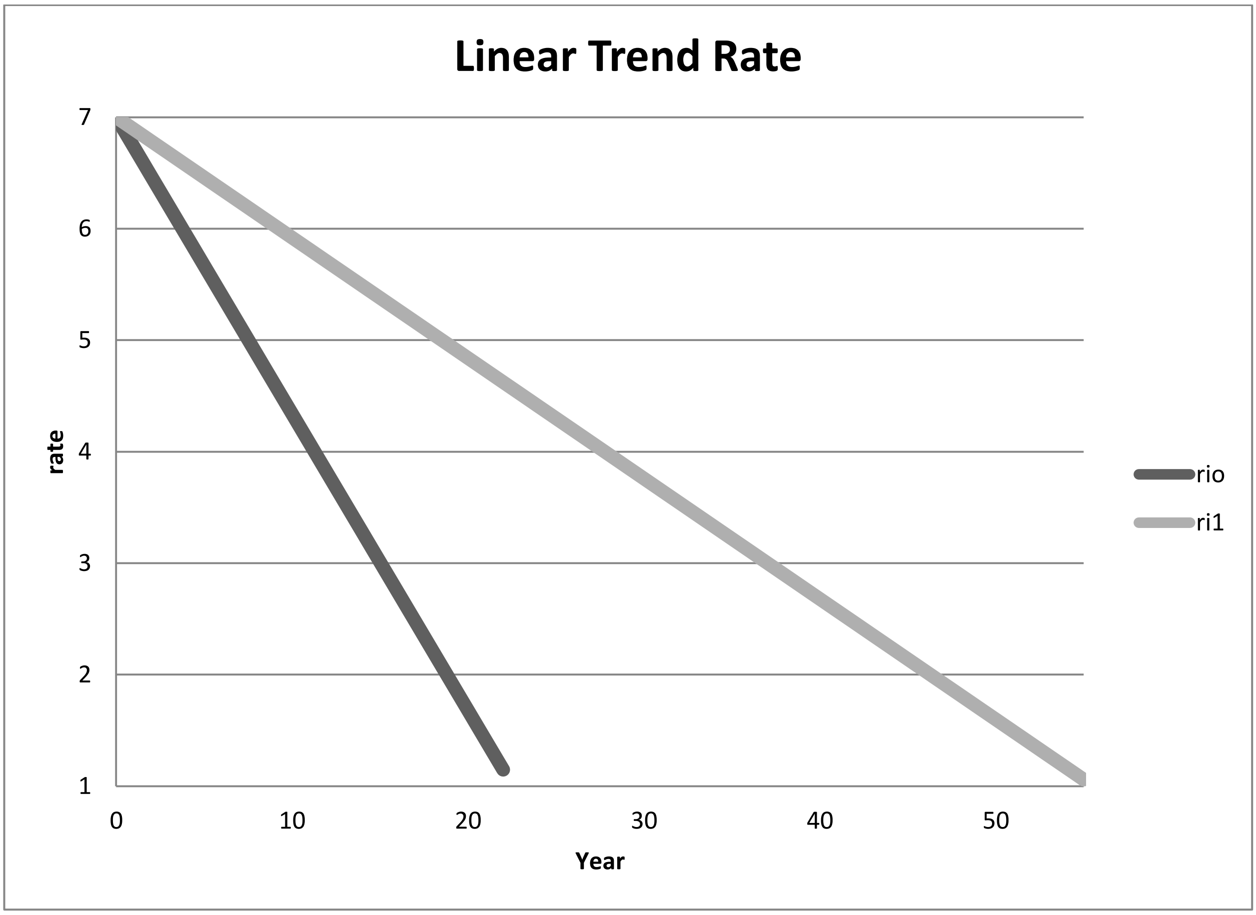


Figure 2 – Rate Linear Trend

Once understood this concept it's easy to understand all the software working process. In fact, as it will be explained in next chapters, the expected life, the total annual cost as well as the overall Bridge Rating are function of the level of maintenance applied to the bridge.

As it will be shown after, every time that the rateing of a component goes under a given threshold R_{rep} the component will be repaired and it will increase aging its R_i.

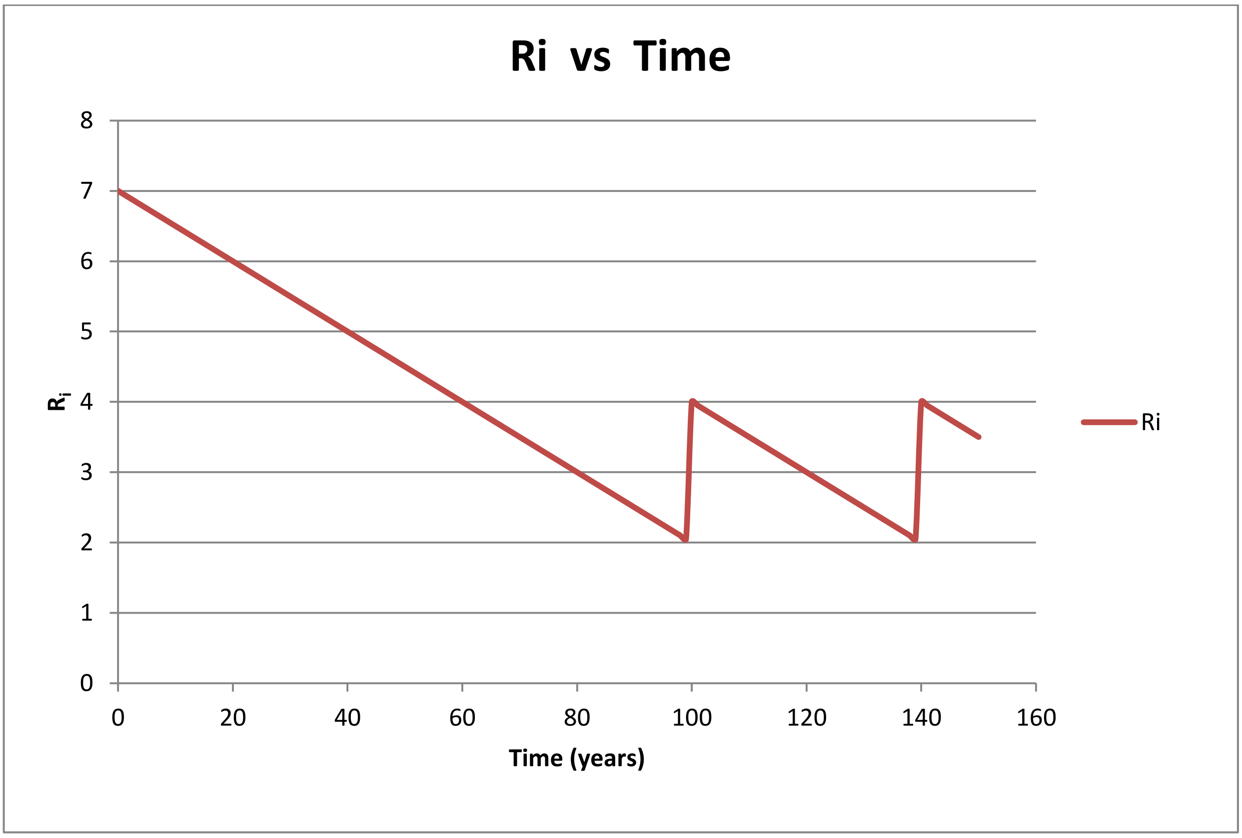


Figure 3 - Trend of the Rating of a component in time

Maintenance

The maintenance is one of the most important points in this model under study. In fact almost the 20 % of the total expenditure of the New York City Department of Transportation is due to maintenance. Moreover, the maintenance, controls the deterioration rating of each of the 13 component thus is important to understand at all how it works. In this model the maintenance operations were divided into 15 main tasks:

- Debris Removal
- Seeping
- Clean Drainage
- Clean Abutment Piers

- Clean Grating
- Clean Joints
- Wash Deck
- Paint (only for steel bridges)
- Spot Paint (only for steel bridges)
- Sidewalks & Curbs Repairs
- Pavement and Curb Seal
- Electric Maintenance
- Mechanical Maintenance
- Wearing Surface
- Wash Underside

Unfortunately it’s impossible, due to the actual budget condition, to assure a full maintenance for every component of every bridge. Hypothetically if a full maintenance was done on all the components of a bridge the expected life of it would be the longest possible. In this way less repairs or rehabilitations are needed and the decreasing drastically the costs for that. As it possible to see, in fact, for given component the rating, R_i, decreases fastest with no maintenance than with full maintenance (figure 4).

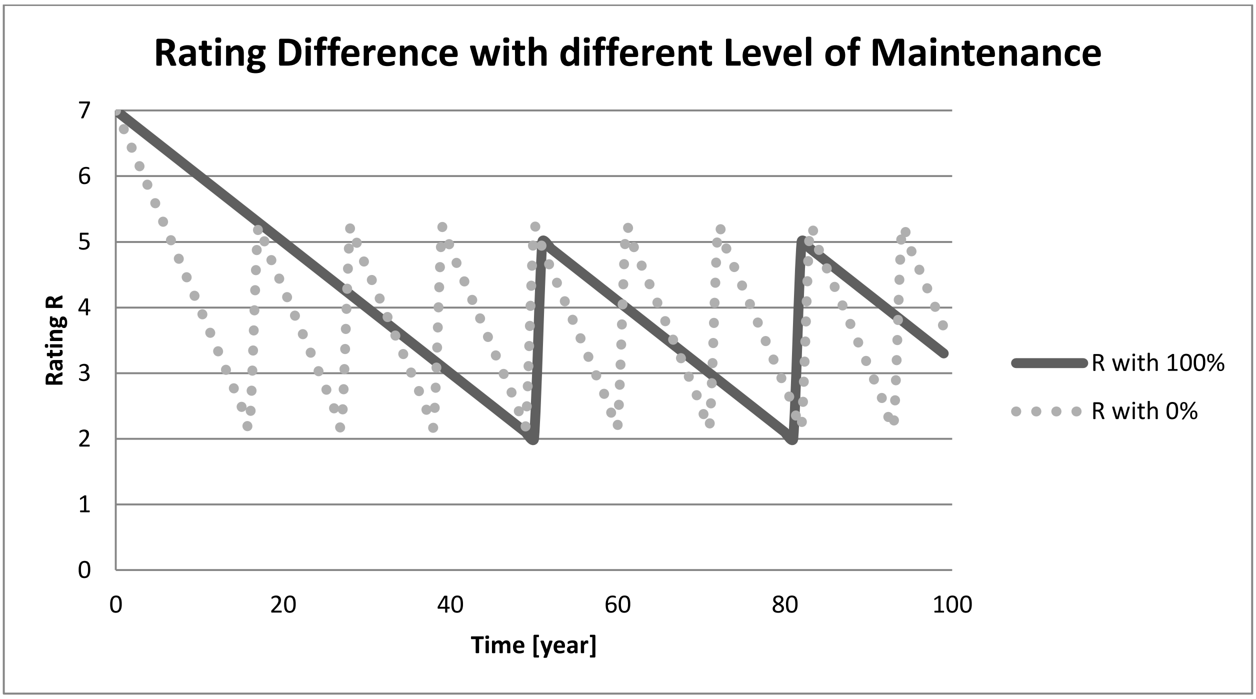


Figure 4 - Difference of R due to M

In the previous picture it's possible to understand that, over a the same lifespan (in the example 70 years), the deterioration of one component with a full maintenance is slower than the one with none maintenance. In this example, during the 70 years the component with 100% maintenance will be repaired three times while, the component with 0% of maintenance, 9 times. As said in the paragraph (2.1), each repair, even if depending on the component, has an average cost of 25 million of dollars, this means that for the example on figure 4, New York City will spend 150 million of dollars more for the blue line with respect to the red one. Naturally, the annual cost of maintenance for the red line will be greater but the total annual cost at the end will be bigger for the "none" maintenance.

Why doesn't New York City Department of Transportation do a full level of maintenance for whole the bridges if it's cheaper than repair?

This approach could be doable if all the bridges were new (with a rating close to 7) and a perfect schedule of maintenance was programmed. Unfortunately the bridges system in New York City has an average age of 85 years old and until the 1970s no maintenance was done.

A previous study conducted at (Columbia University)[1] in 1999 found which could be the total annual cost of a given task of maintenance done at what is thought to be 100% for the entire bridge system in New York and so, dividing the cost by the surface of the decks it possible to have an average of cost per square meter for every maintenance task (Table 2).

	Activity	Annual cost if M=1.0	C_{mj1} [$/m^2]
1	Debris removal	2319653	0.151
2	Sweeping	613071	0.040
3	Cleaning Drainage	863804	0.056
4	Clean abutments& piers	2776013	0.181
5	Clean open grating deck	55490	0.004
6	Clean expansion joints	3262730	0.213
7	Wash deck & splash zone	1455198	0.095
8	Paint	36041997	2.348
9	Spot paint	23743128	1.547
10	Sidewalk & curb repair	1328182	0.087
11	Pavement & curb sealing	2334466	0.152
12	Elect device maint	1107143	0.072
13	Mech component maint	1010502	0.066
14	Replace wearing surfaces	1390305	0.091
15	Wash underside	13189518	0.859

Table 2 Annual Maintenance Activities

[1] Columbia University, 1999, Preventiva Maintencance..

Importance Factor Matrix

Fifteen maintenance activities were established and every bridge is divided into thirteen different components, it's clear that not all the maintenance tasks have the same influence on the rate of deterioration of the bridge.

Therefore the model should keep in account how much a given task influences the overall deterioration of each component. To do that an Influence Factor Matrix was created. The I_{ij} element of the matrix says how much the j-th task is important and useful for the j-th component. Every "I" factor is a number from zero to one. "0" means that i-th task is not important for that component while "1" means that is that is fundamental.

The Importance Factor Matrix (table 3) was established by a team of engineers in charge of maintenance and inspection section of the Department of Transportation. Albeit based on long experience, this matrix was assigned subjectively and thus it will be object of study in this work.

		Components												
	Iij	Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
	Debris rem	0.7	0.5	0.2	0.1	0.8	0.5	0.5	0.8	0.8	0.8	0.9	0.1	0.8
	Sweeping	0.2	0.1	0.1	0	0.5	0.5	0.5	1	0.8	0.9	1	0.1	1
	Clean Drain	0.9	0.9	0.9	0.8	1	1	1	1	1	1	1	0.5	1
T	Clean abut/piers	1	1	1	0.9	1	0.8	0.8	0	0	0.5	0.5	1	0.5
a	Clean grating	0	0	0	0	0	0	0	0	0	0	0	0	0
s	Clean exp jts	1	0.8	1	0.5	1	1	0.8	0.5	0.5	0.9	0.9	0.9	1
k	Wash deck etc	0.5	0.3	0.2	0	0.6	0.4	0.4	1	0	1	1	0.4	1
s	Paint	1	0.5	0	0	0.5	1	1	0	0	0.4	0	1	0.5
	Spot paint	1	0.5	0	0	0.5	1	1	0	0	0	0	1	0.5
	Sidewalk & curb	0	0	0	0	0	0	0	1	1	0.1	0.1	0	0.5
	Pavmt & curb seal	1	1	1	0.5	1	1	1	1	1	1	1	0.5	0.5
	Elect device maint	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mech Comp	1	0.5	0.5	0.2	1	1	1	1	0	0.5	0	1	1

Repl wear surf	0	0.1	0	0	0.1	0.1	0.1	0.5	0.5	1	1	0.1	1
Wash underside	1	1	1	0.5	1	1	1	0	0	0.8	0	1	0.9

Table 3 Influence Factor Matrix

As it will be show in next chapters that value of the index matrix are used normalizing along the columns.

Repair, rehabilitation and user costs

In the model crated by (Testa & Yanev, 2002), as said before, repair, rehabilitation and user costs are taken into account. In fact, it's normal that during the life span of a bridge, based on the level of maintenance that it is subjected, more or less number of repairs is necessary. While a standard repair of a component can be not very expensive and can last for few days or weeks, a partial or full rehabilitation of a bridge is very expensive (the cost for a full rehabilitation is estimated around 5,000 $ per square meter of deck) and can last from one to three years.

The user costs are additional costs introduced in order to take into account of traffic delays due to bridges closures and/or restriction for the circulation. These user costs were estimated by (Yanev & Testa) based on traffic data and economic indicators. A detailed explanation of how that user costs are introduced in the model will be given in the next chapter. It's clear that user costs are strictly dependent on repair and rehabilitation costs.

The Model

As explained in paragraph 2.1 the model is based on the idea that changing the level of maintenance applied on a given components the velocity of deterioration of that component will vary. By varying the r_i the expected total life and the total annual cost change. The annual total cost is the summation of:

- Annual Maintenance
- Annualized Repair Costs over the entire life span of the bridge
- Replacement Costs over the entire life span of the bridge
- New York City Costs over the entire life span of the bridge
- User Costs over the entire life span of the bridge

In the model created by (Testa & Yanev, 2002) it's possible to choose which trend to give to the rate of deterioration. It's possible to choose between linear, exponential and secant trends. As already said the rate of deterioration is the speed with which every component tends to deteriorate over time.

$$r_i = -\frac{dR_i}{dt}$$

For sake of simplicity all the work of this thesis will be done by using the linear rate of deterioration. Therefore the rate of deterioration will be defined as:

$$r_i = (r_{i1} - r_{i0}) \sum_{j=1}^{15} k_{ij} M_i + r_{i0}$$

Where:

- r_{i1} = deterioration rate if a full maintenance is done
- r_{i0} = deterioration rate if no maintenance is performed
- $k_{ij}M_i$ = summation of the products between the Index factor I and the maintenance level

- r_i = rate of deterioration for a given components following the linear trend

The software applied the deterioration rate to each component starting from an initial value (R = 7) to reach the need to a repair as soon as a component rating arrives at a designated level (R_{ri}). At this point the components is repaired or replaced and the R_i is increased by some amount (dR_i). All this values are chosen by the user. These components repairs are grouped at 5 years intervals. The critical components (primary member, piers, abutments and deck) can be repaired only two times in the whole bridge life and they are repaired at the 5 year mark preceding the time at which they reach R_{ri} while the other components at the 5 year mark after.

The failure of the bridge occurs when at least one of the critical components reaches its R critical. Failure decides of course the life of the bridge.

The model takes also into account two different kinds of user costs: the first one considers the disruptions and the delay at each of the component repair events during the lifetime and the second is associated with the disruptions as a result from use the bridge when it has a low overall rating R. This second user cost is calculated as a percentage function of the bridge rating. For example, if the bridge has an overall $R<4$ the software adds a 20% of the estimated cost, if $R<3.5$ it adds a 50% if $R<2$ it adds a 100%.

Analysis of Existing Software

Key Components

Among the 13 components in which the bridge is subdivided there are 4 that are more important:

- Primary Member
- Piers
- Abutments
- Deck

All these components are essential for the right working of the bridge and so, if just one of that fails the entire bridge will fail. These components are then said "key components". This is a true approximation, in fact, they are essential for the correct working of the bridge also in the reality. Without the deck or without the primary member the bridge can't work.

Overview of the working of the software

In their work, (Testa & Yanev, 2002) created a software that can be used in order to compute, by varying the numbers of bridge, the level of maintenance, the bridge type and so on, the total annual cost that includes maintenance, repairs costs, NYC costs and user costs.

In this chapter the program working will be explained. The software is an excel files composed by 14 electronic spreadsheets:

- Task
- Components

- Life
- Matrix I_{ij}
- Costs
- Calculation I
- Calculation II
- Chart Calculation

The first nine sheets are used to insert data and to do calculations while the last five are output graphs. A complete explanation of each sheet is provided below.

Task

The first sheet that appears opening the software is the "Task Sheet". This spreadsheet is composed by two main tables: the Bridge System data and the optimization of for the maintenance frequencies and the relative annual costs.

The bridge system data (figure 5) permits to insert the number and the type of bridge that we want to analyze as well as the total number of spans and their area in square feet.

NYC BRIDGES: non-pedestrian		
# of bridges	684	bridges
# of spans	4169	spans
average # of spans	6.10	spans
overall plan area	15,025,091	sf
avg plan area / bridge	21,967	sf
avg plan area / span	3,604	sf
NYC BRIDGES: pedestrian only		
# of bridges	86	bridges
# of spans	537	spans
average # of spans	6.24	spans
overall plan area	327,345	sf
av plan area / bridge	3,806	sf
av plan area / span	609.6	sf
overall plan area	**15,352,436**	**sf**

Figure 5 - NYC Bridges

As you can see it's possible to distinguish between "pedestrian" and "non pedestrian" bridges.

The other table presents in the Task sheet is the Task Costs (figure 6).

Prev Maint Activity	Freq for 100% (times/yr) Fixed br	Movable br	Kmi	Level Mi	Kmi*Mi	Annual cost: all NYC bridges and M=1.0	Cmli	Kmi/Cmli
Debris removal	12*	26	0.119	0.00	0.000	2,319,653	0.1511	0.7903
Sweeping	26	26	0.049	0.00	0.000	613,071	0.0399	1.2233
Cleaning Drainage	2	2	0.114	0.00	0.000	863,804	0.0563	2.0202
Clean abutments& piers	1	12	0.103	0.00	0.000	2,776,013	0.1808	0.5717
Clean open grating deck	1	2	0.000	0.00	0.000	55,490	0.0036	0.0000
Clean expansion joints	3*	3	0.109	0.00	0.000	3,262,730	0.2125	0.5119
Wash deck & splash zone	1	1	0.055	0.00	0.000	1,455,198	0.0948	0.5832
Paint	0.083	0.083	0.060	0.00	0.000	36,041,997	2.3476	0.0254
Spot paint	0.25	0.25	0.055	0.00	0.000	23,743,128	1.5465	0.0355
Sidewalk & curb repair	0.25	0.25	0.011	0.00	0.000	1,328,182	0.0865	0.1246
Pavement & curb sealing	0.5	0.5	0.109	0.00	0.000	2,334,466	0.1521	0.7170
Elect device maint	12	12	0.000	0.00	0.000	1,107,143	0.0721	0.0000
Mech component maint	12	12	0.082	0.00	0.000	1,010,502	0.0658	1.2440
Replace wearing surfaces	0.2	0.125	0.032	0.00	0.000	1,390,305	0.0906	0.3574
Wash underside	1	1	0.102	0.00	0.000	13,189,518	0.8591	0.1190
sums			1.000	M =	0.000	91,491,200	5.96	

Figure 6 - Activities Costs and Frequencies

In this first columns there are listed the different 15 kind of possible activities. In the second and third columns are shown the recommended frequencies of maintenance for each task if the 100% of maintenance would be possible. K_{mi} & K_{mi}*M_i columns will be explained in the "Matrix K_{ij}" paragraph. M_i is the actual level of maintenance for which the analysis is computed. The "Annual Cost" columns has inside the hypothetical annual costs for each component and for the overall bridge system, controlled by The New York Time Department of Transportation, if the full maintenance (M=100%) would be possible. C_{mli} is the annual cost per square foot.

Components

This sheet is composed just by one table (fig 7) that has inside, for each bridge component, the following value:

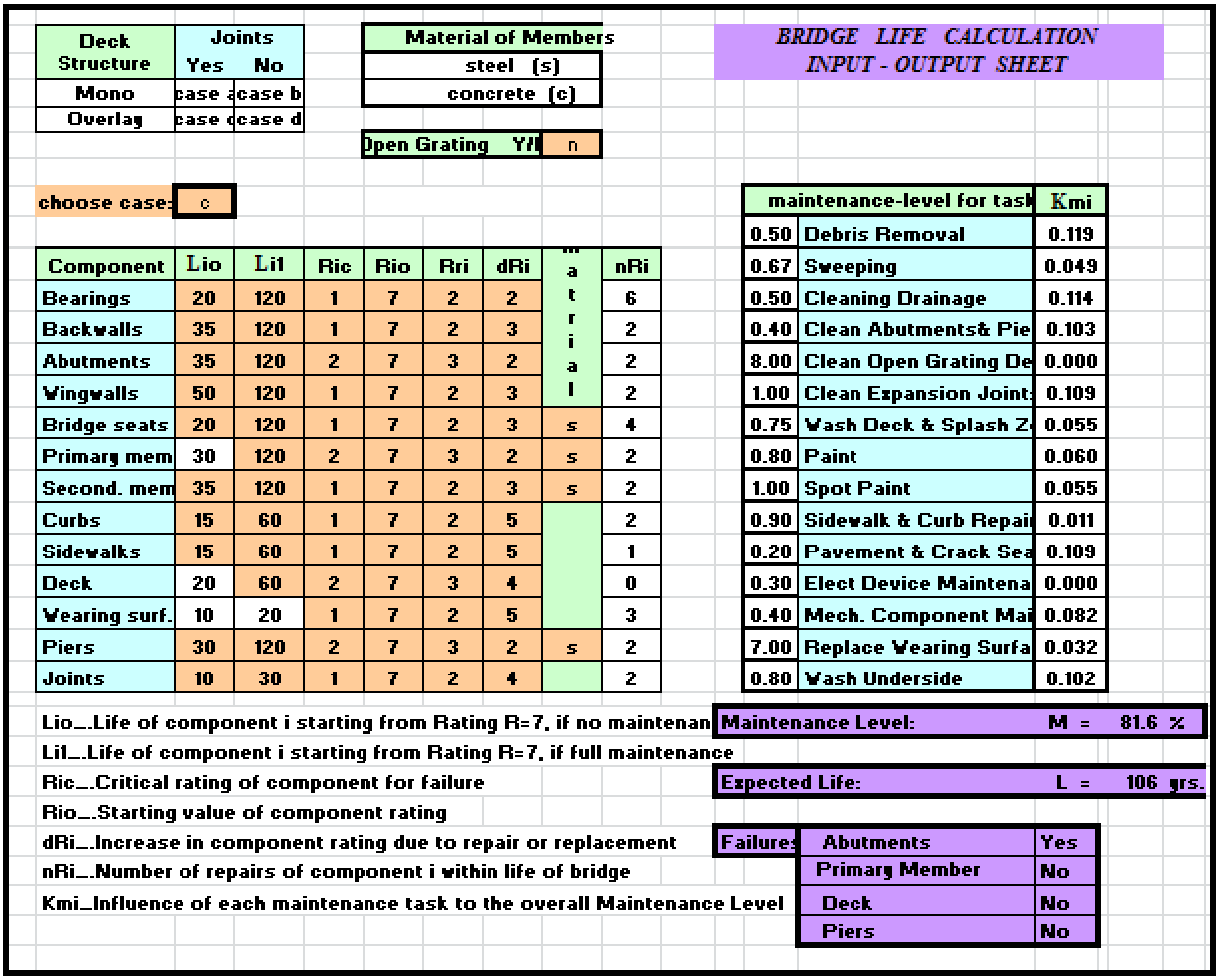
COMPONENT	Lio	Lil	Rio	Ric	weight	Kei	Kei * Rio
Bearings	20	120	7	1	6	0.083	0.5833
Backwalls	35	120	7	1	5	0.069	0.4861
Abutments	35	120	7	2	8	0.111	0.7778
Wingwalls	50	120	7	1	5	0.069	0.4861
Bridge seats	20	120	7	1	6	0.083	0.5833
Primary members	30/35	120	7	2	10	0.139	0.9722
Second. Members	35	120	7	1	5	0.069	0.4861
Curbs	15	60	7	1	1	0.014	0.0972
Sidewalks	15	60	7	1	2	0.028	0.1944
Deck	20/35	60	7	2	8	0.111	0.7778
Wearing surface	10/15	20/30	7	1	4	0.056	0.3889
Piers	30	120	7	2	8	0.111	0.7778
Joints	10	30	7	1	4	0.056	0.3889

Figure 7 - Components

- L_{i0} = expected life with no maintenance
- L_{i1} = expected life with full maintenance
- R_{i0} = rating at start
- R_{ic} = rating for component at failure
- Weight = influence of component i
- K_{ei} = normalized influence of component i on bridge rating on bridge rating

Life

In the "Life" sheet the user can insert and choose the kind of data that he needs. This sheet is subdivided into three main parts. In the first one, bridge life calculation (figure 6), user has to choose the level of maintenance desired for each task with which make the analysis.



Deck Structure	Joints Yes	Joints No
Mono	case a	case b
Overlay	case c	case d

Material of Members	
steel (s)	
concrete (c)	
Open Grating Y/N	n

BRIDGE LIFE CALCULATION INPUT - OUTPUT SHEET

choose case: c

Component	Lio	Li1	Ric	Rio	Rri	dRi	material	nRi
Bearings	20	120	1	7	2	2		6
Backwalls	35	120	1	7	2	3		2
Abutments	35	120	2	7	3	2		2
Wingwalls	50	120	1	7	2	3		2
Bridge seats	20	120	1	7	2	3	s	4
Primary mem	30	120	2	7	3	2	s	2
Second. mem	35	120	1	7	2	3	s	2
Curbs	15	60	1	7	2	5		2
Sidewalks	15	60	1	7	2	5		1
Deck	20	60	2	7	3	4		0
Wearing surf.	10	20	1	7	2	5		3
Piers	30	120	2	7	3	2	s	2
Joints	10	30	1	7	2	4		2

	maintenance-level for task	Kmi
0.50	Debris Removal	0.119
0.67	Sweeping	0.049
0.50	Cleaning Drainage	0.114
0.40	Clean Abutments& Pie	0.103
8.00	Clean Open Grating De	0.000
1.00	Clean Expansion Joint	0.109
0.75	Wash Deck & Splash Z	0.055
0.80	Paint	0.060
1.00	Spot Paint	0.055
0.90	Sidewalk & Curb Repai	0.011
0.20	Pavement & Crack Sea	0.109
0.30	Elect Device Maintena	0.000
0.40	Mech. Component Mai	0.082
7.00	Replace Wearing Surfa	0.032
0.80	Wash Underside	0.102

Lio_.Life of component i starting from Rating R=7, if no maintenan
Li1_.Life of component i starting from Rating R=7, if full maintenance
Ric_.Critical rating of component for failure
Rio_.Starting value of component rating
dRi_.Increase in component rating due to repair or replacement
nRi_.Number of repairs of component i within life of bridge
Kmi_Influence of each maintenance task to the overall Maintenance Level

Maintenance Level: M = 81.6 %

Expected Life: L = 106 yrs.

Failures		
	Abutments	Yes
	Primary Member	No
	Deck	No
	Piers	No

Figure 8 - Bridge Life Calculation - Input- Output Sheet

In this window the user is asked to choose the characteristics of the bridges that he wants to analyze. It's possible to choose between:

- Steel/Concrete Bridges
- Mono/Overlag Deck Structure
- Open Grating or not

In the bottom-right part it's possible to see the overall maintenance level of the bridge and the consequent expected life (in years).

Another important choice has to be done in this sheet: which kind of trend has to be used for the deterioration rate (figure 9). As said before, it possible to choose between linear, exponential and secant trend. Or sake of simplicity all the analyses, in this work, will be done using the linear one.

Input rate dep			
lin L	exp E	sech S	L
L = linear formula			
E = exponential formula			
S = sech formula			

Figure 9 - Trend Input

The last table that composes this sheet is the “Repair Schedule Aid sheet” (figure 10).

Ln ....Projected life of components after repair n
Lrn ....Time at which rating of component reaches selected repair level Rri
Tn ....Time for nth repair of each component

	Lo	Lro	T1	L1	Lr1	T2	L2	Lr2	T3	L3	Lr3	T4	L4	Lr4	T5
Bearings	43	35	**35**	57	50	**50**	71	64	**65**	85	78	**80**	99	92	**90**
Backwalls	69	57	**55**	103	92	**90**	138	126	**125**	172	160	**160**	206	195	**195**
Abutments	59	47	**45**	82	70	**70**	106	94	**90**	106	106	**105**	106	106	**105**
Wingwalls	73	61	**60**	109	97	**95**	146	134	**135**	182	170	**170**	219	207	**205**
Seats	46	38	**40**	69	61	**60**	92	84	**85**	115	107	**105**	137	130	**130**
Primary M	64	51	**50**	90	77	**75**	116	103	**100**	116	116	**115**	116	116	**115**
Second. M	70	58	**60**	105	93	**95**	140	128	**130**	174	163	**165**	209	198	**200**
Curbs	60	50	**50**	110	100	**100**	160	150	**150**	210	200	**200**	260	250	**250**
Sidewalks	120	100	**100**	220	200	**200**	320	300	**300**	420	400	**400**	520	500	**500**
Deck	173	138	**135**	308	273	**270**	443	408	**405**	443	443	**440**	443	443	**440**
Wear. surf	37	31	**30**	67	61	**60**	97	91	**90**	127	121	**120**	157	151	**150**
Piers	70	56	**55**	97	84	**80**	125	111	**110**	125	125	**125**	125	125	**125**
Joints	69	58	**60**	115	104	**105**	162	150	**150**	208	196	**195**	254	242	**240**

	L5	Lr5	T6	L6	Lr6	T7	L7	Lr7	T8	L8	Lr8	T9	L9	Lr9		
Bearings	113	106	**105**	128	120	**120**	142	135	**135**	156	149	**150**	170	163	Bearings	9
Backwalls	241	229	**230**	275	264	**265**	309	298	**300**	344	332	**330**	378	367	Backwalls	9
Abutments	106	106	**105**	106	106	**105**	106	106	**105**	106	106	**105**	106	106	Abutments	2
Wingwalls	255	243	**245**	292	280	**280**	328	316	**315**	365	353	**355**	401	389	Wingwalls	9
Seats	160	153	**155**	183	176	**175**	206	199	**200**	229	221	**220**	252	244	Seats	9
Primary M	116	116	**115**	116	116	**115**	116	116	**115**	116	116	**115**	116	116	Primary M	2
Second. M	209	233	**235**	279	268	**270**	314	302	**300**	349	337	**335**	384	372	Second. M	9
Curbs	310	300	**300**	360	350	**350**	410	400	**400**	460	450	**450**	510	500	Curbs	9
Sidewalks	620	600	**600**	720	700	**700**	820	800	**800**	920	900	**900**	1020	1000	Sidewalks	9
Deck	443	443	**440**	443	443	**440**	443	443	**440**	443	443	**440**	443	443	Deck	2
Wear. surf	187	181	**180**	217	211	**210**	247	241	**240**	277	271	**270**	307	301	Wear. surf.	9
Piers	125	125	**125**	125	125	**125**	125	125	**125**	125	125	**125**	125	125	Piers	2
Joints	300	288	**290**	346	335	**335**	392	381	**380**	438	427	**425**	485	473	Joints	9

Figure 10 - Repair Schedule Aid Sheet

This calculation sheet is used, together with the Calculation I and Calculation II sheets to show the years in which in which the different components the selected repair rating R_{ri} and so should be repaired.

Matrix I_{ij}

This is one of the most important sheets in the whole software. In fact it contains the Importance Factor Matrix I_{ij} (figure 11). As explained before, thanks to this matrix, the program is able to "understand" how each activity of maintenance affects a given bridge component.

I_{ij}	Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
Debris rem	0.7	0.5	0.2	0.1	0.8	0.5	0.5	0.8	0.8	0.8	0.9	0.1	0.8
Sweeping	0.2	0.1	0.1	0	0.5	0.5	0.5	1	0.8	0.9	1	0.1	1
Clean Drain	0.9	0.9	0.9	0.8	1	1	1	1	1	1	1	0.5	1
Clean abut/piers	1	1	1	0.9	1	0.8	0.8	0	0	0.5	0.5	1	0.5
Clean grating	0	0	0	0	0	0	0	0	0	0	0	0	0
Clean exp jts	1	0.8	1	0.5	1	1	0.8	0.5	0.5	0.9	0.9	0.9	1
Wash deck etc	0.5	0.3	0.2	0	0.6	0.4	0.4	1	0	1	1	0.4	1
Paint	1	0.5	0	0	0.5	1	1	0	0	0.4	0	1	0.5
Spot paint	1	0.5	0	0	0.5	1	1	0	0	0	0	1	0.5
Sidewalk & curb	0	0	0	0	0	0	0	1	1	0.1	0.1	0	0.5
Pavmt & curb seal	1	1	1	0.5	1	1	1	1	1	1	1	0.5	0.5
Elect device maint	0	0	0	0	0	0	0	0	0	0	0	0	0
Mech Comp	1	0.5	0.5	0.2	1	1	1	1	0	0.5	0	1	1
Repl wear surf	0	0.1	0	0	0.1	0.1	0.1	0.5	0.5	1	1	0.1	1
Wash underside	1	1	1	0.5	1	1	1	0	0	0.8	0	1	0.9

Figure 11 - Important Factor Matrix

All terms of this matrix were inserted deterministically thanks to the experience of the Department of Transportation engineers. As already said, this matrix will be the sujbet of study in next chapter. The colorful cells can change value by varying, in "Life" sheet, the bridge features from steel to concrete or from bridge with open gratings to bridge without them.

In this sheet every value I_{ij} is normalized with respect to each columns co that in the K_{ij} matrix (figure 12) the sum of the numbers in each column is equal to 1. By normalizing by column the effectiveness of each activity on a given task is highlighted.

Kij	Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
Debris rem	0.075	0.069	0.034	0.029	0.089	0.054	0.055	0.103	0.143	0.090	0.122	0.013	0.078
Sweeping	0.022	0.014	0.017	0.000	0.056	0.054	0.055	0.128	0.143	0.101	0.135	0.013	0.098
Clean Drain	0.097	0.125	0.153	0.229	0.111	0.108	0.110	0.128	0.179	0.112	0.135	0.066	0.098
Clean abut/piers	0.108	0.139	0.169	0.257	0.111	0.086	0.088	0.000	0.000	0.056	0.068	0.132	0.049
Clean grating	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Clean exp jts	0.108	0.111	0.169	0.143	0.111	0.108	0.088	0.064	0.089	0.101	0.122	0.118	0.098
Wash deck etc	0.054	0.042	0.034	0.000	0.067	0.043	0.044	0.128	0.000	0.112	0.135	0.053	0.098
Paint	0.108	0.069	0.000	0.000	0.056	0.108	0.110	0.000	0.000	0.045	0.000	0.132	0.049
Spot paint	0.108	0.069	0.000	0.000	0.056	0.108	0.110	0.000	0.000	0.000	0.000	0.132	0.049
Sidewalk & curb	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.128	0.179	0.011	0.014	0.000	0.049
Pavmt & curb seal	0.108	0.139	0.169	0.143	0.111	0.108	0.110	0.128	0.179	0.112	0.135	0.066	0.049
Elect device maint	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mech Comp	0.108	0.069	0.085	0.057	0.111	0.108	0.110	0.128	0.000	0.056	0.000	0.132	0.098
Repl wear surf	0.000	0.014	0.000	0.000	0.011	0.011	0.011	0.064	0.089	0.112	0.135	0.013	0.098
Wash underside	0.108	0.139	0.169	0.143	0.111	0.108	0.110	0.000	0.000	0.090	0.000	0.132	0.088

Figure 12 - K_{ij} Matrix

After that, a matrix that contains the multiplication of K_{ij} by M_i is computed (Figure 13). This matrix is one of the key of the program, in fact, the deterioration rate for each component has is a function of the sum (on the column) of $K_{ij} * M_i$.

Kij*Mi	Mj	Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
Debris rem	1.00	0.075	0.069	0.034	0.029	0.089	0.054	0.055	0.103	0.143	0.09	0.122	0.013	0.078
Sweeping	1.00	0.022	0.014	0.017	0	0.056	0.054	0.055	0.128	0.143	0.101	0.135	0.013	0.098
Clean Drain	1.00	0.097	0.125	0.153	0.229	0.111	0.108	0.11	0.128	0.179	0.112	0.135	0.066	0.098
Clean abut/piers	1.00	0.108	0.139	0.169	0.257	0.111	0.086	0.088	0	0	0.056	0.068	0.132	0.049
Clean grating	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0
Clean exp jts	1.00	0.108	0.111	0.169	0.143	0.111	0.108	0.088	0.064	0.089	0.101	0.122	0.118	0.098
Wash deck etc	1.00	0.054	0.042	0.034	0	0.067	0.043	0.044	0.128	0	0.112	0.135	0.053	0.098
Paint	1.00	0.108	0.069	0	0	0.056	0.108	0.11	0	0	0.045	0	0.132	0.049
Spot paint	1.00	0.108	0.069	0	0	0.056	0.108	0.11	0	0	0	0	0.132	0.049
Sidewalk & curb	1.00	0	0	0	0	0	0	0	0.128	0.179	0.011	0.014	0	0.049
Pavmt & curb seal	1.00	0.108	0.139	0.169	0.143	0.111	0.108	0.11	0.128	0.179	0.112	0.135	0.066	0.049
Elect device maint	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0
Mech Comp	1.00	0.108	0.069	0.085	0.057	0.111	0.108	0.11	0.128	0	0.056	0	0.132	0.098
Repl wear surf	1.00	0	0.014	0	0	0.011	0.011	0.011	0.064	0.089	0.112	0.135	0.013	0.098
Wash underside	1.00	0.108	0.139	0.169	0.143	0.111	0.108	0.11	0	0	0.09	0	0.132	0.088

Figure 13 - K_{ij}*M_i

In the last part of the worksheet the matrix K_{ij}*K_{ei} and the value k_{mi} are computed. These are then useful to calculate the life of overall maintenance level of the bridge and the expected life.

Calculation I and II

Calculation I and Calculation II are the two keys sheets of the program. Here, in fact, all the process of deterioration of the bridge components is developed. There are two windows where all the parameters useful for the calculation are computed (figure 14 and figure 15).

	Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
ri0	0.300	0.171	0.143	0.120	0.300	0.167	0.171	0.400	0.400	0.250	0.600	0.167	0.600
ri1	0.050	0.050	0.042	0.050	0.050	0.042	0.050	0.100	0.100	0.083	0.300	0.042	0.200
ri inf	0.020	0.020	0.017	0.020	0.020	0.017	0.020	0.040	0.040	0.033	0.120	0.017	0.080
D1=ri1/ri0	0.167	0.292	0.292	0.417	0.167	0.250	0.292	0.250	0.250	0.333	0.500	0.250	0.333
Dinf=ri inf/rio	0.067	0.117	0.117	0.167	0.067	0.100	0.117	0.100	0.100	0.133	0.200	0.100	0.133
di=sumKjiMj	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Rates(non-dim)													
Linear	0.167	0.292	0.292	0.417	0.167	0.250	0.292	0.250	0.250	0.333	0.500	0.250	0.333
Exp	0.167	0.292	0.292	0.417	0.167	0.250	0.292	0.250	0.250	0.333	0.500	0.250	0.333
Sech	0.167	0.292	0.292	0.417	0.167	0.250	0.292	0.250	0.250	0.333	0.500	0.250	0.333
Rates(dim)													
Linear	-0.050	-0.050	-0.042	-0.050	-0.050	-0.042	-0.050	-0.100	-0.100	-0.083	-0.300	-0.042	-0.200
Exp	-0.050	-0.050	-0.042	-0.050	-0.050	-0.042	-0.050	-0.100	-0.100	-0.083	-0.300	-0.042	-0.200
Sech	-0.050	-0.050	-0.042	-0.050	-0.050	-0.042	-0.050	-0.100	-0.100	-0.083	-0.300	-0.042	-0.200

Figure 14 - Calculation of linear distribution

		Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
dj	i sum KjiMi	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Lio	20	35	35	50	20	30	35	15	15	20	10	30	10
B	(7-Ric)/Lil = ril	0.050	0.050	0.042	0.050	0.050	0.042	0.050	0.100	0.100	0.083	0.300	0.042	0.200
C	A - 1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
D	(7-Ric)/Lio = rio	0.300	0.171	0.143	0.120	0.300	0.167	0.171	0.400	0.400	0.250	0.600	0.167	0.600
X	rate"-(B-D)*C-B"	-0.050	-0.050	-0.042	-0.050	-0.050	-0.042	-0.050	-0.100	-0.100	-0.083	-0.300	-0.042	-0.200
	Lio	20	35	35	50	20	30	35	15	15	20	10	30	10
	Rio	7	7	7	7	7	7	7	7	7	7	7	7	7
	Rcritical	1	1	2	1	1	2	1	1	1	2	1	2	1
	Lil	120	120	120	120	120	120	120	60	60	60	20	120	30
	dRc	2	3	2	3	3	2	3	5	5	4	5	2	4

Figure 15 - Computation Parameters for Calculation

The core of the analysis is shown in (figure 14). Here the computed deterioration rate is used to decrease, year after year, the rating of each component. As soon as the rating R_i reach the threshold R_{ri} it means that the component is not working as it should and then is repaired or replaced. The replacement brings up the rating of the component and so on. The keys components, primary member, Piers, Abutments and Deck can be replaced only twice in the entire life. After that the bridge reaches its expected life.

	Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
Years is service	Rating of component i												
weight	6	5	8	5	6	10	5	1	2	8	4	8	4
0	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
1	6.87	6.90	6.92	6.92	6.87	6.91	6.90	6.78	6.77	6.85	6.54	6.91	6.63
2	6.73	6.81	6.84	6.84	6.74	6.82	6.80	6.56	6.54	6.70	6.09	6.83	6.27
3	6.60	6.71	6.76	6.76	6.61	6.73	6.71	6.35	6.31	6.54	5.63	6.74	5.90
4	6.47	6.61	6.68	6.68	6.48	6.65	6.61	6.13	6.08	6.39	5.17	6.65	5.54
5	6.34	6.51	6.60	6.59	6.34	6.56	6.51	5.91	5.85	6.24	4.71	6.56	5.17
6	6.20	6.42	6.53	6.51	6.21	6.47	6.41	5.69	5.62	6.09	4.26	6.48	4.81
7	6.07	6.32	6.45	6.43	6.08	6.38	6.32	5.47	5.39	5.93	3.80	6.39	4.44
8	5.94	6.22	6.37	6.35	5.95	6.29	6.22	5.25	5.16	5.78	3.34	6.30	4.07
9	5.81	6.12	6.29	6.27	5.82	6.20	6.12	5.04	4.93	5.63	2.88	6.22	3.71
10	5.67	6.03	6.21	6.19	5.69	6.11	6.02	4.82	4.70	5.48	7.00	6.13	3.34
11	5.54	5.93	6.13	6.11	5.56	6.03	5.93	4.60	4.47	5.32	6.54	6.04	2.98
12	5.41	5.83	6.05	6.03	5.43	5.94	5.83	4.38	4.24	5.17	6.09	5.95	2.61
13	5.28	5.73	5.97	5.95	5.30	5.85	5.73	4.16	4.01	5.02	5.63	5.87	2.24
14	5.14	5.64	5.89	5.86	5.16	5.76	5.63	3.95	3.78	4.87	5.17	5.78	1.88
15	5.01	5.54	5.81	5.78	5.03	5.67	5.54	3.73	3.55	4.71	4.71	5.69	5.51
16	4.88	5.44	5.74	5.70	4.90	5.58	5.44	3.51	3.32	4.56	4.26	5.61	5.15
17	4.74	5.34	5.66	5.62	4.77	5.49	5.34	3.29	3.09	4.41	3.80	5.52	4.78
18	4.61	5.25	5.58	5.54	4.64	5.41	5.24	3.07	2.86	4.26	3.34	5.43	4.42
19	4.48	5.15	5.50	5.46	4.51	5.32	5.14	2.85	2.63	4.10	2.88	5.34	4.05
20	4.35	5.05	5.42	5.38	4.38	5.23	5.05	2.64	7.00	3.95	7.00	5.26	3.68
21	4.21	4.95	5.34	5.30	4.25	5.14	4.95	2.42	6.77	3.80	6.54	5.17	3.32
22	4.08	4.86	5.26	5.21	4.12	5.05	4.85	2.20	6.54	3.65	6.09	5.08	2.95
23	3.95	4.76	5.18	5.13	3.98	4.96	4.75	1.98	6.31	3.49	5.63	5.00	2.59
24	3.82	4.66	5.10	5.05	3.85	4.87	4.66	1.76	6.08	3.34	5.17	4.91	2.22
25	3.68	4.56	5.02	4.97	3.72	4.78	4.56	6.55	5.85	7.00	4.71	4.82	5.85
26	3.55	4.47	4.95	4.89	3.59	4.70	4.46	6.33	5.62	6.85	4.26	4.73	5.49
27	3.42	4.37	4.87	4.81	3.46	4.61	4.36	6.11	5.39	6.70	3.80	4.65	5.12
28	3.28	4.27	4.79	4.73	3.33	4.52	4.27	5.89	5.16	6.54	3.34	4.56	4.76
29	3.15	4.18	4.71	4.65	3.20	4.43	4.17	5.67	4.93	6.39	2.88	4.47	4.39
30	3.02	4.08	4.63	4.57	3.07	4.34	4.07	5.45	4.70	6.24	7.00	4.39	4.03
31	2.89	3.98	4.55	4.48	2.94	4.25	3.97	5.24	4.47	6.09	6.54	4.30	3.66
32	2.75	3.88	4.47	4.40	2.80	4.16	3.88	5.02	4.24	5.93	6.09	4.21	3.29
33	2.62	3.79	4.39	4.32	2.67	4.08	3.78	4.80	4.01	5.78	5.63	4.12	2.93
34	2.49	3.69	4.31	4.24	2.54	3.99	3.68	4.58	3.78	5.63	5.17	4.04	2.56
35	2.36	3.59	4.23	4.16	2.41	3.90	3.58	4.36	3.55	5.48	4.71	3.95	6.20
36	2.22	3.49	4.16	4.08	2.28	3.81	3.48	4.15	3.32	5.32	4.26	3.86	5.83
37	2.09	3.40	4.08	4.00	2.15	3.72	3.39	3.93	3.09	5.17	3.80	3.78	5.46
38	1.96	3.30	4.00	3.92	2.02	3.63	3.29	3.71	2.86	5.02	3.34	3.69	5.10
39	1.83	3.20	3.92	3.84	1.89	3.54	3.19	3.49	2.63	4.87	2.88	3.60	4.73
40	3.69	3.10	3.84	3.75	4.76	3.46	3.09	3.27	7.00	4.71	7.00	3.51	4.37

Figure 16 - Rate for each Components over the years

The last important table is the one that compute the number of time a component is replaced or repaired. This table (figure 15), computed thanks to “Calculation I” and “Calculation II” sheets will be used in “Costs” to compute the annualized expenditure due to repair and replacement.

83	Calculated Life of Bridge: 83 yrs.												
Calculation of Hi @ life of bridge:	1	1	1	1	1	1	1	1	1	1	1	1	1
Implem. of repairs of comp.i within life	3	2	2	1	2	2	2	3	4	2	8	2	7
Tc1	1	1	1	1	1	1	1	1	1	1	1	1	1
Tc2	1	1	1	0	1	1	1	1	1	1	1	1	1
Tc3	1	0	0	0	0	0	0	1	1	0	1	0	1
Tc4	0	0	0	0	0	0	0	0	1	0	1	0	1
Tc5	0	0	0	0	0	0	0	0	0	0	1	0	1
Tc6	0	0	0	0	0	0	0	0	0	0	1	0	1
Tc7	0	0	0	0	0	0	0	0	0	0	1	0	1
Tc8	0	0	0	0	0	0	0	0	0	0	1	0	0
Tc9	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 17 - Repairs count

Costs

The last input/output data sheet is the "Costs" one (figure 18). In the upper part of this sheet, the user can insert the values of costs for the different kind of repairs associated with the different components. In the upper left part there is a table that report in summary three values for each maintenance activity: the actual level of maintenance performed, the cost per square foot if a full maintenance is done(C_{mli}) and the final cost per square foot at the given level of maintenance (C_{mi}).

COST CALCULATION - NEW YORK CITY BRIDGES

MAINTENANCE COSTS per sqft

Maintenance Task	Cmli	Mi	Cmi
Debris Removal	0.15	1.00	0.15
Sweeping	0.04	1.00	0.04
Cleaning Drainage	0.06	1.00	0.06
Clean Abutm.& Piers	0.18	1.00	0.18
Clean Open Grat. De	0.00	1.00	0.00
Clean Expansion Joi	0.21	1.00	0.21
Wash Deck & Splash	0.09	1.00	0.09
Paint	2.35	1.00	2.35
Spot Paint	1.55	1.00	1.55
Sidewalk & Curb Rep	0.09	1.00	0.09
Pavem. & Crack Sea	0.15	1.00	0.15
Elect Device Maint.	0.07	1.00	0.07
Mech. Comp. Maint.	0.07	1.00	0.07
Replace Wearing Su	0.09	1.00	0.09
Wash Underside	0.86	1.00	0.86
	5.96		5.96

REPAIR COSTS

Component	dRi	Cost per repair		Total annual	/sqft of br	Repairs
Bearings	2	100,000	$ each	14,666.67	0.49	2
Backwalls	3	100,000	$ each	1,333.33	0.04	1
Abutments	2	100,000	$ each	2,666.67	0.09	2
Wingwalls	3	100,000	$ each	1,333.33	0.04	1
Bridge seats	3	100,000	$ each	1,333.33	0.04	1
Primary m.	2	100.00	$/sqft	40,000.00	1.33	2
Second. m.	3	100.00	$/sqft	20,000.00	0.67	1
Curbs	5	10.00	$/ft	160.00	0.01	2
Sidewalks	5	10.00	$/sqft	2,880.00	0.10	2
Deck	4	80.00	$/sqft	32,000.00	1.07	2
Wearing surf	5	12.00	$/sqft	21,600.00	0.72	9
Piers	2	100,000	$ each	12,000.00	0.40	2
Joints	4	25,000	$ each	10,500.00	0.35	7
					5.35	

BRIDGE DATA

Surface area - sqft:	30,000	# spans:	10

ANNUALIZED COST RESULTS

Maintenance Level	100.0 %
Expected Life	150 years

Maintenance Costs per sqft.:	5.96
Repair Costs per sqft:	5.35
Replacement Costs per sqft:	12.00
NYC Costs per sqft:	7.24
User Costs per sqft:	8.77
TOTAL ANNUAL COST / SQFT	**39.32**

NYC COSTS

Repair based	25.00	$ / sqft
Cny,rp =	5.67	$ / sqft / year
Rating based	20.00	$ / sqft
Cny,r =	1.58	$ / sqft / year

USER COSTS

Repair based	30.00	$ / sqft
Cu,rp =	6.80	$ / sqft /y
Rating based	25.00	$ / sqft
Cu,r =	1.97	$ / sqft /y

REPLACEMENT COST

Present cost:	1,800.00	$ / sqft

Figure 18 - Costs Sheet

In the bottom part it's possible to insert the bridge data for the bridge that we are analyzing and the repair, replacement and user costs.

In the bottom left part of the sheet there is a summary table reporting for our bridge, all the detailed cost of the sum of them: the Total Annual Cost per square foot.

Summary

In this sheet all the input data and the results of the analysis are reported (figure 19). In this simple table all the analysis information are reported. In fact all the unit costs for replacement and repairs are reported as well as the input bridge data or the detailed results with the total annualized cost.

Components & Repair Costs			Tasks, Cost at Full Maintenance & Effectiveness			
Bearings	100,000	$ each		Cmli		Kmi/Cmli
Backwalls	100,000	$ each		$/ft²	$/m²	
Abutments	100,000	$ each	Debris Removal	0.15	1.63	0.790
Wingwalls	100,000	$ each	Sweeping	0.04	0.43	1.223
Bridge seats	100,000	$ each	Clean Drainage	0.06	0.61	2.020
	$/ft²	$/m²	Clean Abutments and Pie	0.18	1.95	0.572
Primary members	100	1,080	Clean open Grating Deck	0.00	0.04	0.000
Second. members	100	1,080	Clean Expansion Joints	0.21	2.29	0.512
Curbs	10	30	Wash Deck & Splash Zor	0.09	1.02	0.583
Sidewalks	10	110	Paint	2.35	25.27	0.025
Deck	80	860	Spot Paint	1.55	16.65	0.035
Wearing surf.	12	130	Sidewalk & Curb Rep	0.09	0.93	0.125
Piers	100,000	$ each	Pavement & Crack Seal	0.15	1.64	0.717
Joints	25,000	$ each	Elect Device Mnt	0.07	0.78	0.000
			Mech Component Maint	0.07	0.71	1.244
Input Bridge Data			Wearing Surf replacement	0.09	0.97	0.357
	ft²	m²	Wash Undrside	0.86	9.25	0.119
Bridge Area	30,000	2,790	RESULTS			
No. of Spans	10		Maintenance Level		100.0	%
Material (steel/conc	s		% of full maintenance cost		100.0	%
Open Gratings (y/n	n		Deterioration Rate used		E	
Deck (mono/overlay	o		Expected Life		150	years
Deck joints (y/n)	y				$/ft²/yr	$/m²/yr
	$/ft²	$/m²	Maintenance Costs		5.96	64.15
User cost - repair based	30	323	Repair Costs		5.35	57.58
- rating based	25	269	Replacement Costs		12.00	129.17
NYC cost - repair based	25	269	NYC Costs		7.24	77.95
- rating based	20	215	User Costs		8.77	94.39
Replacement Cost	1,800	19,380	TOTAL ANNUAL COST		39.32	423.23

Figure 19 - Summary Table A

Graphs

The others sheets contain graph like the annual cost per square foot subdivided in maintenance, repair and replacement cost, the unit maintenance cost VS the level of maintenance in percentage, the expected live VS the maintenance level and so on. It's possible to have an idea about how this graphs looks like with the following pictures.

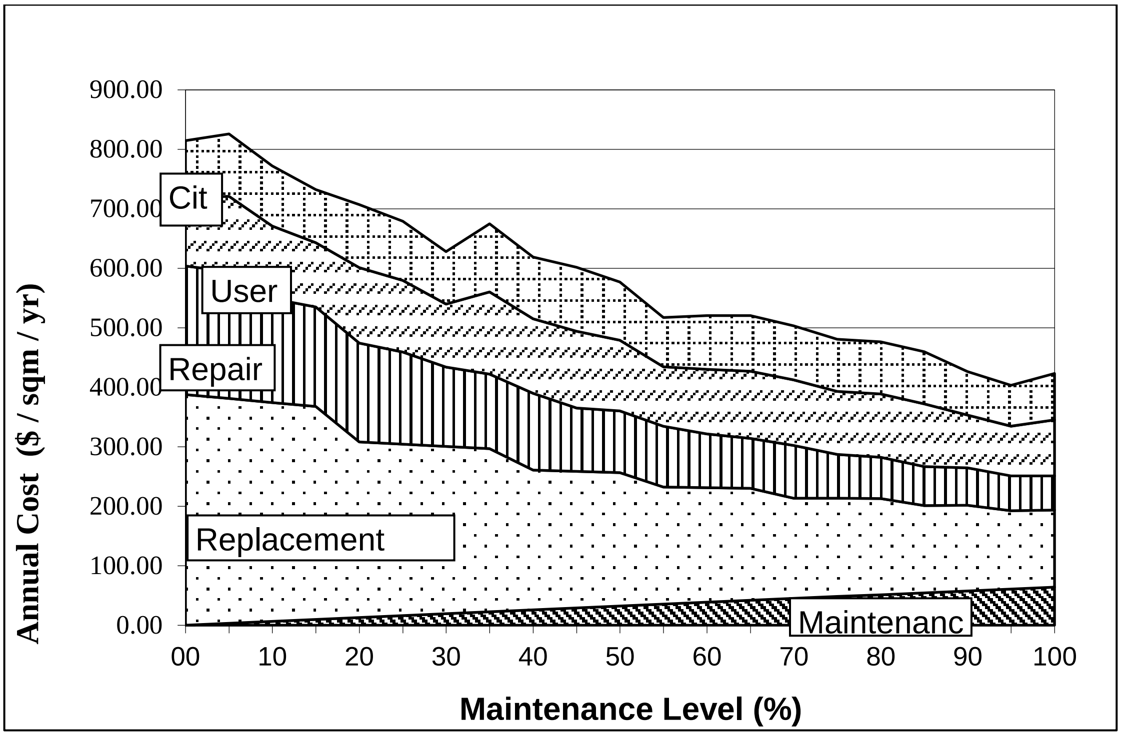


Figure 20 - Maintenence Level VS Annual Cost per square meter for uniform changes of Mi's

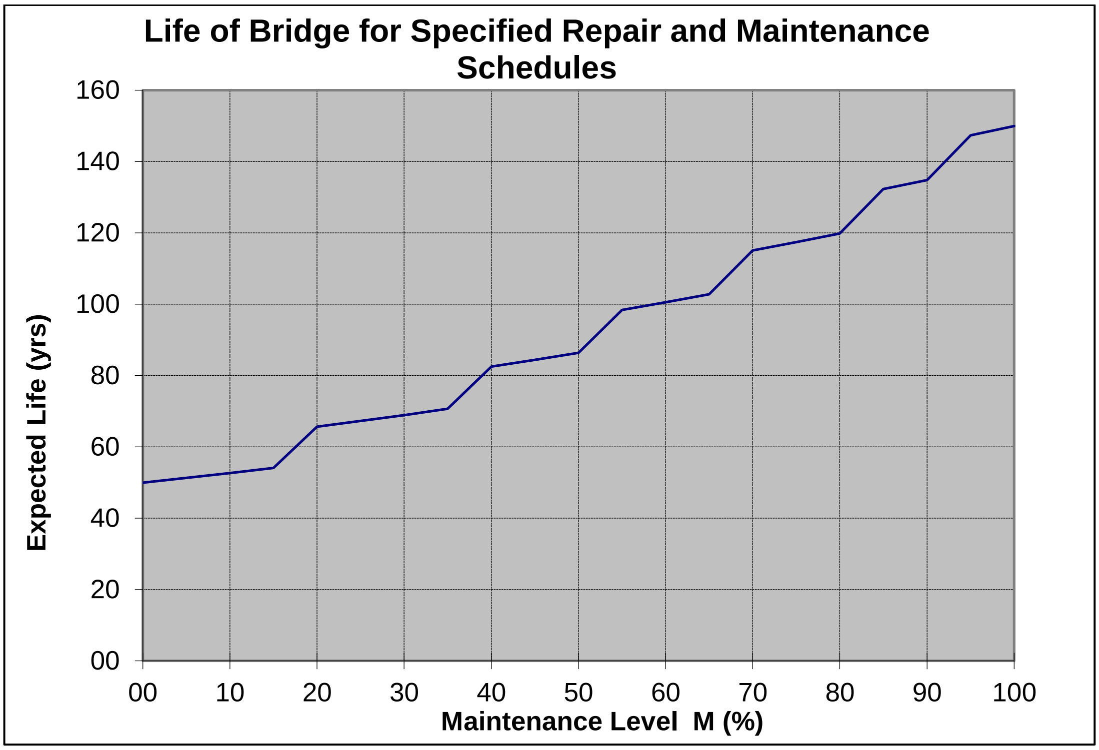


Figure 21 - Expected Life VS Maintenance Level

Advantages of this Software

As all the programs this software presents some advantages and some disadvantages that we will highlight and try to correct by proposing some solutions. In the following paragraph all the advantages will be listed.

User friendly and speed

One of the biggest advantages of this software is the velocity with which it's possible to running different scenarios (easily changing the parameters) and thus analyze different kind of bridge situations. Moreover, being an excel spreadsheet, it can be quickly understood by all kind of users. The interaction cell, in which the user can add or modify data are few and all easily identifiable having a colored fill.

New York City Cost & User Cost

The program, as explained before, was thought in order to take into account the NYC cost and the User cost. These two kinds of costs were inserted to make the simulations more realistic. In fact they consider the discomfort due to a low bridge rating (R) as well as the time for the city department to make repairs or replacement of part of the bridges. Once the two costs are well calibrated based on people survey and detailed analyses they can become an important tool to run accurate simulations.

Broad range of parameter and components

The program permits to play around with a lot of parameters. Acting on 13 different bridge components and 15 possible tasks it has the possibility to launch an optimization analysis in order solve problems of annual budget allocation for New York City. In fact a limited maintenance budget resource should generally be allocated so as to maximize the overall maintenance level M. The level of maintenance M, takes into account subjective estimation of the I_{ij} matrix coefficient and so, as we'll see in the "disadvantage chapter". It is also seen here, however, that there are differences in annualized cost among the various possible allocations at similar values of M.

Disadvantages and Problems of this Software

As all the software at their first version, also the bridge management software that we are analyzing has some questions to address. There are mainly three problems that should be correct. In the next paragraph, these three problems will be presented and in the next chapter a possible solutions will be presented.

Uniform level of maintenance

As we said in the past chapter, the user, when he/she is running an analysis, can choose which levels of maintenance performing for all the tasks. In fact, for every task the user can choose a level of maintenance that goes from 0% (no maintenance) to 100% (full maintenance or more). The full maintenance for every task is a utopia because it is almost impossible that the Department of Transportation had enough budgets to allocate in maintenance. It has also to be said that the M = 100% is the level of full maintenance evaluated by a group of specialist but it's not the actual maximum level that could be done, as it will be shown in the last chapater. The chief engineer, by using also this kind of software, will have to decide how to best spend the budget by allocating the money in the task that better improve the total rating of the bridge.

The problem would rise if all the levels of maintenance are set at the same percentage. If this happened the Index Factor Matrix I would have no influence on the rate of deterioration r_i and therefore no influence on the overall bridge rating. This problem can be easily explained mathematically. In fact, as it was illustrated in the chapter 2, the deterioration rate, for every component, goes as:

$$r_i = (r_{i1} - r_{i0}) \sum_{j=1}^{15} k_{ij} M_i + r_{i0}$$

Where:

- r_{i1} = deterioration rate if a full maintenance is done
- r_{i0} = deterioration rate if no maintenance is performed
- $k_{ij}M_i$ = summation of the products between the index factor I and the maintenance level

- r_i = rate of deterioration for a given components following the linear trend

The normalized index factors k_{ij} are normalized by the columns. This means that for every different component, the summation of the k is equal to 1. If there is an uniform maintenance level, therefore all the M_i are equal, and then the summation for all the task $k_{ij}M_{ij}$ won't be dependent anymore on the k_{ij} but it will just be function of the maintenance level.

For example, supposing that we are making a uniform level of maintenance M = 75 %, for the primary member the index factor are:

	Iij	Kij	Kij*Mi
Debris rem	0.50	0.05	0.04
Sweeping	0.50	0.05	0.04
Clean Drain	1.00	0.11	0.08
Clean abut/piers	0.80	0.09	0.06
Clean grating	0.00	0.00	0.00
Clean exp jts	1.00	0.11	0.08
Wash deck etc	0.40	0.04	0.03
Paint	1.00	0.11	0.08
Spot paint	1.00	0.11	0.08
Sidewalk & curb	0.00	0.00	0.00
Pavmt & curb seal	1.00	0.11	0.08
Elect device maint	0.00	0.00	0.00
Mech Comp	1.00	0.11	0.08
Repl wear surf	0.10	0.01	0.01
Wash underside	1.00	0.11	0.08
	SUM Kij*Mi =		**0.75**

Table 4- Example Uniform Maintenance

As it's possible to observe the level summation of $K_{ij}*M_i$ is equal to 75% that exactly the uniform level of maintenance done on the bridge. This means that, as explained before, the rate of deterioration is depends only on M and not on the Importance Factor Matrix. A possible solution for this problem will be addressed in the next chapter.

Few numbers of repair for the APPD components

The second question that will be addressed of this software is related with the method that it uses to determine the expected life of the bridge. As it was explained in chapter 2 the program runs the analysis until when the rating (R_i) of a primary component reaches the critical threshold R_{ic}. The critical components are Abutments, Primary member, Piers and Deck (APPD). As soon as one of these critical ratings is reached, the component fails and with it the whole bridge. In order to avoid that a general component goes under its threshold value, as soon as the given component rating (R_i) reaches the rating of repair (R_{ri}), another threshold decided by the user, the component is repaired.

The lack in stringency of the software is due to the fact the APPD components can be potentially repaired only 2 times in their life-span. The programmer had to impose this trick in order to make the analysis finish and not to go ahead to infinity. In fact, without this trick (table 5), every component, as soon as it reaches the R_{ri} is repaired and the critical threshold R_{ic} would never be reached.

Allowable Repairs and Relative Year									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
Bearings	70	95	125	150	180	205	235	260	290
Backwalls	75	125	170	215	260	310	355	400	445
Abutments	70	110							
Wingwalls	85	130	180	230	280	330	380	430	480
Bridge seats	70	110	150	195	235	275	320	360	400
Primary memb.	70	105							
Second. memb.	75	125	170	215	260	310	355	400	445
Curbs	35	70	105	140	175	210	245	280	315
Sidewalks	35	70	105	140	175	210	245	280	315
Deck	35	70							
Wearing surf.	15	30	45	55	70	85	100	110	125
Piers	70	105							
Joints	20	35	50	65	85	100	115	130	145

Table 5 - Allowable Repairs and Relative Year

Even if this method permits to make the simulation ends given a reasonable expected life for the bridge, it is not engineering meaningful. In fact, as all the components of the bridges can be repaired all the times their $R_i < R_{ri}$ so should be allow to the APPD ones. It doesn't make sense that they could be repair or replace only two times in the life of the bridge.

In order to make more accurate the program, deleting this end process but always staying in realistic range of life span, the entire "end-process" should be modify. An alternative solution and end process will be presented in the following chapter.

The component rating R_i is independent from the components weight

As explained in the previous paragraph, the program runs the analysis until when the component rating (R_i) of one among the Deck, Primary Member, Abutments or Piers reaches the critical rating (R_{ic}).

It's possible to perceive, by playing around with the software, that the component rating R_i is related in any way with the component normalized weight of the component with respect to the overall bridge components. This practically means that the importance a given component with respect to the other ones doesn't influence the expected life of the bridge therefore the annual cost of maintenance. As previously said, it's possible to assign at each component an importance factor from 1 to 10 (table 6). These factors, once normalized with respect to all the other ones, allow immediately to understand which are the most important components for the bridge correct behavior and which ones are not.

Component	Weight	Kei
Bearings	6	0.083333
Backwalls	5	0.069444
Abutments	8	0.111111
Wingwalls	5	0.069444

Bridge seats	6	0.083333
Primary members	10	0.138889
Second. Members	5	0.069444
Curbs	1	0.013889
Sidewalks	2	0.027778
Deck	8	0.111111
Wearing surface	4	0.055556
Piers	8	0.111111
Joints	4	0.055556

Table 6 - Component Importance

In this table is highlighted in red the most important component that naturally is the primary member and the lowest one that are the sidewalks.

For a more accurate representation, the importance of the components should interact with the deterioration rate. A new approach to determine the failure of a components as well as the failure of the whole bridge will be presented in the next chapter.

Solutions for problems highlighted in chapter 3

In this chapter, plausible solution to the problems highlighted in the previous chapter will be investigated and presented. As we said there are three main problems that are the independence of the of the deterioration rate from the normalized importance factor and the strictly dependence on the uniform maintenance level, the fact that in not function of the importance of the bridge components and the max number of repairs to which the abutment, the primary member, the piers and the deck are subjected.

Significance of independence of M when uniform

As already said the maintenance problem occurs when every task is done at the same percentage of maintenance. This is very clear if we look at the formula that define the deterioration rate:

$$r_i = (r_{i1} - r_{i0}) \sum_{j=1}^{15} k_{ij} M_i + r_{i0}$$

Where:

- r_{i1} = deterioration rate if a full maintenance is done
- r_{i0} = deterioration rate if no maintenance is performed
- $k_{ij}M_i$ = summation of the products between the index factor I and the maintenance level
- r_i = rate of deterioration for a given components following the linear trend

Thinking about this from a physical prospective it's possible to realize that it is not really a problem. In fact this approach makes sense. If the level of maintenance is uniform it means that all the tasks, from debris removal to wash underside are executed at the same level. If these are done with the same intensity it doesn't matter how much one of this is important for a given bridge component with respect to the other because at the end of the day all the task, the less and the more important ones, will done at the same level.

In order to make the reader understand this concept, a small example is shown below.

The example is done by simplifying the software and by assuming that our system (bridge) has only two components and there are only three tasks doable on them. For sake of simplicity the two components are called "component 1" and " component 2" while the tasks are "task 1", "task 2" and "task 3".

An Importance factor matrix for this simplify system is assumed (figure 22) as well as a realistic uniform level of maintenance for all the tasks (M = 80 %).

I_{ij}	Comp. 1	Comp. 2
Task A	0.5	0.3
Task B	1	0.5
Task C	0	0.1
Sum	1.5	0.9

Figure 22 - Importance Factor Matrix for example

By following the procedure illustrated by (Testa & Yanev) every I_{ij} factor is normalized with respect to the column (every I_{ij} factor is devided by the sum or the column) to have the K_{ij} factor that are reported in (figure 23).

Kij	Comp. 1	Comp. 2
Task A	0.33	0.33
Task B	0.67	0.56
Task C	0.00	0.11

Figure 23 - Normalized Importance Factor Matrix

And at the end, the last step is done: every K_{ij} factor is multiplied by the level of maintenance established for the relative task (in this case M = 0.8) and the $K_{ij}*M_i$ values are found (figure 24).

$K_{ij}*M_i$	M_j	Comp. 1	Comp. 2
Task A	0.80	0.27	0.27
Task B	0.80	0.53	0.44
Task C	0.80	0.00	0.09
sum KijMi		0.80	0.80

Figure 24 - $K_{ij}*M_i$ Matrix

Once the Kij*Mi matrix is done it's possible to do the sum of this elements and, as it's possible to see in the last row, are both equal. In fact, it's possible to set whatever importance factor for a given element but if the level of maintenance is equal for all the task it doesn't influence the deterioration rate.

All the maintenance task are done at a given level, for example M = 80%, and so every element will be effected by an equal maintenance, in this case 80%.

By summarizing, the importance factor matrix is a very important tool to analyze and model the behavior and the response of different maintenance tasks over a bridge.

Solution to the fact that k should be function of k_{ei}

As explained in the previous chapter, it's strange that the both the deterioration rate and the bridge failure mode are not function at all of the relative importance of each bridge components, with respect to the other ones. If a component, for example the deck, is more important than another one, let's say the curbs, it should be considered in the calculation.

This solution that will be presented here is only one among the possible ones. The conceptual change that will be illustrated is relative to the introduction of the K_{ei} (the normalized weight of the bridge components) in the factor that decides the failure of the bridge.

The solution is a new failure test different from the previous one. By defining the following quantities:

$$A = \sum_{i=1}^{4} k_{ei} \cdot R_{APPDi}$$

$$B = \sum_{i=1}^{13} k_{ei} \cdot R_{i}$$

$$S = \sum_{i=1}^{4(APPD)} k_{ei} \cdot R_{ci}$$

$$T = \sum_{i=1}^{13} k_{ei} \cdot R_{ci}$$

The failure will be governed by the following rule. There will be failure when:

$$\text{MIN } (A;B) < \text{MAX } (S;T)$$

Every critical rating components R_{ci} is multiply for the relative normalized weight K_{ei}. In this way the relative importance of each component with respect to the others, enters in the calculation. Then, as it was said before, there will be establish two new failure limits. The first is due to the sum of the K_{ei}*R_{ic} for all the components while the other is the sum of K_{ei}*R_{ic} for only the APPD components. This calculation is illustrated in the table 7.

Component	Ric	Weight	Kei	Kei * Ric
Bearings	1	6	0.083	0.083
Backwalls	1	5	0.069	0.069
Abutments	2	8	0.111	0.222
Wingwalls	1	5	0.069	0.069
Bridge seats	1	6	0.083	0.083
Primary members	2	10	0.139	0.278
Second. Members	1	5	0.069	0.069
Curbs	1	1	0.014	0.014
Sidewalks	1	2	0.028	0.028
Deck	2	8	0.111	0.222
Wearing surface	1	4	0.056	0.056
Piers	2	8	0.111	0.222
Joints	1	4	0.056	0.056
			SUM_{TOT}	**1.472**
			SUM_{APDD}	**0.944**

Table 7 - New Failure Test Index

These two numbers will be compared with deterioration rating at every year. And, in particular, the first one will be compared with the weighted average of the 13 component's deterioration rates while the second value (SUM_{APPD}) will be compared with the weighted average of the four most important components: abutments, piers, primary member and deck. As soon as one of these two quantities reaches one of the two new threshold values, the bridge fails.

This new kind of verification permits to make more accurate analyses and to consider also, as an important parameter, the importance of a given component with respect to the others.

It has been possible to add the part that allows to verify the failure of the bridge and its relative expected life. Further implementation of the software will allow to find also other important values such as the consequent total annual cost of maintenance, replacement, repairs and add costs.

In order to give an idea about the changes that there are in the expected life, an example is proposed. A uniform level of maintenance is made increase from zero to 100% and the expected life is reported for both methods. In the figure 25 there are the two trends of this analysis.

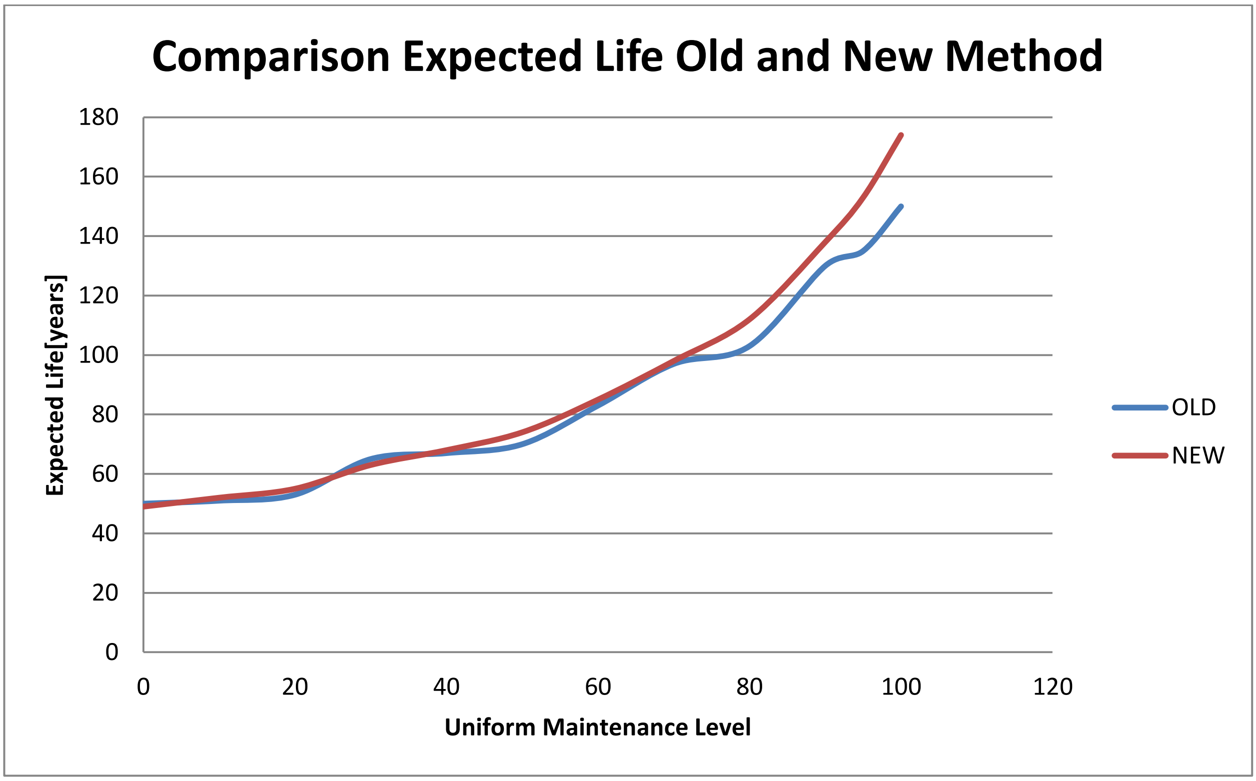


Figure 25 - Expected Life for Old and New Methods

As it's possible to see, for the most used level of maintenance (above the 60%) the new method of failure test gives a longer expected life. It will be implemented then.

Once that the software is updated with the annual cost it will be possible to evaluate if this new kind of failure test is better or not with respect to the old one.

Solution number of repair for APPD members

The limitation given by this problem is that the maximum expected life that is possible to reach using the software is 150 years. Is that a realistic value of expected life?

All around the world there are bridges that have a much higher life than 150 years, it's possible to mention the Ponte Vecchio (figure 26) in Florence as well as the majority of the Venice bridges.

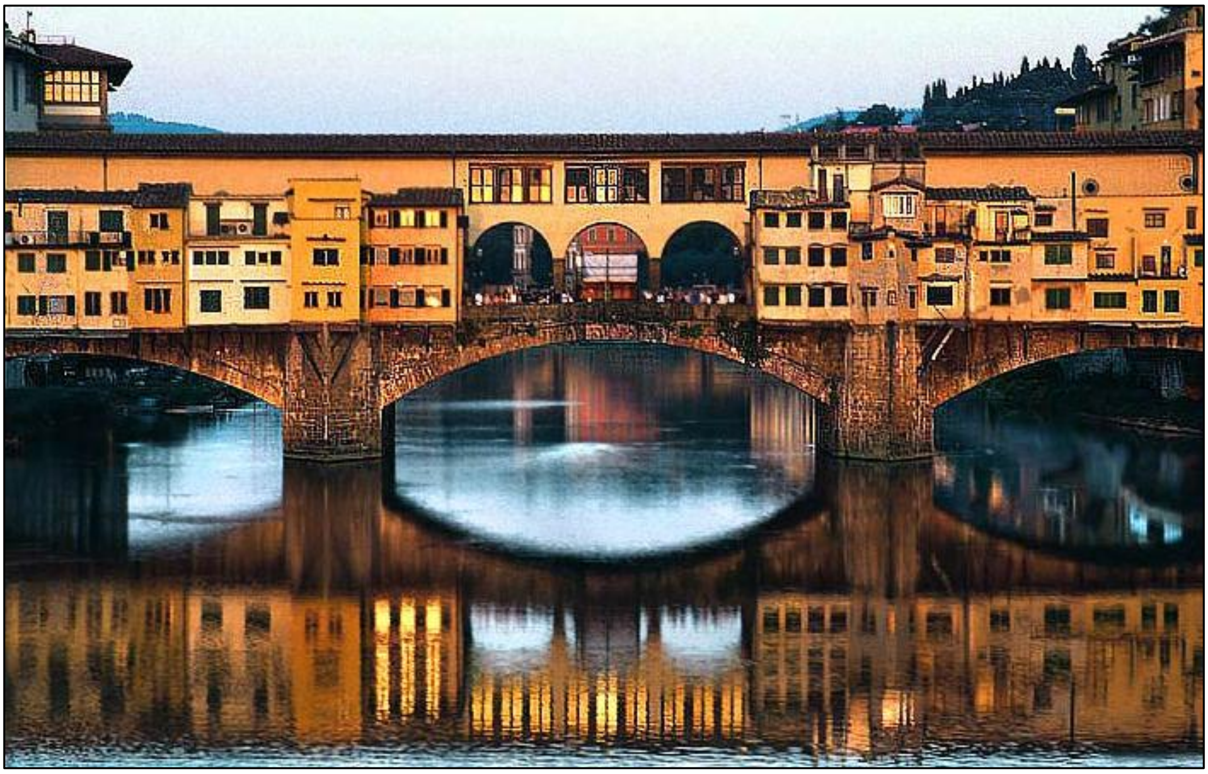


Figure 26 - Ponte Vecchio – Florence

Unfortunately that kind of bridges is different. The today bridges were and are built with other intents. They have to support huge loads given by multiple lines of car and trucks and sometimes also subway trains. They are subjected to great value of bending moment, torsion and axial force and especially they have to deal with fatigue due to dynamic loads. It's easy to understand that they are subjected a more repairs and replacements during their life. However, the replacement operations, especially for primary components such as primary member, piers, abutments and deck, are not easy at all. Moreover they can't assure a completely new level of status. Every time that one of these APPD elements is replacement the bridge decreases the overall rating R.

Although it would be possible to modify the program in order to do not limit the number of repairs that is possible to do on the abutments, the primary member, the piers and the deck this operation is not suggested. In order to do that table 8 would have be modified increasing the number of repairs allowed.

Allowable Repairs and Relative Year									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th
Bearings	70	95	125	150	180	205	235	260	290
Backwalls	75	125	170	215	260	310	355	400	445
Abutments	70	110							
Wingwalls	85	130	180	230	280	330	380	430	480
Bridge seats	70	110	150	195	235	275	320	360	400
Primary memb.	70	105							
Second. memb.	75	125	170	215	260	310	355	400	445
Curbs	35	70	105	140	175	210	245	280	315
Sidewalks	35	70	105	140	175	210	245	280	315
Deck	35	70							
Wearing surf.	15	30	45	55	70	85	100	110	125
Piers	70	105							
Joints	20	35	50	65	85	100	115	130	145

Table 8 - Allowable Repairs and Relative Year

Analyses

In this chapter some results of relevant analyses ran with this software will be presented. In order to highlight the difference between the old standard software and the modified one the same analyses will be done using both the version of the software. In the first section will be shown the results due to the normal program while in the last section of this chapter will be presented the results from the modified program.

For both the kind of analyses the same bridge and the same unit cost will be used. Bridge sample and unit cost are presented in the following paragraphs.

Bridge sample for analyses

An analysis is different from another one based on the parameter that you put as variable data. Most important are the bridge data, that define the dimension, type, material and characteristic of the bridge and the cost data, that given the unit cost for repair, replacement and maintenance of components.

Input Bridge Data

In order to run analyses it needed to choose the kind and the dimension of the bridge to analyze. In order to make a realistic example, a standard bridge that can be found in New York City area is chosen. The characteristics of the bridge are list here:

- Bridge Area = 50 000 ft^2 (equal to 2 790 m^2)
- 10 spans
- Material = Steel with joints
- Overlay Deck
- With Opening Gratings

Input Components and Repairs Costs

Every analysis has to account, as also said before, of costs of replacement and repair of single components or whole bridges. The unit costs are summarizing in the following list. All the values are an average of real money that the Department of Transportation of New York City usually spends to accomplish a given task. These unit costs were estimated in a study at Columbia University during 1999.

- Bearings 100 000 $ each
- Backwalls 100 000 $ each
- Abutments 100 000 $ each
- Wingwalls 100 000 $ each
- Bridge seats 100 000 $ each
- Primary member 100 $/ft^2
- Secondary member 100 $/ft^2
- Curbs 10 $/ft^2
- Sidewalks 10 $/ft^2
- Deck 80 $/ft^2
- Wearing Surface 12 $/ft^2
- Piers 100 000 $ each
- Joints 25 000 $ each

New York Cost & User Cost

Among all the other data that have to be specified there are the New York Cost and the User Cost. As already explained they try to take into account the discomfort that a replacement or a repair makes to the city or to the citizens.

The two costs are here summarized:

- New York City Cost
  - Repair Based: 25.00 $\$/ft^2$
  - Rating Based: 20.00 $\$/ft^2$
- User Cost
  - Repair Based: 30.00 $\$/ft^2$
  - Rating Based: 25.00 $\$/ft^2$

Replacement Cost

The cost due to a replacement of a component is set as 1800 $\$/ft^2$.

Standard Software Analyses

In this section different kind of analyses, ran with the standard software, will be presented. The program is the one presented in the second chapter with the "problems" highlighted in the third chapter.

Utopian Full Maintenance

Here is presented the result due to a hypothetical analysis where a full maintenance of 100 % is done on the bridge. As we already said several time this level of maintenance is impossible to be reached in New York City due to its cost. This would have been possible if the full maintenance had done, on every bridge, from when they were built. Unfortunately there was a long period in which engineers didn't think a regular maintenance was so important for the life of the bridge and they preferred to repair or replace a piece when it failed to prevent that it did.

A full maintenance, when done correctly, is the one that brings to the longer expected life (in this software fixed in 150 years) and in the lowest total annual cost (based on the value estimated by the specialist and not based on the software optimizations). This value, that is the sum of annualized repair, replacement, user, New York City cost plus the annual maintenance cost figure 26), is much lower to respect a "realistic maintenance" one to do the small replacement cost.

Maintenance Level	100.0	%
Expected Life	150	years
Maintenance Costs per sqft.:	$	5.96
Repair Costs per sqft:	$	4.72
Replacement Costs per sqft:	$	12.00
NYC Costs per sqft:	$	7.24
User Costs per sqft:	$	8.77
TOTAL ANNUAL COST / SQFT	$	38.69

Figure 27 - Annualized Costs Table

maintenance-level for task		Kmi
1.00	Debris Removal	0.110
1.00	Sweeping	0.045
1.00	Cleaning Drainage	0.105
1.00	Clean Abutments& Piers	0.095
1.00	Clean Open Grating Deck	0.084
1.00	Clean Expansion Joints	0.100
1.00	Wash Deck & Splash Zone	0.050
1.00	Paint	0.054
1.00	Spot Paint	0.050
1.00	Sidewalk & Curb Repair	0.010
1.00	Pavement & Crack Sealing	0.100
1.00	Elect Device Maintenance	0.000
1.00	Mech. Component Maint.	0.075

1.00	Replace Wearing Surfaces	0.030
1.00	Wash Underside	0.093

Figure 28 - Maintenance at 100%

Standard Maintenance

The following result can be considered as a reference for all the analyses that will be shown. This is a realistic level of maintenance that can be done on a bridge in New York City. As then reported in (table 10) the overall level of maintenance is 78.6 % (a 72% of the hypothetical full maintenance cost) and the consequent expected life is equal to 104 years.

maintenance-level for task		Kmi
0.75	Debris Removal	0.110
0.95	Sweeping	0.045
0.80	Cleaning Drainage	0.105
0.75	Clean Abutments& Piers	0.095
0.90	Clean Open Grating Deck	0.084
0.80	Clean Expansion Joints	0.100
0.75	Wash Deck & Splash Zone	0.050
0.60	Paint	0.054
0.75	Spot Paint	0.050
0.75	Sidewalk & Curb Repair	0.010
0.75	Pavement & Crack Sealing	0.100
0.90	Elect Device Maintenance	0.000
0.65	Mech. Component Maint.	0.075
0.95	Replace Wearing Surfaces	0.030
0.90	Wash Underside	0.093

Figure 29 - Standard Maintenance Level

That gives the following results:

RESULTS		
Maintenance Level	78.6	%
% of full maintenance cost	72.0	%
Deterioration Rate used	L	
Expected Life	104	years
	$\$/ft^2/yr$	$\$/m^2/yr$
Maintenance Costs	4.29	46.18
Repair Costs	7.07	76.1
Replacement Costs	17.37	186.97
NYC Costs	9.46	101.81
User Costs	11.43	122.98
TOTAL ANNUAL COST	49.62	534.05

Table 9 - Costs of Standard Analysis

Comparison between Full Maintenance and Standard One

In this small section the differences between realistic values of maintenance analysis and the full maintenance one are highlighted. In the table 11 the expected life as well as the different annualized costs are reported for the full and for a 78% level of maintenance.

	FULL	REALISTIC	Differences	
Maintenance Level [%]	100	78.62	21.38	%
Expected Life [year]	150	104	46	Years
	$/ft2/yr	$/ft2/yr		
Maintenance Costs	5.96	4.29	1.67	$/ft2/yr
Repair Costs	4.72	7.07	-2.35	$/ft2/yr
Replacement Costs	12.00	17.37	-5.37	$/ft2/yr
NYC Costs	7.24	9.46	-2.22	$/ft2/yr
User Costs	8.77	11.43	-2.66	$/ft2/yr
TOTAL ANNUAL COST	**38.69**	**49.62**	**-10.92**	**$/ft2/yr**

Table 10 - Cost Differences Full/Realistic Maintenance

From figure 30 is possible to appreciate the cost differences between the two methods. The full maintenance allows to reach an expected life 46 years longer than the realistic one.

Speaking about annual cost, it's possible to see that the only one in which the full is bigger than the realistic is the maintenance cost. This is reasonable in fact the level of maintenance, as therefore the time and the work to reach it, are grater. For what concern all the other annual cost, the full maintenance would be much cheaper than whatever realistic one. As it's possible to see from the total values the full maintenance would be 22% cheaper than the realistic one.

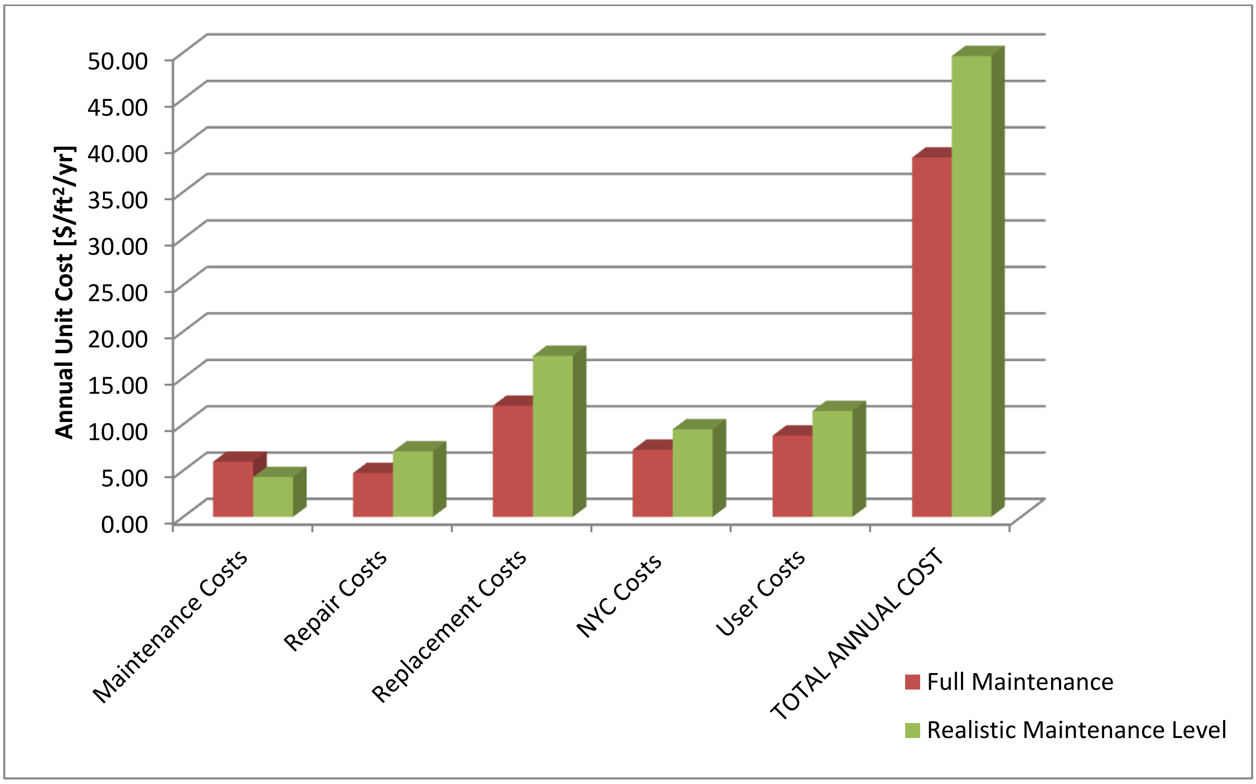


Figure 30 - Full VS Realistic Maintenance Cost

In a bridge like the one that is analyzing that mean an annual saving of money of about 540'000 dollars. Unfortunately, as said, the full maintenance for all bridge is undoable and thus all the further analysis will be done using the "realistic" level of annual maintenance as a reference value.

1° Simulation: Step Maintenance increase for each element separately

The first simulation consists in increasing one maintenance level at time from 0% to 90%. In this way is possible to see, based on the level of maintenance, which is the total annual cost trend for each tasks. The main purpose of this analysis is to show that even if the total annual unit cost is an important parameter the expected life is much more significant. The trend of the expected life (figure 31) and the unit annual cost (figure 32) is shown in the following pictures.

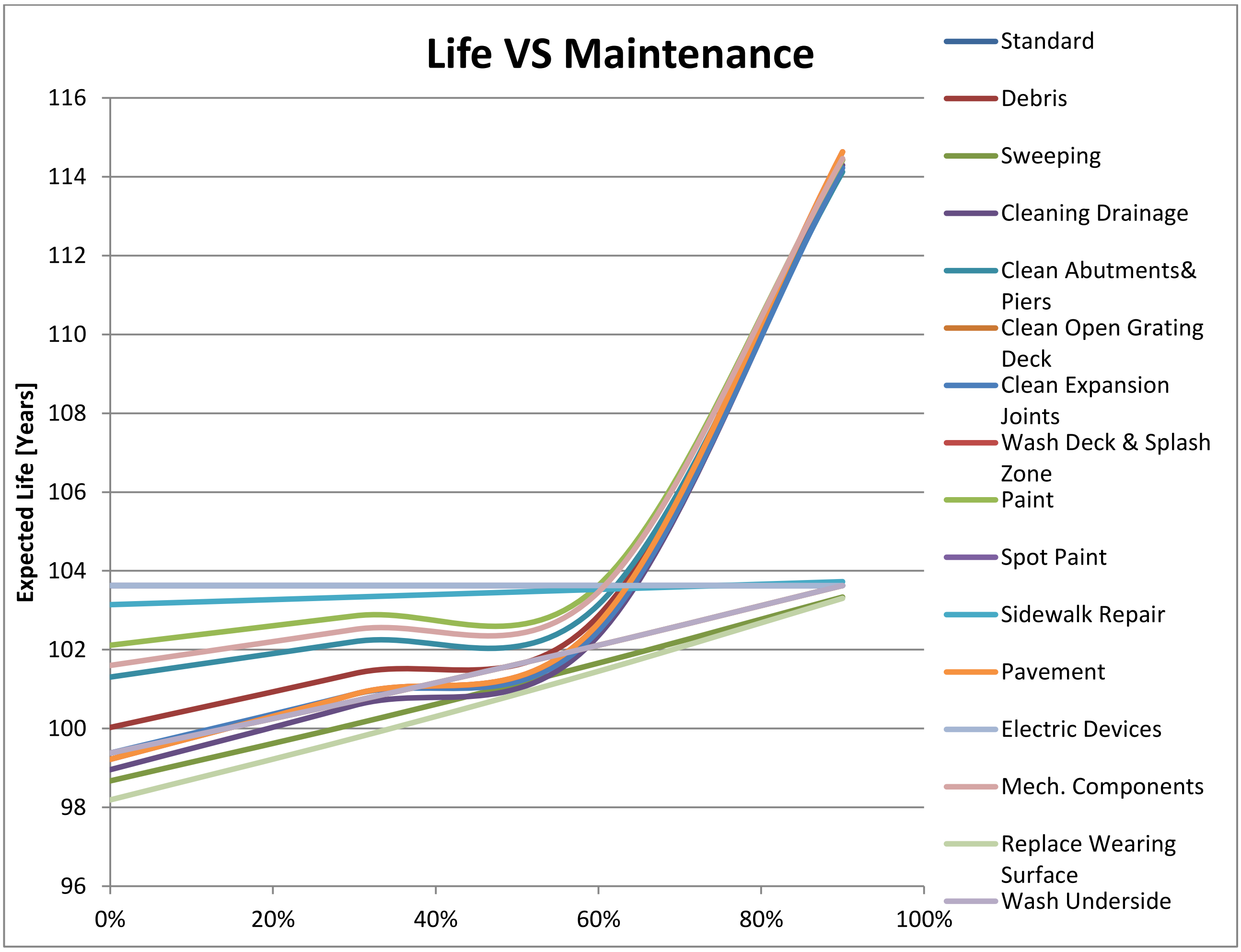


Figure 31 - Life VS Maintenance Trend

It' clear, as it could be imagined that the more maintenance is done the longer is the expected life of the bridge. By the way, there is some difference in the maintenance level VS Life from task to task. While some tasks has a perfectly linear behavior (for example Paint, Mech. Components..) other ones has a non -linear behavior increasing relevantly the expected life when they are done over the 60%.

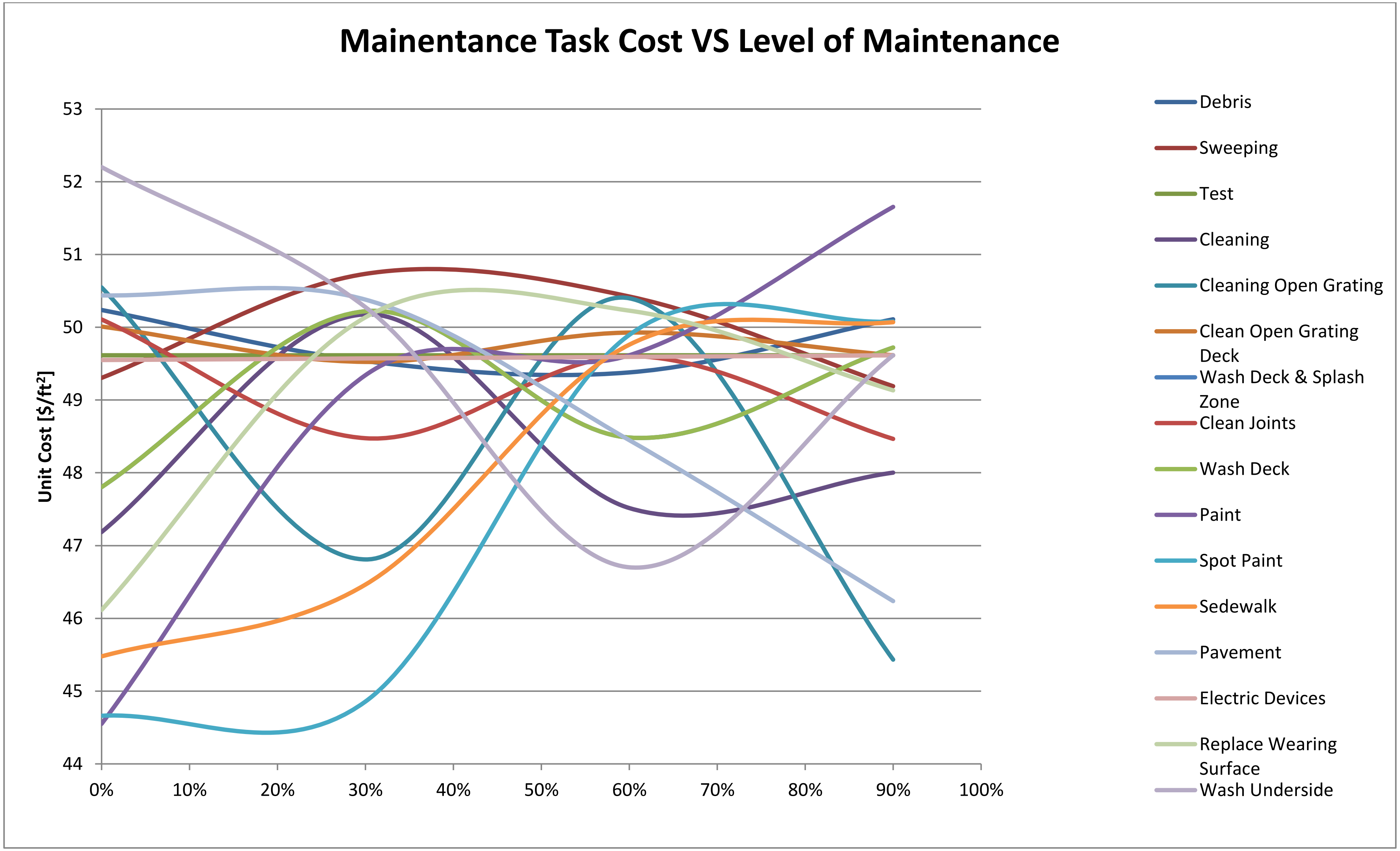


Figure 32 - Unit Cost VS Level of Maintenance

As it's possible to see in figure 31 there is some task that will give a lower cost when is not done. This means that for an economical point of view it could be better to do not make that task with respect to do it at a high level. One of these examples can be "Clean opening Grating". On the other hand, there is some task that is better to be performed at a high annual level (above the 65%). One of these can be "Clean Joints". All the costs above are the total ones that keep into account all the five cost and not only the maintenance one and thus there is not a linear behavior that it could be imagined. In fact the total costs are function of the numbers of replaces, repairs and discomfort due to that works.

Simulation 2. Keeping only Index Factor I_{ij} bigger than 0.5

This simulation is done base on the Importance factor matrix. The purpose of this analysis is to see if doing a most effective maintenance is better than do a standard one. If fact, each element of the importance factor matrix in figure 33, means how important is the task for a given component with respect to the other components. For example, the element I_{16} = 0.8 of the following matrix means that clean the abutments and the piers is very important end effective for the primary members deterioration rate and so for its expected life.

In this analysis the standard Importance factor matrix (figure 33) is modified. For the most important components (Abutments, Primary Member, Piers and Deck) all the importance factor of the matrix, smaller than 0.5, are deleted.

I_{ij}	Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
Debris rem	0.7	0.5	0.2	0.1	0.8	0.5	0.5	0.8	0.8	0.8	0.9	0.1	0.8
Sweeping	0.2	0.1	0.1	0	0.5	0.5	0.5	1	0.8	0.9	1	0.1	1
Clean Drain	0.9	0.9	0.9	0.8	1	1	1	1	1	1	1	0.5	1
Clean abut/piers	1	1	1	0.9	1	0.8	0.8	0	0	0.5	0.5	1	0.5
Clean grating	0	0	0	0	0	0	0	0	0	0	0	0	0
Clean exp jts	1	0.8	1	0.5	1	1	0.8	0.5	0.5	0.9	0.9	0.9	1
Wash deck etc	0.5	0.3	0.2	0	0.6	0.4	0.4	1	0	1	1	0.4	1
Paint	1	0.5	0	0	0.5	1	1	0	0	0.4	0	1	0.5
Spot paint	1	0.5	0	0	0.5	1	1	0	0	0	0	1	0.5
Sidewalk & curb	0	0	0	0	0	0	0	1	1	0.1	0.1	0	0.5
Pavmt & curb seal	1	1	1	0.5	1	1	1	1	1	1	1	0.5	0.5
Elect device maint	0	0	0	0	0	0	0	0	0	0	0	0	0
Mech Comp	1	0.5	0.5	0.2	1	1	1	1	0	0.5	0	1	1
Repl wear surf	0	0.1	0	0	0.1	0.1	0.1	0.5	0.5	1	1	0.1	1
Wash underside	1	1	1	0.5	1	1	1	0	0	0.8	0	1	0.9

Figure 33 - Standard Importance Factor Matrix

Putting a zero as the importance factor means that that task is not made on that components and thus it is done better one the other components. Being the APPD components the most important ones, the ones that bring to failure the bridge, we want to look how the expected life and the total cost behave by doing the maintenance only where it is more effective.

The modified importance factor matrix that is used for this analysis is the one represented in figure 34.

I_{ij}	Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
Debris rem	0.7	0.5	0	0.1	0.8	0.5	0.5	0.8	0.8	0.8	0.9	0	0.8
Sweeping	0.2	0.1	0	0	0.5	0.5	0.5	1	0.8	0.9	1	0	1
Clean Drain	0.9	0.9	0.9	0.8	1	1	1	1	1	1	1	0.5	1
Clean abut/piers	1	1	1	0.9	1	0.8	0.8	0	0	0.5	0.5	1	0.5
Clean grating	1	0.5	0.7	0.1	1	1	1	0.1	0.1	0.8	1	1	0.9
Clean exp jts	1	0.8	1	0.5	1	1	0.8	0.5	0.5	0.9	0.9	0.9	1
Wash deck etc	0.5	0.3	0	0	0.6	0	0.4	1	0	1	1	0	1
Paint	1	0.5	0	0	0.5	1	1	0	0	0	0	1	0.5
Spot paint	1	0.5	0	0	0.5	1	1	0	0	0	0	1	0.5
Sidewalk & curb	0	0	0	0	0	0	0	1	1	0.1	0.1	0	0.5
Pavmt & curb seal	1	1	1	0.5	1	1	1	1	1	1	1	0.5	0.5
Elect device maint	0	0	0	0	0	0	0	0	0	0	0	0	0
Mech Comp	1	0.5	0.5	0.2	1	1	1	1	0	0	0	1	1
Repl wear surf	0	0.1	0	0	0.1	0	0.1	0.5	0.5	1	1	0	1
Wash underside	1	1	1	0.5	1	1	1	0	0	0.8	0	1	0.9

Figure 34 – Modified Importance Factor Matrix with APPD factors >0.4

The results of this analysis are reported in table 12. In the table are reported the results for the standard analysis (1st column), of the modify analysis (2nd column) and the difference between the two.

	Standard	APPD > 0.5	Differences APPD - Standard	
Maintenance Level [%]	78.6	78.8	0.2	%
Expected Life [year]	104	115	11	Years
	$/ft2/yr	$/ft2/yr		
Maintenance Costs	4.29	4.29	0.00	$/ft2/yr
Repair Costs	7.07	7.46	0.39	$/ft2/yr
Replacement Costs	17.37	15.67	-1.70	$/ft2/yr
NYC Costs	9.46	10.33	0.87	$/ft2/yr
User Costs	11.43	12.47	1.05	$/ft2/yr
TOTAL ANNUAL COST	**49.62**	**50.23**	**0.61**	**$/ft2/yr**

Table 11 - Result Simulation 2

While the maintenance level is mostly the same for the two analyses (in fact the difference is just a 0.2%) the total expected life is completely different. In fact, for the modified matrix analysis, the total like increases from 104 to 115 years.

From an economical point of view it possible to see that the optimized one is a little bit more expensive (figure 35). Naturally the annual cost for the maintenance is equal for both the analysis but then, while the modified one is annually cheaper concerning the replacement costs the standard one is more economically sustainable for what regard the repair, the NYC and the user cost.

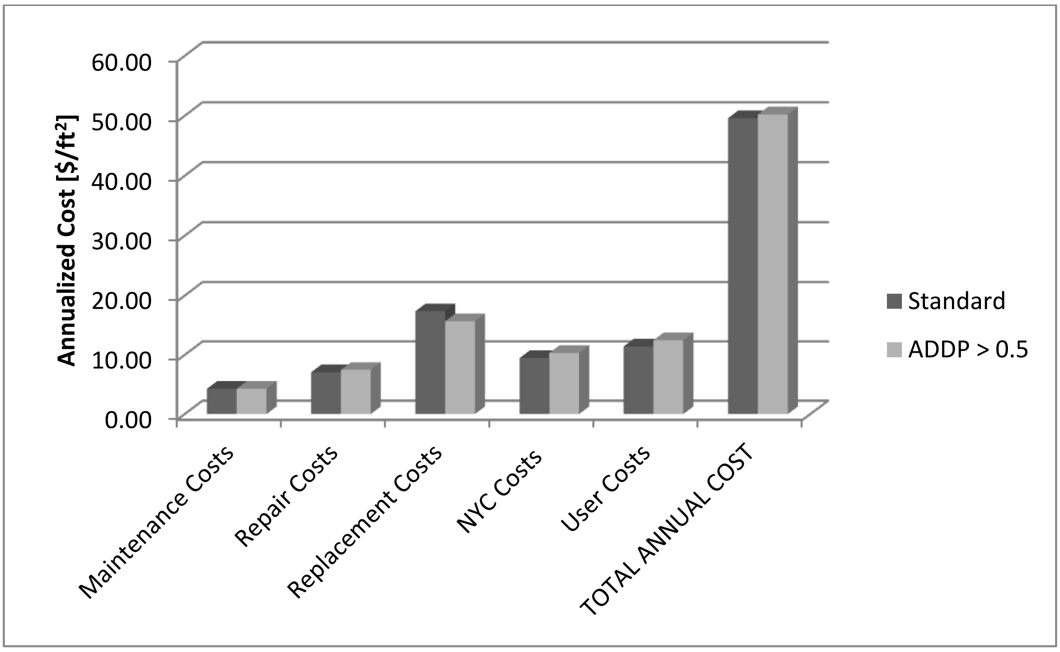


Figure 35 - Annualized Cost for the two analyses

The annual difference cost between the standard and the APPD>0.5 one is just 0.61 $\$/ft^2$ that for a 50 000 ft^2 bridge as the one it is analyzed means an annual additional cost of 30'515 $. It has to be remembered that this additional cost of about 30000 $/years give 11 more years of life to the bridge (plus 11%) with respect to the standard one.

Simulation 3. Keeping only Index Factor I_{ij} equal to 1

The simulation number 2 provided to keep only the importance factor bigger or equal to 0.5 for the APPD elements produced a great result with respect to the standard one. For this reason in this simulation is an extremes version of the last one. In this version, there will be kept, for the APPD components, only the importance factor equal to 1. The objected of this analysis is to simulate what would happen if the maintenance tasks were applied only where they are perfectly effective regarding the ADDP components. The modified matrix will become the one illustrated in figure 36.

I_{ij}	Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
Debris rem	0.7	0.5	0	0.1	0.8	0	0.5	0.8	0.8	0	0.9	0	0.8
Sweeping	0.2	0.1	0	0	0.5	0	0.5	1	0.8	0	1	0	1
Clean Drain	0.9	0.9	0	0.8	1	1	1	1	1	1	1	0	1
Clean abut/piers	1	1	1	0.9	1	0	0.8	0	0	0	0.5	1	0.5
Clean grating	1	0.5	0	0.1	1	1	1	0.1	0.1	0	1	1	0.9
Clean exp jts	1	0.8	1	0.5	1	1	0.8	0.5	0.5	0	0.9	0	1
Wash deck etc	0.5	0.3	0	0	0.6	0	0.4	1	0	1	1	0	1
Paint	1	0.5	0	0	0.5	1	1	0	0	0	0	1	0.5
Spot paint	1	0.5	0	0	0.5	1	1	0	0	0	0	1	0.5
Sidewalk & curb	0	0	0	0	0	0	0	1	1	0	0.1	0	0.5
Pavmt & curb seal	1	1	1	0.5	1	1	1	1	1	1	1	0	0.5
Elect device maint	0	0	0	0	0	0	0	0	0	0	0	0	0
Mech Comp	1	0.5	0	0.2	1	1	1	1	0	0	0	1	1
Repl wear surf	0	0.1	0	0	0.1	0	0.1	0.5	0.5	1	1	0	1
Wash underside	1	1	1	0.5	1	1	1	0	0	0	0	1	0.9

Figure 36 - Modify Matrix with APPD > 1

The analysis is run with the same level of maintenance task as usual and the result are the one reported in the table 13.

	Standard	APPD = 1	Differences APPD- Standard	
Maintenance Level [%]	78.60	78.50	-0.10281	%
Expected Life [year]	103.63	103.64	0.008178	Years
	$/ft2/yr	$/ft2/yr		
Maintenance Costs	4.29	4.29	0.00	$/ft2/yr
Repair Costs	7.07	7.07	0.00	$/ft2/yr
Replacement Costs	17.37	17.37	0.00	$/ft2/yr
NYC Costs	9.46	9.51	0.05	$/ft2/yr
User Costs	11.43	11.49	0.06	$/ft2/yr
TOTAL ANNUAL COST	**49.62**	**49.73**	**0.11**	**$/ft2/yr**

Table 12 - Result Simulation 3

As it possible to see from this results table, while the overall level of maintenance differs of about 0.1 % from the standard matrix to the ADDP modified one, the expected life of is mostly the same: 103 years.

By analyzing the costs, the maintenance, the repair and the replacement cost are equal for both the simulation while the two additional costs (the New York City and the User ones) are a little greater for the modified matrix. These differences bring to a total annual cost difference of 0.11 $/ft^2 that for the sample bridge, with a deck area of 50,000 ft^2, is 5708 $.

It does not seems worthy for a Department to Transportation to act that kind of maintenance that brings to spend each year 5700 $ more than the standard one and without any substantial improvement in the expected life of the structure.

Simulation 4. Keep only the importance factor greater than 0.4 for each task

In the simulation 2 it has been shown that by changing the Importance Factor matrix such that for the APPD components there are only values bigger than 0.5 the life expected life will increase of 11 years while the total annual cost only of 0.61 $/ft^2. Therefore in this simulation we try to extend this concept to the entire matrix. In order to do that all the importance factor I_{ij} smaller than 0.5 are deleted. This matrix is seeable in the following picture.

I_{ij}	Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
Debris re	0.7	0.5	0	0	0.8	0.5	0.5	0.8	0.8	0.8	0.9	0.1	0.8
Sweeping	0	0	0	0	0.5	0.5	0.5	1	0.8	0.9	1	0.1	1
Clean Dr	0.9	0.9	0.9	0.8	1	1	1	1	1	1	1	0.5	1
Clean ab	1	1	1	0.9	1	0.8	0.8	0	0	0.5	0.5	1	0.5
Clean gr	1	0.5	0.7	0	1	1	1	0	0	0.8	1	1	0.9
Clean ex	1	0.8	1	0.5	1	1	0.8	0.5	0.5	0.9	0.9	0.9	1
Wash de	0.5	0	0	0	0.6	0	0	1	0	1	1	0	1
Paint	1	0.5	0	0	0.5	1	1	0	0	0	0	1	0.5
Spot pain	1	0.5	0	0	0.5	1	1	0	0	0	0	1	0.5
Sidewalk	0	0	0	0	0	0	0	1	1	0	0	0	0.5
Pavmt &	1	1	1	0.5	1	1	1	1	1	1	1	0.5	0.5
Elect dev	0	0	0	0	0	0	0	0	0	0	0	0	0
Mech Co	1	0.5	0.5	0	1	1	1	1	0	0.5	0	1	1
Repl wea	0	0	0	0	0.1	0	0	0.5	0.5	1	1	0.1	1
Wash un	1	1	1	0.5	1	1	1	0	0	0.8	0	1	0.9

Figure 37 - Importance Factor Matrix I_{ij} > 0.5

The results of this analysis are reported in the table 14. As it can be seen the overall maintenance level is mostly the same while the expected life, as in the simulation 2, is completely different.

	Standard	ALL > 0.5	Differences APPD- Standard	
Maintenance Level [%]	78.6	78.7	0.1	%
Expected Life [year]	104	114	10	Years
	$/ft2/yr	$/ft2/yr		
Maintenance Costs	4.29	4.29	0.00	$/ft2/yr
Repair Costs	7.07	7.50	0.43	$/ft2/yr
Replacement Costs	17.37	15.75	-1.62	$/ft2/yr
NYC Costs	9.46	10.51	1.05	$/ft2/yr
User Costs	11.43	12.70	1.27	$/ft2/yr
TOTAL ANNUAL COST	**49.62**	**50.75**	**1.14**	**$/ft2/yr**

Table 13 - Results Simulation 4

In fact, in the modified case, the life will increase from 104 to 114 years. In order to gain these 10 years the department of transportation as to afford a total annual cost 1.14 $/ft bigger than the one due to the standard simulation. For a 50000 ft^2 bridge this means almost 60'000 $ more every years. By comparing the simulation 2 with the simulation 4 (figure 38) it's possible to deduce that it would be better to put value equal or greater than 0.5 only in the APPD components (Abutments, Primary Member, Piers and Deck) with respect to apply this technique to all the components. In fact that permits to gain one year of life more and to save each year 26400 $ (about 50%).

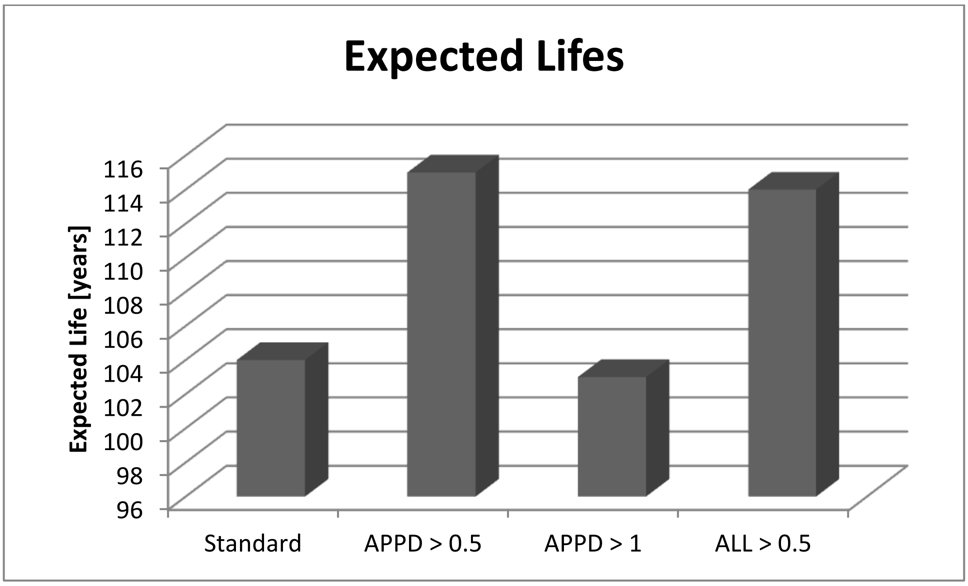


Figure 38 - Expected Life for the 4 simulations done

By summarizing, up to the current state of the simulations, it's better to modify the APPD columns of the importance factor matrix to keep only the value greater than 0.4.

By thinking in a practical point of view, doing this trick in the matrix means to made, to the abutments, to the primary member, to the piers and to the deck only the maintenance task that really decrease their rating of deterioration.

Simulation 5. Different Weight of component

This simulation is done in order to verify if the bridge component weights have some effect on the annualized total cost. In fact, as it was explained in chapter two, to every bridge component is assigned a number from 1 to 10 that state its importance.

For this analysis the standard 50,000 ft^2 (about 4600 m^2) steel bridge is used as a sample. As it was explained in the beginning, the weights of each component as well as the Importance factor matrix, are decided deterministically by a group of expert engineers and so are not surely correct.

In the table 15 are reported the old and the new bridge weight (w_i) *and* their normalization (k_{ei}). The maintenance level for each task is the usual one indicated in figure 27.

	Old Weight		New Weight	
Bearings	6	0.083333	6	0.076923
Backwalls	5	0.069444	5	0.064103
Abutments	8	0.111111	10	0.128205
Wingwalls	5	0.069444	5	0.064103
Bridge seats	6	0.083333	6	0.076923
Primary members	10	0.138889	10	0.128205
Second. Members	5	0.069444	5	0.064103
Curbs	1	0.013889	1	0.012821
Sidewalks	2	0.027778	2	0.025641
Deck	8	0.111111	10	0.128205
Wearing surface	4	0.055556	4	0.051282
Piers	8	0.111111	10	0.128205
Joints	4	0.055556	4	0.051282

Table 14 - Old & New Weight

The analysis showed that any change happens by changing the relative importance of a component with respect to the others.

Concrete Bridge VS Steel Bridge

This simulation is done in order to let the reader know that the required maintenance for a concrete bridge and a steel bridge is completely different. In fact, a steel bridge, require much more maintenance such as painting the structure in order to avoid that it rust. The bridge that will be here analyzed is always a 30,000 ft^2 but made of concrete, without steel joints, open grating and with a mono deck structure. It has to be considered that this is a structure as big as the one that was considered before and then the cost could be easily compared. Moreover the maintenance task levels are setting equal for the steel and the concrete bridge analysis. The only important change between the two simulations is the Importance Factor Matrix. In fact, as soon as the concrete bridge type is set, automatically, the software changes the matrix putting. The matrix relative to a concrete bridge with mono deck and without open gratin is the one in (figure 39).

I_{ij}	Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
Debris rem	0.7	0.5	0.2	0.1	0.8	0.5	0.5	0.8	0.8	0.8	0.9	0.1	0.8
Sweeping	0.2	0.1	0.1	0	0.5	0.5	0.5	1	0.8	0.9	1	0.1	1
Clean Drain	0.9	0.9	0.9	0.8	1	1	1	1	1	1	1	0.5	1
Clean abut/piers	1	1	1	0.9	1	0.8	0.8	0	0	0.5	0.5	1	0.5
Clean grating	0	0	0	0	0	0	0	0	0	0	0	0	0
Clean exp jts	0	0	0	0	0	0	0	0	0	0	0	0	0
Wash deck etc	0.5	0.3	0.2	0	0.6	0.4	0.4	1	0	1	1	0.4	1
Paint	0	0	0	0	0	0	0	0	0	0	0	0	0
Spot paint	0	0	0	0	0	0	0	0	0	0	0	0	0
Sidewalk & curb	0	0	0	0	0	0	0	1	1	0.1	0.1	0	0.5
Pavmt & curb sea	1	1	1	0.5	1	1	1	1	1	1	1	0.5	0.5
Elect device maint	0	0	0	0	0	0	0	0	0	0	0	0	0
Mech Comp	1	0.5	0.5	0.2	1	1	1	1	0	0.5	0	1	1
Repl wear surf	0	0.1	0	0	0.1	0.1	0.1	0.5	0.5	1	1	0.1	1
Wash underside	1	1	1	0.5	1	1	1	0	0	0.8	0	1	0.9

Figure 39 - Importance Factor Matrix for Concrete Bridge w/o open Grating

As it's possible to see, all the four rows relative to grating, joints, and painting are put equal to zero. This means that that tasks are not accomplished in the bridge.

The usual results table reporting all the costs for the different categories as well as the expected is reported here.

	Steel	**Concrete**	Differences	
Maintenance Level [%]	78.62	78.93	-0.31	%
Expected Life [year]	104	129	-25	Years
	$/ft2/yr	$/ft2/yr		
Maintenance Costs	4.29	4.29	0.00	$/ft2/yr
Repair Costs	7.07	6.46	0.61	$/ft2/yr
Replacement Costs	17.37	13.97	3.40	$/ft2/yr
NYC Costs	9.46	8.50	0.95	$/ft2/yr
User Costs	11.43	10.28	1.14	$/ft2/yr
TOTAL ANNUAL COST	49.62	43.51	6.11	$/ft2/yr

Table 15- Steel VS Concrete Bridge

As it was specified, the two simulations were done keeping the annual cost due to the maintenance constant. Therefore, as it's possible to see in the "differences" column, the annual maintenance cost is the same for the two kinds of structures. However, the overall annual cost of maintenance that takes into account also the replacement, repair and User cost is clearly less for the concrete bridge. In fact, a concrete bridge has an annualized total cost that is about 14 % less than the steel one. As illustrated in the figure 38 this is mainly due to the replacement annual cost. In fact, steel bridges have a lot of components that, if not painted or and prevented from corrosion and rust, have to be changed often.

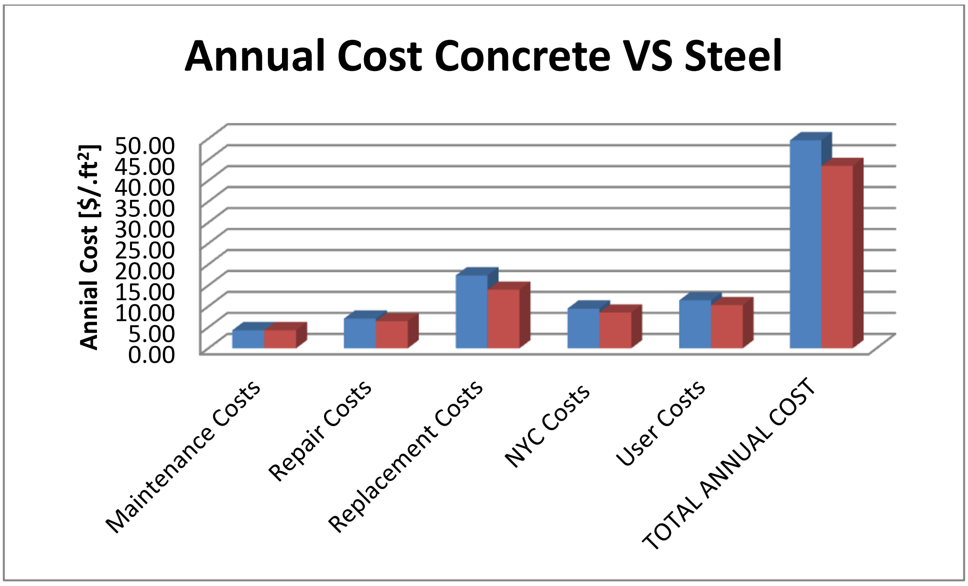


Figure 40 - Annual Costs Steel VS Concrete

By having a concrete bridge with respect to steel one of the same dimension, permits to save more than 300,000 dollars per year. Moreover, as always seeable in the table 15, the expected life of the concrete bridge is 25 years longer with respect to the steel one.

It's proved by this analysis that a steel bridge generally requires much more maintenance (and so much more money) than a concrete one. It would be suggestible that during the design phase this cost/life/maintenance factors are studied and considered.

Cost Effective Analyses

In this chapter the simulations will be done by basing the maintenance tasks level on economic consideration. In fact, by an important study conducted at Columbia University in 1999 found the annual total cost that the New York City Department of Transportation would spend every here to do a full maintenance on the bridge. In the program, as already said, the level of each maintenance activity M_i, can be varied continuously from 0 to 100% to the recommended full maintenance with a corresponding cost:

$$C_{mi} = M_i C_{m1i}$$

In the following simulations, expected life and total annualized costs are compared for different levels of maintenance with respect to the budget level needed for the full recommended maintenance frequencies and not based on a realistic level of maintenance.

The reduced budgets are apportioned by cutting maintenance tasks selectively rather than cutting uniformly all the tasks. This software option allows to cut budget by re-allocating the budget on the tasks that are more useful and/or cheaper. Therefore the overall level of maintenance M won't be the same fraction as the budget expressed as a percentage of the budget for full recommended maintenance. Being a hypothetic optimization the actual maintenance level will be much higher than the usual values. In fact only when all task frequencies are reduced uniformly will M and the budget percentage be the same. This means that the actual level of maintenance, in this kind of simulation, is greater than 100%.

What does an overall level of maintenance greater than 100% mean?

As explained in the first part of this work, given the relevance of each task to each component (k_{ij}) and the significance (k_{ei}) of each component to the overall bridge rating, a single indicator of level of maintenance on a bridge ranging from zero to one can be written as

$$M = \sum_{i=1}^{15} k_{mi} \cdot M_i$$

Where M_i is the level on maintenance of each single task while

$$k_{mi} = \sum_{j=1}^{13} k_{ij} \cdot k_{ei}$$

The optimization of the software tries to find the best compromise costs-benefits. By varying the maintenance level (and so by acting only on the annual cost of maintenance) it find the best relation between the costs and the effects that the maintenance tasks have on the deterioration rate. In this way is possible that some tasks are cut almost to zero and some other is increased also by tens of times.

The interface that the user has to deal with is the following one illustrated in the figure 41.

			Allocation by Kmi/Cm1i			
Results			Kmi/Cm1i			
M =	4.4	%	0.7746	0.0462		
L =	51	yrs.	1.1856	0.0707	Specified % of Full Maint Cost	30
Maintenance Costs	0.06		1.9948	0.1189	Multiplier	0.06
Repair Costs	19.89		0.5681	0.0339	Ctr e - to use this alloc	
Replacement Costs	35.16		0.0000	0.0000		
NYC Costs per sqft	9.85		0.5052	0.0301	Set % to use multiplier	
User Costs per sqft	11.89		0.5674	0.0338	for alloc proportional to	
TOTAL ANNUAL COST	76.84		0.0251	0.0015	Multiplier will equal the	
			0.0350	0.0021	annual maintenance	
M (as % of full maint cost)	1.0	%	0.1157	0.0069		
Deterioration rate formula	E		0.8180	0.0488		
			0.0000	0.0000		
For optimization			1.2217	0.0728		
fixed budget amount	2.38	$/ft²	0.3405	0.0203		
fixed maint level M	50.0	%	0.1175	0.0070		

Figure 41 - Optimization Interface

In the red cell on the right the user has to specify which percentage of the total annual cost of maintenance he/she wants to use. On the central columns it's possible to see the value of k_{mi}/C_{m1i} (on the left) and the final optimized level of maintenance (on the right).

The program works based on the following formula that gives the oprtimize level of maintenance for each task.

$$M_{iOPT} = \frac{\%M \cdot C_{m1}}{100} \cdot \frac{k_{mi}}{C_{m1i}}$$

Where:

- M_{iOPT} = optimized level of maintenance for the task i
- C_{m1} = total annual cost per square foot at full maintenance equal to 5.96 $/ft^2
- %M = desire percentace of annual maintenance budget
- K_{mi} = Influence of each maintenance task to the overall Maintenance Level
- C_{m1i} = annual cost per square foot of bridge for maintenance task i at level M_i = 1

Once that the optimization is done, it's sufficient putting the new value of maintenance as input parameter and run the normal analysis. in the following simulations some example will be presented.

Simulation 1. Increasing %M.

In this simulation the percentage of budget is made increase from 10 to 100 %. This will result in new and different actual level of maintenance on the structure (figure 42).

%M	10	20	30	40	50	60	70	80	90	100
Debris rem	0.22	0.45	0.67	0.90	1.12	1.35	1.57	1.79	2.02	2.24
Sweeping	0.69	1.37	2.06	2.74	3.43	4.12	4.80	5.49	6.18	6.86
Clean Drain	1.16	2.32	3.48	4.63	5.79	6.95	8.11	9.27	10.43	11.59
Clean abut/piers	0.33	0.66	0.99	1.31	1.64	1.97	2.30	2.63	2.96	3.28
Clean grating	14.44	28.88	43.32	57.76	72.19	86.63	101.07	115.51	129.95	144.39
Clean exp jts	0.29	0.58	0.87	1.17	1.46	1.75	2.04	2.33	2.62	2.91
Wash deck etc	0.33	0.65	0.98	1.30	1.63	1.95	2.28	2.61	2.93	3.26
Paint	0.01	0.03	0.04	0.06	0.07	0.09	0.10	0.11	0.13	0.14
Spot paint	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
Sidewalk & curb	0.07	0.14	0.21	0.28	0.35	0.42	0.49	0.56	0.63	0.70
Pavmt & curb seal	0.48	0.95	1.43	1.90	2.38	2.85	3.33	3.80	4.28	4.75
Elect device maint	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mech Comp	0.70	1.40	2.11	2.81	3.51	4.21	4.91	5.62	6.32	7.02
Repl wear surf	0.20	0.39	0.59	0.79	0.99	1.18	1.38	1.58	1.78	1.97
Wash underside	0.07	0.14	0.20	0.27	0.34	0.41	0.47	0.54	0.61	0.68

Figure 42 - Level Of Actual Maintenance due to %M

In some cases, as for example the clean grating task, the values of actual maintenance are much greater than 100 %. In fact, just at the first step of (%M = 10) the suggestion of the software is to do this task 14 times more than the usual full maintenance. This is due to to two reasons. The fisrt one is that the bridge under studied is with open grating and so it’s very important, for its expected life, that they are keep clean. The second reason is that this task is cheap to do.

In order to make the reader understand the different between that suggested level of maintenance due to the optimization the following graph (figure 43) is analyzed. All the values are taken for the same %M, in this case 50% of the annual maintenance budget.

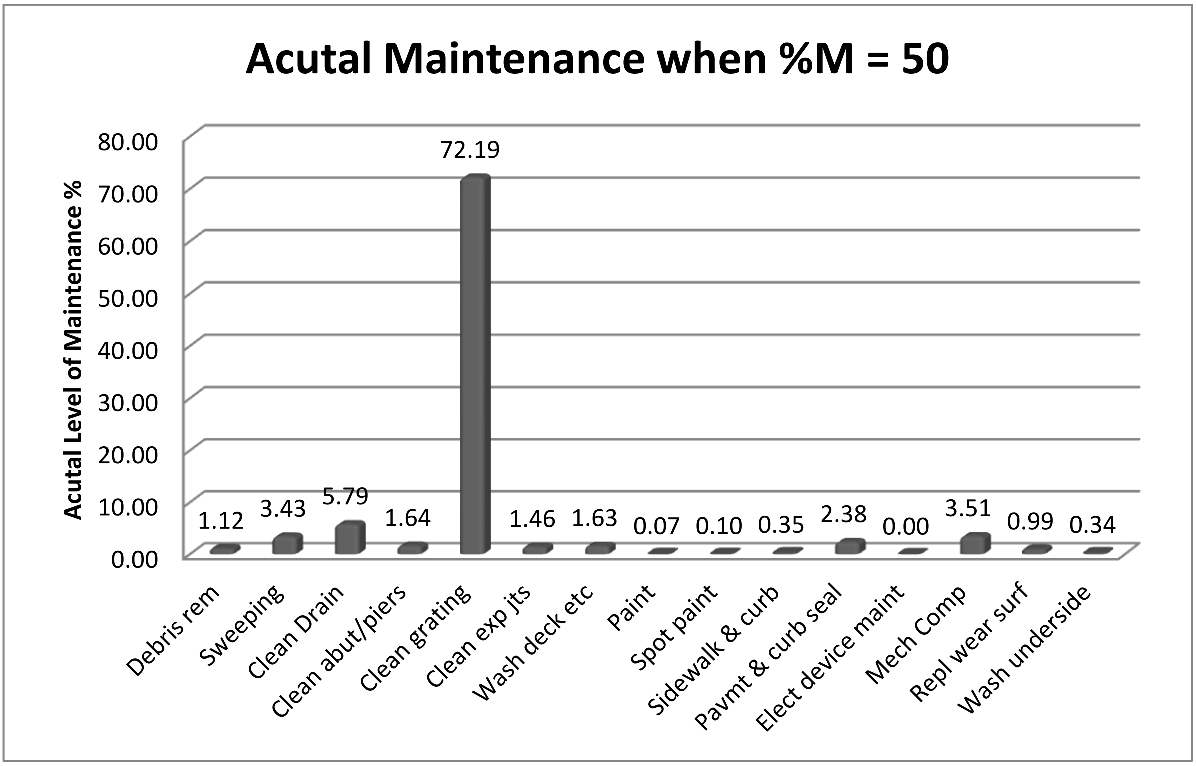


Figure 43 - Acutal Maintenance when %M = 50

As it's possible to see, the difference between the acutal suggested level of maintenance are huge. The optimization reduces very much the level of maintenance of the more espencive task. In fact, as you can see, even if the paint as well as the spot paint of a steel bridge are very important, they are very expensive and then reducted to 7 and 10 % every year.

The optimization suggests to make more effective and more often the "simple" task as sweeping, clean drain, clean grating, wash deck, pavement and curb seal and mechanich components.

Naturally the Importance Factor Matrix plays the main role in the definition of this optimize value. As it will be shown in next simulations, by changing some importance parameters make this suggested values varied. In fact, as already said, the importance factor matrix defines the effectivness of the maintenance task over the bridge components and thus over the overall expected life and behavior of the structure.

In the figure 44, instead, are shown all the task trend when the %M is made increase from 10 to 100 % of the budget. As already said the clean grating is the most cost-effective and so it is the one that shoud be increased and make in a better way in order to reach high value of expected life.

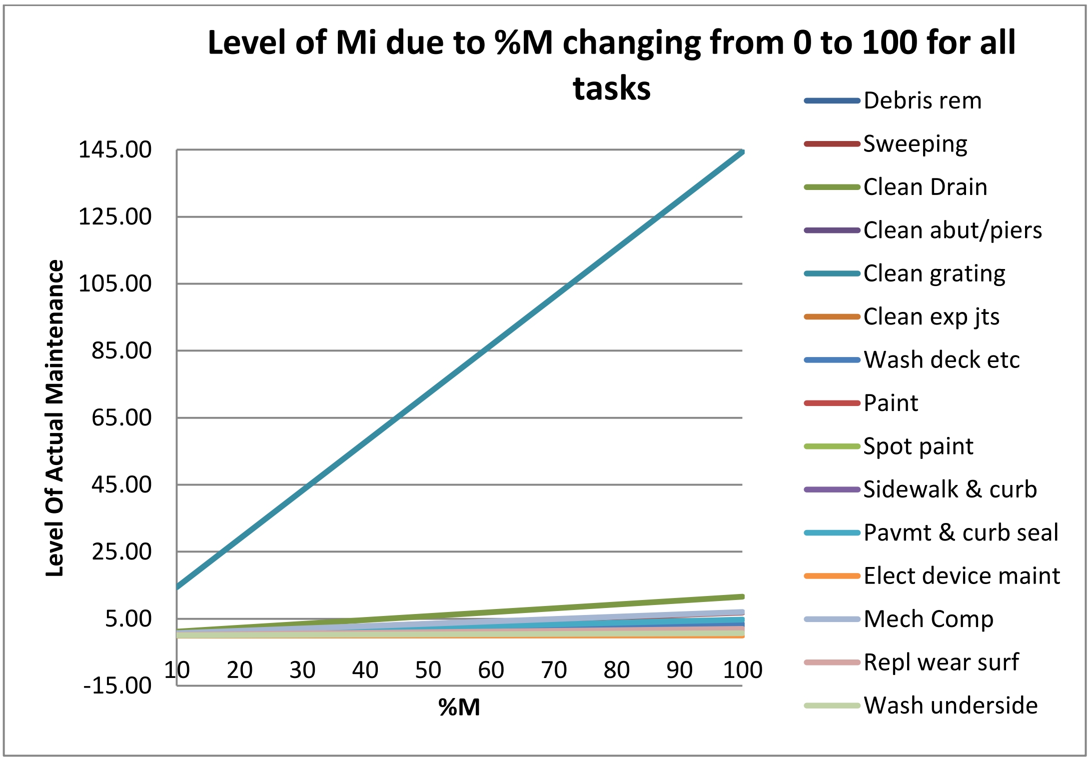


Figure 44 - Level of Mi due to %M changing from 0 to 100 for all tasks

In fact, it is the most cost-effective task. On the other side, one of the less cost-effective tasks is the maintenance on the electronic device. The program suggests to do not make this kind of maintenance. From the software results due to the optimization it's clear that there are other tasks that are not the best concerning cost-benefit. The figure 45 repeats the previous graph without the two most effective tasks ("Cleaning Grating" & Cleaning Drain) in order to better appreciate the utility of the other tasks.

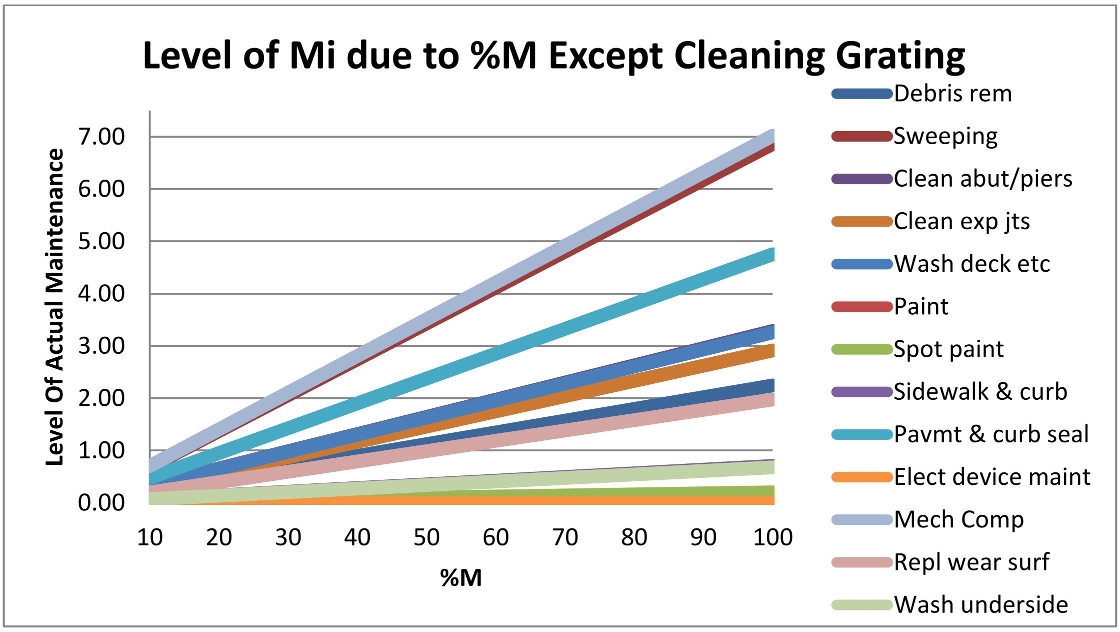


Figure 45

It is easy to see that immediately after "Electronic Device maintenance" the not cost-effective tasks are "spot paint" and "wash underside". Even if there were all budget to be spent it wouldn't be recommended to make these two task at 100%.

The list of the task in order to cost-effectiveness (from the more cost-effective to the less one) is the following:

1. Clean Grating
2. Clean Drain
3. Mechanical Component
4. Sweeping
5. Pavement & Curb Seal
6. Clean Abutments/Piers
7. Wash Deck
8. Clean Joint
9. Debris Removal
10. Replacement Wear Surface
11. Sidewalk and Curbs
12. Wash Underside
13. Spot Paint
14. Paint
15. Electronic Device

Concerning the expected life, the optimization procedure gives a huge increment in it. Most likely the fact that all the tasks are made with high value (also around 100 times the normal maintenance level) makes the expected like increase. In the figure 46 is reported the trend of the expected life when the %M is making increase.

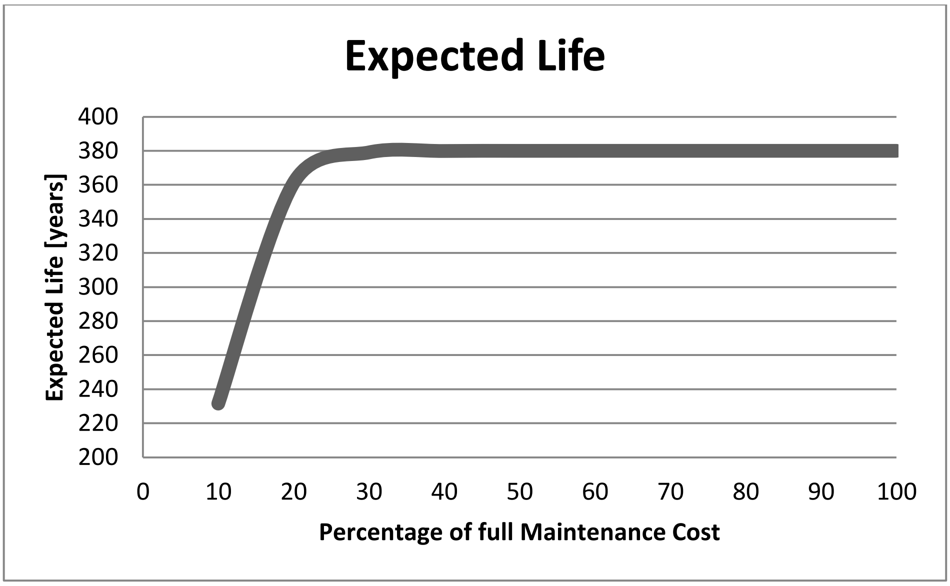


Figure 46 - Expexted Life

The maximum expacted life is 380 years that is more than double with respect to 150 years of the “normal” maximum life. The 380 years life are reached already at the when a bit more than the 20 percent of the full manitenance budget is spent. In fact the life is limited at 380 years and even if in the first part it grows linear with the money that are spent it find a plateau at %M = 30%.

In order to evaluate which level of %M is the better from an economical point of view, an ispection of the annual costs and especially of the Tolal Annual Cost should be done. In fact, the annual maintenance cost, together with the expected life, are not sufficient to declare which is the best level of %M that should be done.

In order to address this problem an evalutation of the total annual cost is done. In the figure 47 is illustrated the trend of the total annual cost when the %M is making increase from 10 to 100%.

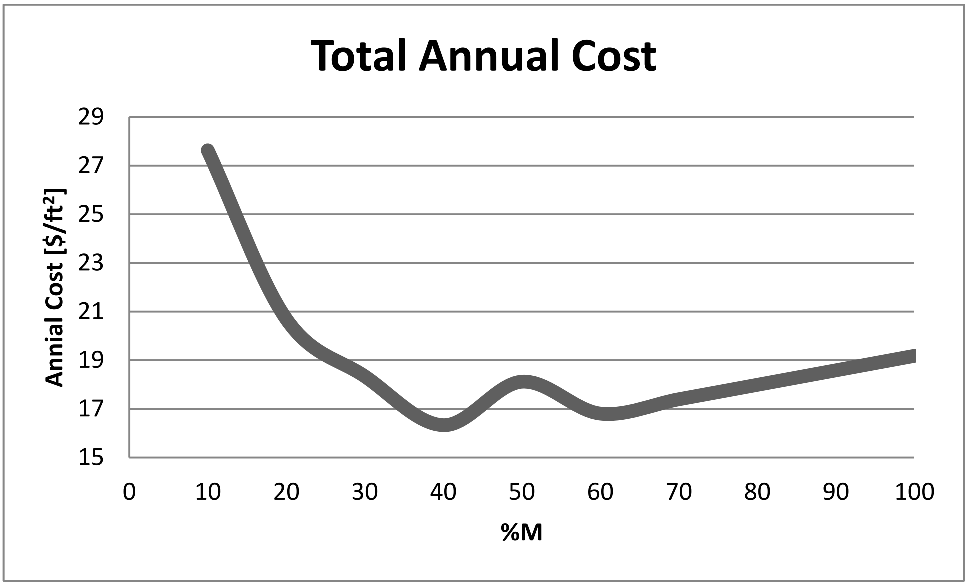


Figure 47 - Total Annual Cost Trend

This analysis shows that the best result in price is when the %M is set at 40 %.

Simulation 2. Comparison between different Importance Facto Matrix

In this simulation, as was done in a previous one, the Importance Factor Matrix is changed. The previous result will be compared with three different kind of modified importance factor matrix:

1. Matric Composed only by elements greater than 0.4
2. Matrix with only 1
3. Normal Matrix but the APPD components have only factors greater then 0.4

These are the same kind of different simulations that where done in the previous chapter for the normal analysis (not optimized).

The two parameter that are reported here, that could be the ones that represent better the effectiveness of the different options, are the expected life and the total annual cost. As in the previous simulation these are reported in two graphs (figure 48 and figure 49).

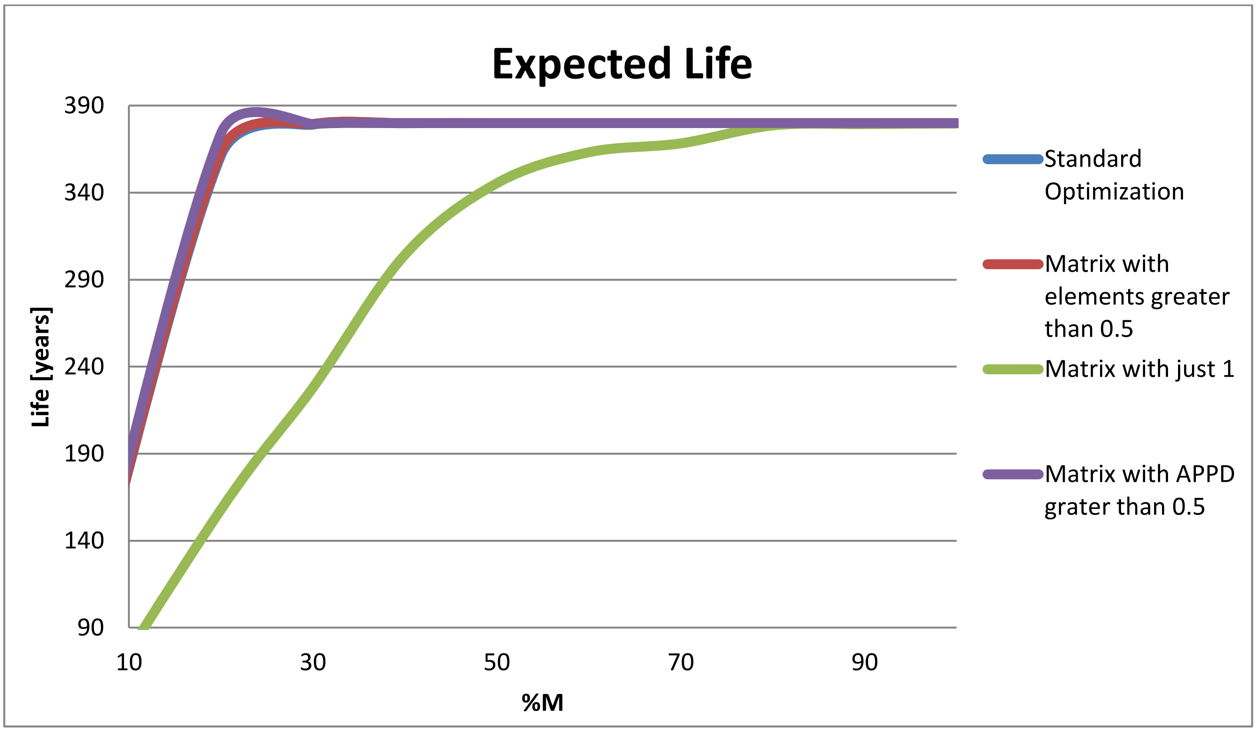


Figure 48 - Expected Life for Different Kind of Matrix

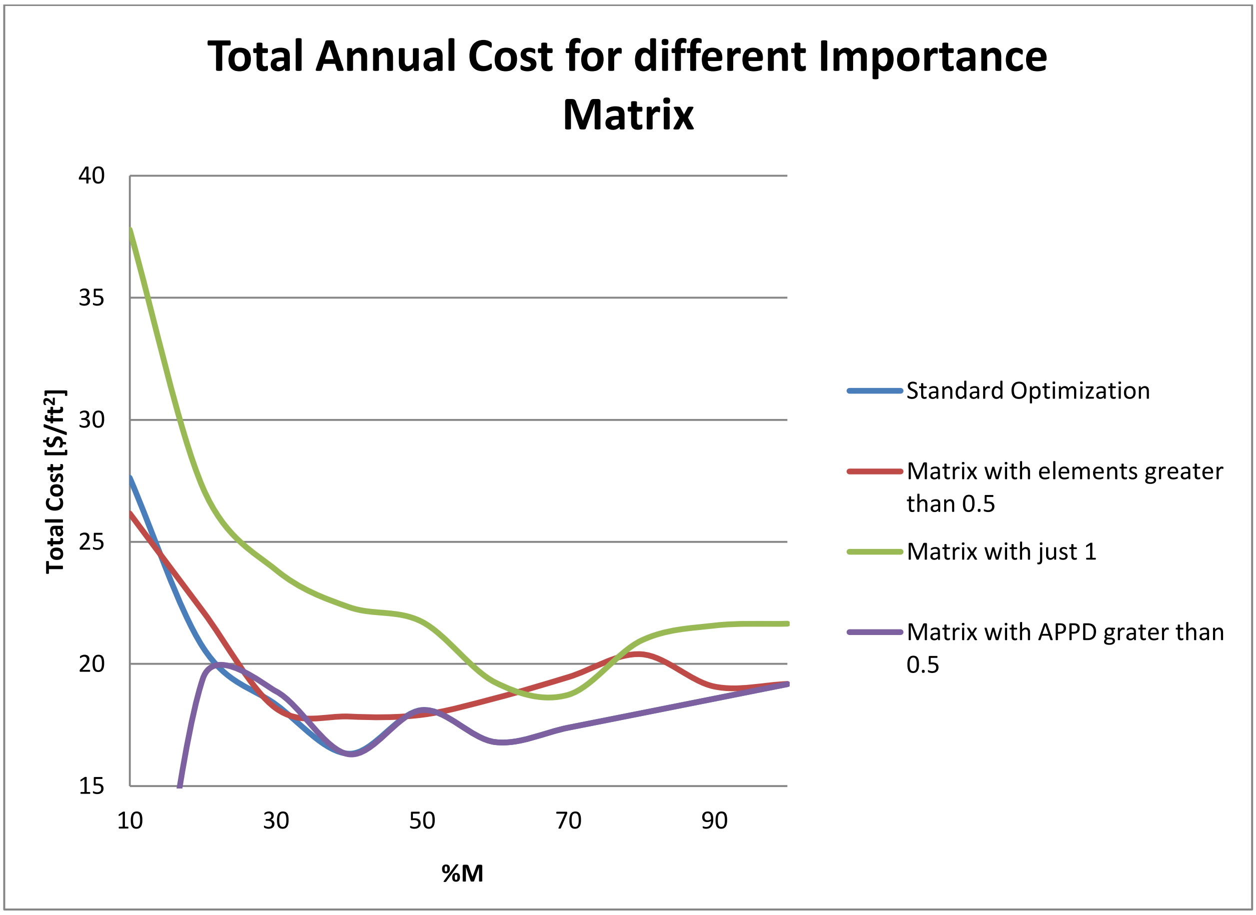


Figure 49 - Total Cost for Different Matrix

From this two graph can be find that the best combination ever is for a value of %M equal to 40 percent and with the Importance Factor Matrix modified in the way that the values relative to the APPD components (Abutement, Piers, Primary Member and Deck) are only the one equal or greater then 0.5.

In fact this, by guaranting an expected life equal to 380 years, has a total annual cost of 16.29 dollars per square foot. By having a bridge of 50000 ft^2 the annual cost is 814,500 $.

Best Omptimization Option

In order to summarize, here the best option with the best acutal maintenance level for the tasks are reported.

As just said, from the omptimization analyses, resulted that the APPD with value > 0.5 matrix is the best. This matrix is reported in figure 50.

Iij	Brgs	BkW	Abut	WgW	Seats	Prim	Sec	Curbs	SW	Deck	Wear	Piers	Joints
Debris rem	0.7	0.5	0	0.1	0.8	0.5	0.5	0.8	0.8	0.8	0.9	0	0.8
Sweeping	0.2	0.1	0	0	0.5	0.5	0.5	1	0.8	0.9	1	0	1
Clean Drain	0.9	0.9	0.9	0.8	1	1	1	1	1	1	1	0.5	1
Clean abut/piers	1	1	1	0.9	1	0.8	0.8	0	0	0.5	0.5	1	0.5
Clean grating	1	0.5	0.7	0.1	1	1	1	0.1	0.1	0.8	1	1	0.9
Clean exp jts	1	0.8	1	0.5	1	1	0.8	0.5	0.5	0.9	0.9	0.9	1
Wash deck etc	0.5	0.3	0	0	0.6	0	0.4	1	0	1	1	0	1
Paint	1	0.5	0	0	0.5	1	1	0	0	0	0	1	0.5
Spot paint	1	0.5	0	0	0.5	1	1	0	0	0	0	1	0.5
Sidewalk & curb	0	0	0	0	0	0	0	1	1	0.1	0.1	0	0.5
Pavmt & curb seal	1	1	1	0.5	1	1	1	1	1	1	1	0.5	0.5
Elect device maint	0	0	0	0	0	0	0	0	0	0	0	0	0
Mech Comp	1	0.5	0.5	0.2	1	1	1	1	0	0	0	1	1
Repl wear surf	0	0.1	0	0	0.1	0	0.1	0.5	0.5	1	1	0	1
Wash underside	1	1	1	0.5	1	1	1	0	0	0.8	0	1	0.9

Figure 50 - Best Matrix

The partial annual cost divided by replacement, repair, user and NYS costs is represented in the following graph

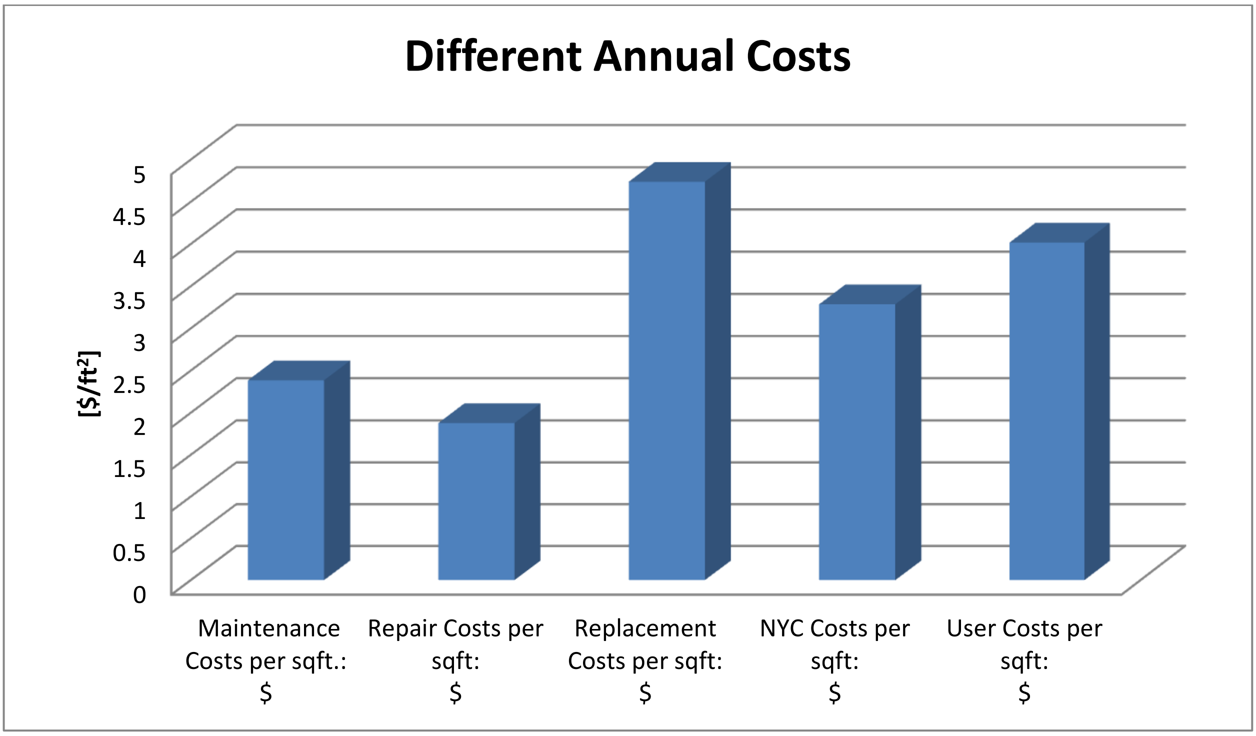


Figure 51 - Different Costs

The value of suggested maintenance are:

maintenance-level for task	
0.86	Debris Removal
2.70	Sweeping
4.76	Cleaning Drainage
1.35	Clean Abutments& Piers
59.70	Clean Open Grating Deck
1.20	Clean Expansion Joints
0.97	Wash Deck & Splash Zone
0.05	Paint
0.08	Spot Paint
0.25	Sidewalk & Curb Repair
1.95	Pavement & Crack Sealing
0.00	Elect Device Maintenance
2.90	Mech. Component Maint.
0.74	Replace Wearing Surfaces
0.28	Wash Underside

Figure 52 - Best Actual Level of Maintencance

Conclusion

In the first part of this work the actual condition of the bridge management in New York City was illustrated. The number of bridge in New York City area is extremely high and so the Department of Transportation is elaborating, in collaboration with the Columbia University, a software that allows to find a better allocation of the annual budget for the management of the bridges system.

The annual cost that the Department of transportation has to deal with is the sum of four different summands: annual maintenance cost, annualized repair cost, annualized replacement cost, annualized user and NYC cost. The final goal of this program is optimizing the frequencies of each maintenance task in order to reach the maximum expected life at the minimum annual cost.

In this work the importance of subjective parameters that are present in the software was shown.

The relative weight of the bridge component as well as the importance factor matrix parameters were assigned deterministically by a group of expert. These values are the big subjective elements in the software and it was possible to see that by changing some of them the final results of expected life of the structure and annual cost are different.

For sake of simplicity all the calculation and simulation were done based on a 50000 square feet bridge. The sample bridge was a steel bridge with steel joints and open grating.

It has been shown that, with a “usual” level of maintenance (without any optimization process), the best Importance Facto Matrix is the one with the values of the four most important components equal or greater than 0.5. This means that the maintenance tasks on the APPD components is done only if it is “useful”.

For what concerns the optimization some analyses were done. The “normal” level of maintenance established by the group of engineers is not more taken into consideration. The optimization tries to find the best level and frequencies for the maintenance task in order to decrease the annual cost and increase the expected life of the structure. The fact is that the optimization process finds the lower annual cost due only to maintenance without taking into account the other costs. In this work the best compromise between total cost and expected life was found.

From this work can be understand that subjectivity in quantifying the relation between bridge maintenance expenditure and bridge condition is commonly encountered and questioned in allocating resources. It has been tried to address this subjective behavior of the software by finding, for some specific case, the importance factor matrix to reach the best result concerning expected life and total annual cost.

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