Chapter 5
Decision Support Systems for IAM

5.1 Decision Levels: Strategic, Tactical, and Operational

Federal, state, provincial, territorial, and municipal governments and all other asset owners around the world must make decisions to invest public funds to maintain, rehabilitate, upgrade, and expand public infrastructure while budget limitation brings a need for seeking the most cost-effective and optimum solutions. Thus, decision-making is an essential step of this journey for most asset owners, and mature organizations in AM always are seeking optimum solutions through advanced tools and techniques.

Decisions trigger the need for plans where alternatives are compared and shortlisted. Selected alternatives become the basis for the budget, which is most commonly done on an annual basis. This level of planning and decisions is called operational, and it accompanies annual planning, but it is unable to consider the impact of decisions in the long term (also known as the strategic level).

Mature organizations in AM need to be proactive, and having long-term plans is required to avoid surprise and plan ahead of failure. As was discussed earlier, lack of data and uncertainty are always challenging in this kind of planning; however, it should not stop developing such strategic renewal planning as that is the nature of projecting the future.

The asset management team must put enough effort and use the best solutions in the literature to build the most accurate forecasting models; however, a tactical (medium-term) plan always gives a chance to adjust the strategic plan where is required and recover uncertainty. For example, if the model says a specific asset should be replaced in the next 3 years while recent observation indicates an emergency replacement is required or vice versa. The operation team should use a 3–5 year window in a tactical plan to address these sorts of changes.

Alternatives are often compared in terms of the return on investment, and if more mature, in terms of future maintenance needs during their lifecycles, all the way to the point on time when replacement is needed. This is triggered by valuation

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methods enforced by accounting laws at public organizations, which require financial analysis of any investment, accompanied by depreciation methods and estimation of salvage values. This financial provision needs to be accompanied by an engineering analysis that enables tracking KPIs interrelated to the selected alternative that will change over time as a consequence of the new infrastructure or facility being funded (through maintenance, rehabilitation, upgrade, or expansion). Such long term analysis is called strategic; it allows to have a global view of the infrastructure systems and their interactions; and it enables the forecasting of future levels of performance indicators, some financial, but most relevant to the ability to service the public, support economic growth, provide social well-being, and protect the environment.

However, decisions on new infrastructure had also repercussions on the demand and often affect other systems, which is most likely neglected in current classical AM practice and should be captured in planning for key infrastructure such as urban transit systems. For example, consider the construction of a new railway transit line that will serve several existing towns and villages connecting them to the rest of the rail network and the city. Not only does the new railway require maintenance after being opened but also it will affect the modal distribution of other existing transportation options such as cars and buses using roads; therefore, the level of congestion on the road links used by those villages and towns to travel to the city may experience a reduction on the number of vehicles per hour during the peak hour, resulting in an improvement on the level of congestion and shortened travel time. The reduced number of vehicles could result also in a reduction of road collisions at the intersections used before by work commuters. If the new railway line is used at night time to move cargo (goods and merchandises) between the city and the so mentioned towns and villages, then the main roads currently used by trucks to move the same will experience less traffic loading and their rate of deterioration will be reduced. Let us think the new railway comes accompanied by park-and-ride, drop-and-kiss facilities at all new stations: all intersections leading to the stations might likely observe an increase in the number of vehicles during the peak time (and likely, but not as severe, at other peaks but because of the stratified work-exit-time), associated to an increase in the level of congestion and a drop in the level of safety of road users. In a nutshell, any new piece of infrastructure must be assessed in a multi-systems context to attempt to clearly capture its benefits and drawbacks in the short, medium, and long terms.

The need for a 3–5 years tactical planning comes from the fact that long-term plans are always followed with a degree of uncertainty in deterioration, intervention effectiveness, as well as constraints such as available budget. This brings a need to review coming years incorporating the most recent information, which may reprioritize actions.

Furthermore, most decision support systems provide a prioritized list of projects, which often disregards any measures of spatial and temporal proximity between the selected actions to be implemented. For example, think of the maintenance of a pavement, which requires mill and overlay. Now imagine there are multiple sections of the road schedule next year and the year after and they are one next to the other. In such a case, keeping the list of maintenance projects as is will lead to traffic disruptions next year and the year after. Perhaps merging both either this year or next year is better as traffic will be disrupted only once. The disruption of traffic has impacts on the safety of motorists and other road users (pedestrians, cyclists); every time that maintenance repairs occur, a temporary traffic management plan needs to be set in place to prevent road accidents and manage the detours of traffic. The disruption of traffic produces longer travel times and affects the productivity of labor in the region (people idling in traffic) and increases the cost structure of goods being moved (freight traveling). In addition, longer travel time implies more fuel and more gas emissions, having a detriment to the environment. Therefore, merging various segments where maintenance was originally scheduled for next year and the following year resulted in advantages in terms of safety and disruptions to the users (Mohammadi et al., 2020).

Besides, bundling these projects reduce construction cost and drop wastes such as multiple mobilizations and demobilizations. Bundling the maintenance of various segments together also aid in securing contractors from other nearby locations because the magnitude of works increases and makes profitable the participation of contractors located farther away. Having larger packages of works could reduce the cost quoted and bring maintenance services otherwise not available (hot in-place recycle per instance) when the package of works increases (Mohammadi et al., 2020).

From a political standpoint, most governments step into power for a given period of time, commonly 4–5 years. Therefore, having a tactical plan helps to have a concrete target for what is accomplishable within such a period. However, it is discouraged for governments to attempt to change tactical plans, as those plans come from long-term planning as explained before.

From an IAM perspective, a mature platform first plans for a long-term (i.e., strategic), which can be 10, 20, or even longer years depending on the type of infrastructure to ensure the long impacts of current decisions are captured and goals will be achieved. Then, the next 3–5 years will be focused to extract tactical plans, based on which actions are later prioritized annually (i.e., operational).

5.2 Decision-Making Approaches: Ranking, Prioritization, Optimization

Every agency prepares a budget to preserve its assets, and always some sort of planning precedes budgeting. The quality of the planning and the budgeting process have a major impact on the condition of the asset network and on the lifecycle cost of maintaining the assets. This section explains the several approaches used to select investments to preserve infrastructure assets. We kick off with the simplest one (ranking) and increase the level of sophistication until we arrive at optimization.

5.2.1 Ranking

The ranking (also known as worst-first) is the simplest approach; it is usually performed in accordance with agency guidelines where treatments are selected to match current condition (a weighting factor may be used to create a condition index) and alternatives for a given year are sorted (ranked) and selected until all the available budget is spent.

A typical ranking will obey the following steps:

- Step 1. The agency assesses the level of condition for all infrastructure assets in its jurisdiction.
- Step 2. Agency rules are used to assign a matching treatment according to the results of Step 1.
- Step 3. A cost estimate is prepared for each asset.
- Step 4. Choices are sorted using given criteria: this can go as sophisticated as cost-benefit ratios to as simple as the worst-first approach (worst condition first, best condition last).
- Step 5. Choices are selected until the available budget for the given year is spent.

Example 5.1

Let’s start with a simple case where some storm pipes are assessed and Table 5.1 provides the condition level, assigned intervention based on their current condition, and the corresponding cost.

Assuming an available budget of $10 million for the coming year, in a basic ranking approach, pipes are ranked based on their condition levels as Table 5.2. Then, respecting the available budget, the first three pipes can be maintained in the first year.

This approach can be improved by assigning a weighting factor to each alternative. For example, the criticality of each pipe (e.g., depending on where it is located in the network) can be assigned a 0–1 weight (less means more critical) as described in Table 5.3.

Table 5.1 Example 5.1 dataset

Pipe ID	Condition level (%)	Treatment	Cost ($M)
16A	38	Major maintenance	3.5
18C	45	Major maintenance	2.5
3F	49	Minor maintenance	1.25
15A	55	Minor maintenance	2
4B	75	Preventive maintenance	0.6
10C	80	Preventive maintenance	0.5
8B	83	Preventive maintenance	0.55
5A	40	Major maintenance	4
6D	60	Minor maintenance	1.5
7D	66	Minor maintenance	1.75

Table 5.2 Example 5.1 solution

Pipe ID	Ranking	Condition level (%)	Treatment	Cost ($M)
16A	1	38	Major maintenance	3.5
5A	2	40	Major maintenance	4
18C	3	45	Major maintenance	2.5
3F	4	49	Minor maintenance	1.25
15A	5	55	Minor maintenance	2
6D	6	60	Minor maintenance	1.5
7D	7	66	Minor maintenance	1.75
4B	8	75	Preventive maintenance	0.6
10C	9	80	Preventive maintenance	0.5
8B	10	83	Preventive maintenance	0.55

Table 5.3 Example 5.1 solution (2)

Pipe ID	Condition level (%)	Weight (Criticality)	Treatment	Cost ($M)
16A	38	0.8	Major maintenance	3.5
5A	40	0.35	Major maintenance	4
18C	45	0.55	Major maintenance	2.5
3F	49	0.95	Minor maintenance	1.25
15A	55	1	Minor maintenance	2
6D	60	0.65	Minor maintenance	1.5
7D	66	0.66	Minor maintenance	1.75
4B	75	0.4	Preventive maintenance	0.6
10C	80	0.35	Preventive maintenance	0.5
8B	83	0.76	Preventive maintenance	0.55

For the same example.

In this case, instead of ranking by only condition level, the ranking factor would be a combination (i.e., multiplying) of condition level and weight (Table 5.4).

Then by ranking pipes based on (condition×criticality), a new list of prioritized pipes will be identified, which is different than Table 5.5.

The ranking approach still can be enhanced by considering multiple condition indicators, which is explained in this coming example.

Example 5.2

Consider the maintenance for pavements of six road sections on a small municipality with a budget of USD$ 5,000,000 per year. The six segments and their current level of damage and structural capacity are presented in Table 5.6.

For this example, a set of rules to select the most appropriate treatment are based on detailed damage indicators of average rutting (mm), average cracked area (%), and deflection basin area (DBA) scaled from 11 (weak) to 36 (strong). The agency has the following rules to judge on the applicable treatments:

Table 5.4 Example 5.1 solution (3)

Pipe ID	Condition level (%)	Weight (Criticality)	Condition*criticality	Treatment	Cost ($M)
16A	38	0.8	30.4	Major maintenance	3.5
5A	40	0.35	14	Major maintenance	4
18C	45	0.55	24.75	Major maintenance	2.5
3F	49	0.95	46.55	Minor maintenance	1.25
15A	55	1	55	Minor maintenance	2
6D	60	0.65	39	Minor maintenance	1.5
7D	66	0.66	43.56	Minor maintenance	1.75
4B	75	0.4	30	Preventive maintenance	0.6
10C	80	0.35	28	Preventive maintenance	0.5
8B	83	0.76	63.08	Preventive maintenance	0.55

Table 5.5 Example 5.1 solution (4)

Pipe ID	Ranking	Condition level (%)	Weight (Criticality)	Condition*criticality	Treatment	Cost ($M)
5A	1	40	0.35	14	Major maintenance	4
18C	2	45	0.55	24.75	Major maintenance	2.5
10C	3	80	0.35	28	Preventive maintenance	0.5
4B	4	75	0.4	30	Preventive maintenance	0.6
16A	5	38	0.8	30.4	Major maintenance	3.5
6D	6	60	0.65	39	Minor maintenance	1.5
7D	7	66	0.66	43.56	Minor maintenance	1.75
3F	8	49	0.95	46.55	Minor maintenance	1.25
15A	9	55	1	55	Minor maintenance	2
8B	10	83	0.76	63.08	Preventive maintenance	0.55

Table 5.6 Full network of pavement sections

Section	Average rutting (mm)	Average cracked area (%)	Deflection basin area (11 min, 36 max)	PCI	Best treatment	Total cost (USD$ million)
Main St. Sect.1	11.5	4	30	86	Microsurface	0.5
McGill St. Sect.4	20	15	34	84	Mill and overlay	1
Spence Av. Sect.2	25	30	14	27	Full reconstruction	3
Edmont St. Sect.5	20	30	21	47	Partial reconstruction	2
Edmon St. Sect.8	2	8	29	85	Crack sealing	0.25
Stevens St. Sect. 7	15	18	24	66	Mill and overlay	1

```
IF(B2<3,IF(C2<10,"Crack Sealing"),IF(B2<13,"microsurfacing",IF(C2<20,"Mill & Overlay",IF(D2>18,"Partial Reconstruction","Full Reconstruction"))))
```

	Section	Average Rutting (mm)	Average Cracked Area (%)	Deflection Basin Area (11min, 36 max)	PCI	Best Treatment
2	Spence Av.-Sect.2	25	30	14	27.1538462	IF(B2<3,IF(C2<10,"Crack Sealing"),IF(B2<13,"microsurfacing",IF(C2<20,"Mill & Overlay",IF(D2>18,"Partial Reconstruction","Full Reconstruction"))))

Fig. 5.1 Example of decision rule implemented on MS-excel

- Rutting <3 mm and cracked area <10% do crack sealing
- 3 mm < Rutting <13 mm can receive micro surfacing
- Rutting >13 mm check cracked area, if less than 20% segment can receive mill and overlay of HMA layer
- Rutting >13, cracked area > 20%, DBA > 18, partial reconstruction (new HMA + base re-compaction and sealing)
- Rutting >13 and cracked area >20%, if DBA <18 do full reconstruction

These rules can be built into an MS-Excel (or any other platform) to automate the decision making as illustrated in Fig. 5.1.

PCI is used to guide ranking as criteria and is formed from the damage indicators using an equal weight of surface defects and structural capacity with the following equation:

$$\begin{aligned} \mathrm{PCI} = {} & \{0.5^{*}\ [100 - (\mathrm{Rutting}/13)^{*}\ \mathrm{Cracked\ area}\%]\} \\ & + 0.5^{*}\ [100^{*}(\mathrm{DBA} - 11)/25] \end{aligned} \tag{5.1}$$

Ranked options are presented in Table 5.7 and the first two segments are selected for maintenance this year, leaving all other segments for future periods.

The problem with ranking is that it neglects several aspects important to the management and scheduling of investments:

Table 5.7 Example of ranking for pavement sections—Worst first ranked options

Section	Average rutting (mm)	Average cracked area (%)	Deflection basin area (11 min, 36 max)	PCI	Best treatment	Total cost (USD$ millions)
Spence Av. Sect.2	25	30	14	27	Full reconstruction	3
Edmont St. Sect.5	20	30	21	47	Partial reconstruction	2
Stevens St. Sect. 7	15	18	24	66	Mill and overlay	1
McGill St. Sect.4	20	15	34	84	Mill and overlay	1
Edmon St. Sect.8	2	8	29	85	Crack sealing	0.25
Main St. Sect.1	11.5	4	30	86	Microsurface	0.5

1. The rate of deterioration is not considered.
2. Long-term impacts on the network are not considered.
3. Economic analysis for alternative strategies is not considered.
4. Gained efficiencies by full optimization of resources are not considered.

Example 5.3

Let us look at how considering the rate of deterioration changes in investment planning. Let us continue with the same example; imagine that the rate of deterioration of the sections is known. This allows us to forecast the condition next year, the required treatment (next year), and its associated cost as shown in Table 5.8. As seen on the table, the first two road segments originally scheduled to be reconstructed (Spence Av. Sect.2 and Edmont St. Sect.5) are still candidates for the same investments.

However, all other sections have further deteriorated and are now candidates for more expensive investments, for instance, Main St. moved from micro-surfacing (at 0.5 USD million) to mill and overlay at 1 USD million.

From an economic analysis perspective, the worst first strategy requires 5 million USD in 2021 and 5.5 million in the year 2022.

Now we ask: What would have been the case if we start by preserving the roads in better condition before fixing the ones in poor condition (called good first approach)?

Table 5.9 shows the case for the assumed 5 million USD budget. As seen, all segments except Spence Av. Sect.2 could have received a treatment that would have rejuvenated them leaving us with a need for 3 million USD for the year 2021, instead of the 5.5 million USD of the worst first approach. A net saving of 2.5 million dollars or 50% of the annual budget.

This example clearly shows the limitation of ignoring deterioration. The ranking is a limited approach that prioritizes investments for 1 year, and hence is the equivalent of a one-year prioritization.

Table 5.8 Lack of consideration of deterioration rate on ranking

Section	2021 average rutting (mm)	2021 average cracked area (%)	2021 deflection basin area (11 min, 36 max)	2021 PCI	2021 best treatment	2022 total cost (USD$ millions)	2022 average rutting (mm)	2022 average cracked area (%)	2022 deflection basin area (11 min, 36 max)	2022 PCI	2022 best treatment	2022 total cost (USD$ millions)
Spence Av. Sect.2	25	30	14	27	Full reconstruction	3						
Edmont St. Sect.5	20	30	21	47	Partial reconstruction	2						
Stevens St. Sect. 7	15	18	24	66	Mill and overlay	1	18	20	21	56.15	Partial reconstruction	2
McGill St Sect.4	20	15	34	84	Mill and overlay	1	23	20	33	76.31	Partial reconstruction	2
Edmon St. Sect.8	2	8	29	85	Crack sealing	0.25	6	12	27.5	80.23	Microsurfacing	0.5
Main St. Sect.1	11.5	4	30	86	Microsurfacing	0.5	15	7	28.5	80.96	Mill and overlay	1

Estimated values for 2022 are based on Engineer’s criteria

Table 5.9 Good first approach

Section	Average rutting (mm) : Before / After	Average cracked area (%): Before / After	Deflection basin area (11min, 36 max): Before / After	PCI: Before / After	Best treatment	Total Cost (USD$ millions)
Main St.-Sect.1	8 / 0	5 / 0	30 / 30	86	Microsurfacing	0.5
Edmon St. Sect.8	2 / 2	8 / 0	29 / 29	85	Crack sealing	0.25
McGill St.-Sect.4	20 / 0	15 / 0	34 / 34	84	Mill and overlay	1
Stevens St. Sect. 7	15 / 0	18 / 0	24 / 24	66	Mill and overlay	1
Edmont St. Sect.5	20 / 0	30 / 0	21 / 34	47	Partial reconstruction	2
Spence Av.-Sect.2	25	30	14	27	Full reconstruction	3

Note: Shaded cells represent road segments that will receive treatment

5.2.1.1 Risk-Based Ranking

Applying a risk assessment to prioritize assets is also a common method to improve ranking where the highest rank is given to an SGR project with the highest measured risk score. Risk management is an extensive topic, but for this purpose, the decision-maker needs to evaluate the risk score (RS) for each asset/system and its required SGR project by estimating two main components of the probability of failure (P) and consequence of failure (C) (Eq. 5.2). By including the consequences (e.g., safety, security, reliability, and availability) of any interruption in the service, this method is seeking a performance-based approach enhancing ranking.

$$\mathrm{RS} = P \times C \tag{5.2}$$

Probability of Failure

The probability of failure for an asset or a system can be estimated using Eq. 5.3 linking failure (F) to asset performance (i.e., reliability [R]) as was described in Sect. 2.3.6.1. P can be defined in a 0–100 or 0–1 range.

$$P = F = 1 - R \tag{5.3}$$

Condition assessment (e.g. 1–5 scale) can be scaled to apply here and measure P. For instance, a grade 1 can be interoperated to 20% reliability and therefore 80% chance of failure.

Consequence of Failure

It would be more challenging to estimate the consequence of failure, as a variety of consequences can be identified such as safety, social, financial, and environmental.

A simplified alternative solution to numerically estimate risk score would be using a guideline, which predefines several levels for a chance of failure as well as consequences. For instance, a very low to a very high level of impact is classified by the organization for each type of consequence to help decision-makers to assign a level to a consequence of failure for each asset/system.

5.2.2 *Prioritization*

Prioritization analyses look into the cost-effective preservation and rehabilitation strategies based on life cycle costs. The most prevalent methods for prioritization are the benefit/cost ratio and the cost/effectiveness method. The output of prioritization is a list of projects requiring action, along with the timing and cost. Compared to ranking, in prioritization, the effectiveness of each treatment can be also tracked and several feasible treatments can be considered at a single (or multiple) point of time while more factors can be used in the decision-making.

These are the steps involved in a (multi-year) prioritization:

- Step 1. Forecast future condition (levels of damage indicator)
- Step 2. Treatment and timing options
- Step 3. Evaluate strategy effectiveness
- Step 4. Perform economic analyses
- Step 5. Use objective measures to prioritize needs
- Step 6. Project future needs

5.2.2.1 Forecast Future Condition (Levels of Damage Indicator)

To explain the steps, we will continue with the same example (Example 5.2). First, we forecast future conditions for 10 years using 3 deterioration curves: one for rutting, another for the cracking area, and the last one for the degradation of the structural capacity (measured by DBA). These curves are applicable to assets at different points of their lifespan, so for instance, Main St. is at 8 mm in terms of rutting, which is then expected to move to 11.5 after one year (Fig. 5.2).

The developed equations from the points are called deterioration models. Figures 5.3, 5.4, and 5.5 show developed models for a group of roads that belong to a given HG. The best-fitted curve is driven by ordinary least squares regression using the average values observed (See Sect. 3.2).

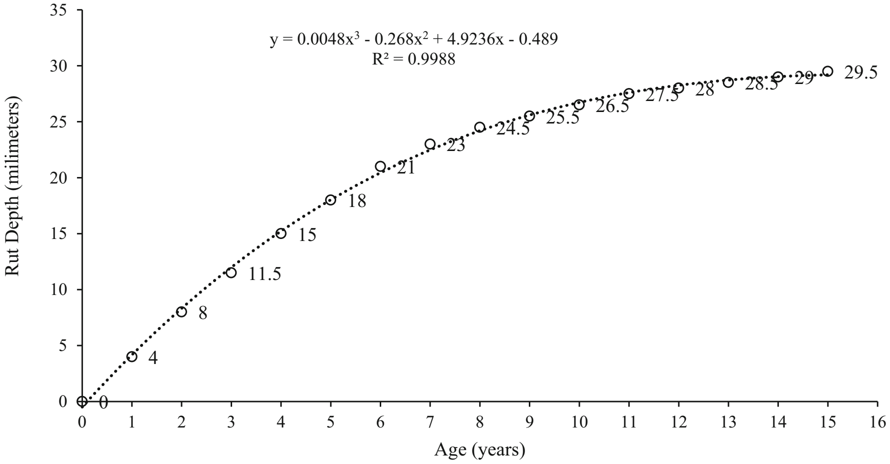


Fig. 5.2 Sample rutting deterioration curve

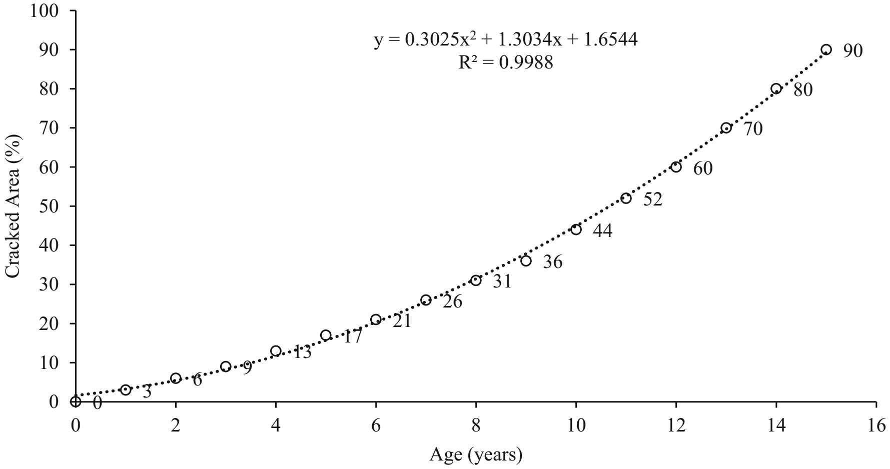


Fig. 5.3 Sample cracking deterioration curve

5.2.2.2 Treatment and Timing Options

We also have the decision rules that aid identify the best timing for treatment as shown in Table 5.10. They summarize the treatments available and their effectiveness. They are employed during the economic analysis.

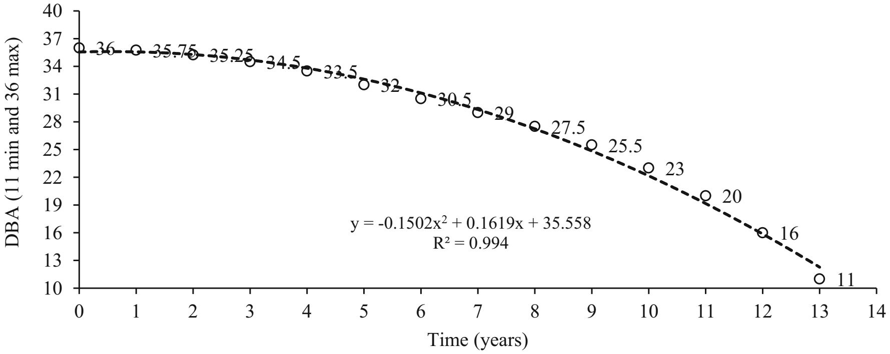


Fig. 5.4 Sample DBA (structural capacity) decay curve

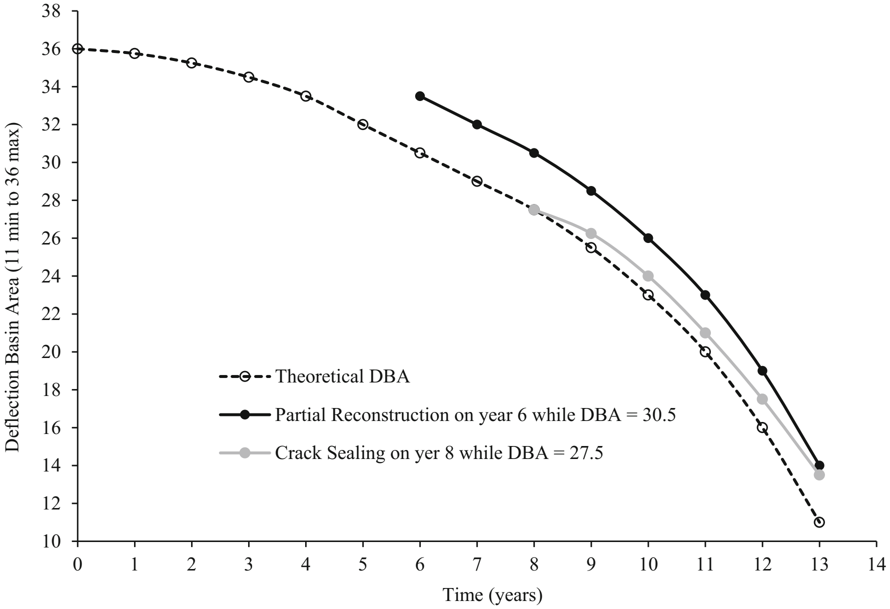


Fig. 5.5 Decay and treatment effectiveness for crack sealing and partial reconstruction

Table 5.10 Treatments and triggers

Rules for treatments	Rutting	Cracking	DBA
Crack sealing	Less 3	Less 10%	N.A.
Micro-surfacing	From 3 to 13	N.A.	N.A.
Mill and overlay	More 13	Less 20	N.A.
Partial reconstruction	More 13	More 20	More 18
Full reconstruction	More 13	More 20	Less 18

Notes: *N.A.* not applicable

5.2.2.3 Evaluate Strategy Effectiveness

The rules of rejuvenation used in the previous examples are summarized in Table 5.11. They are estimated for data analyses of previous sections treated and the post-treatment trends.

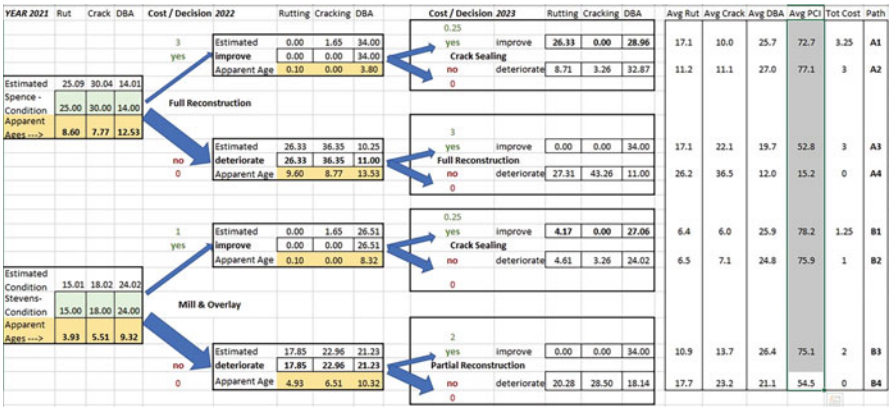
Using the decision rules and taking advantage of the deterioration curves, we can consider the effectiveness of each treatment on the lifespan of the pavement. For example, consider the effectiveness of the structural capacity of partial reconstruction (applied to a pavement that exhibited a DBA of 30.5) and crack sealing applied to the pavement with 27.5 of DBA (Fig. 5.6).

Table 5.11 Strategy effectiveness

Treatment	Rutting effect	Cracking effect	Deflection basin area effect	Rate of deterioration of structure
Crack sealing	None	Reset to zero	None	50% reduction[a]
Microsurfacing (including coat seal)	Reset to zero	Reset to zero	None	50% reduction[a]
Mill and overlay	Reset to zero	Reset to zero	+ 1 unit on DBA[a]	N.A.
Partial reconstruction	Reset to zero	Reset to zero	+ 3 unit on DBA[a]	N.A.
Full reconstruction	Reset to zero	Reset to zero	Max. population value 34 (reset)	N.A.

Notes: *N.A.* not applicable

[a] To be estimated from data



Avg Rut	Avg Crack	Avg DBA	Avg PCI	Tot Cost	Path
17.1	10.0	25.7	72.7	3.25	A1
11.2	11.1	27.0	77.1	3	A2
17.1	22.1	19.7	52.8	3	A3
26.2	36.5	12.0	15.2	0	A4
6.4	6.0	25.9	78.2	1.25	B1
6.5	7.1	24.8	75.9	1	B2
10.9	13.7	26.4	75.1	2	B3
17.7	23.2	21.1	54.5	0	B4

Fig. 5.6 Sample decision tree for prioritization analysis of 2 segments in 2 years

5.2.2.4 Perform Economic Analysis

Considering now the segments for Spence Avenue and Stevens Street only for the prioritization analysis along with the corresponding treatment as per the previous decision rules and the associated cost. As seen in Fig. 5.6, this opens eight different time paths, four for each road segment. But it does not stop there; there are 16 combinations possible for the four paths of the first segment and the four paths of the second segment. This is often called the decision tree from which economic analysis needs to be conducted to select the prioritized list of choices.

Let us now look at the combinations from both segments (16 in total) on the left portion of Table 5.12. In addition, on the right-hand side, we have the dominance analysis that eliminates 10 options that are inferior (or dominated by the combination given in the "Inferior" column).

So, if your budget is 4.25 million, you can choose combination A2 B1 (Spence full reconstruction 2022 and nothing on 2023, Stevens mill and overlay in 2022, and crack sealing in 2023); but if your budget is 4 million, your combination would be A2B2 (Spence full reconstruction 2022 and nothing on 2023, Stevens mill and overlay in 2022 and nothing in 2023); and so on. Budget levels are possible for 1, 1.25, 3, 4, and 4.25 million. Evidently, this oversimplified example ignores the reality of having to plan for several years and for networks with hundreds of segments.

Table 5.12 Time path combinations and dominance analysis

Combination	Total PCI	Total cost	Avg PCI
A1 B1	151	4.50	75.5
A1 B2	149	4.25	74.3
A1 B3	148	5.25	73.9
A1 B4	127	3.25	63.6
A2 B1	155	4.25	77.7
A2 B2	153	4.00	76.5
A2 B3	152	5.00	76.1
A2 B4	132	3.00	65.8
A3 B1	131	4.25	65.5
A3 B2	129	4.00	64.3
A3 B3	128	5.00	63.9
A3 B4	107	3.00	53.6
A4 B1	93	1.25	46.7
A4 B2	91	1.00	45.5
A4 B3	90	2.00	45.1
A4 B4	70	0.00	34.8

Combination	Total cost	Avg PCI	Inferior
A2 B1	**4.25**	**78**	**No**
A2 B2	**4**	**77**	**No**
A2 B3	5	76	Yes A2B2
A1 B1	4.5	75	Yes A2B2
A1 B2	4.25	74	Yes A2B1
A1 B3	5.25	74	Yes A2B2
A2 B4	**3**	**66**	**No**
A3 B1	4.25	66	Yes A2B4
A3 B2	4	64	Yes A2B4
A3 B3	5	64	Yes A2B4
A1 B4	3.25	64	Yes A2B4
A3 B4	3	54	Yes A2B4
A4 B1	**1.25**	**47**	**No**
A4 B2	**1**	**46**	**No**
A4 B3	2	45	Yes A4B2
A4 B4	**0**	**35**	**No**

Imagine what this would look like for a network with a few hundred assets, a couple of decades, and more than one criterion (for instance, adding travel time, road safety, or any other criteria that are forecasted on time and can rejuvenate or change according to treatments scheduled). For this reason, mathematical optimization became common to solve this problem.

5.2.2.5 Performance Targets and Funding Needs

The projection of future needs is a rather difficult task that requires the estimation of funding needs to accomplish desired performance targets (Fig. 5.7). For instance, consider in the example presented before (Table 5.12); we want to ensure certain performance goals in the form of pavement surface condition and structural preservation such as the rutting in the network not surpassing 14 mm and DBA to remain above 25. In such a case, the only feasible path is A2 B1 for a budget requirement of 4 million in the year 2022 and 25,000 in the year 2023.

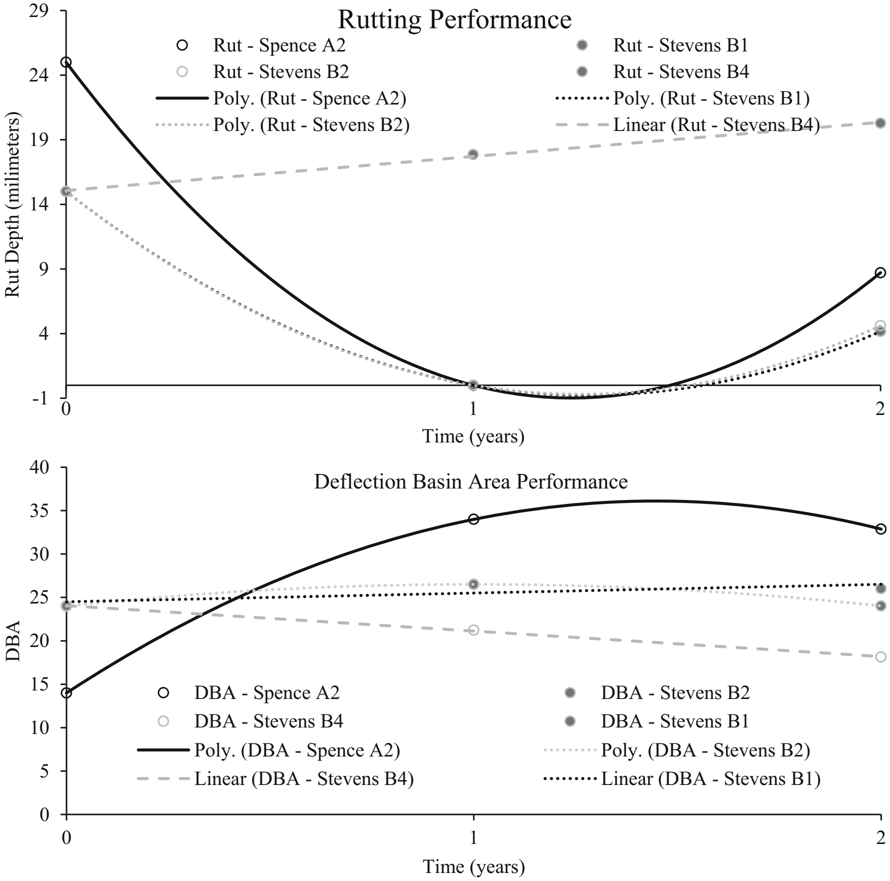


Fig. 5.7 Performance projection and targets

5.2.2.6 Use Objective Measures to Prioritize Needs

In the previous example, we utilized pavement condition and cost as the measures to prioritize and select time paths for each asset across time. However, there are other measures that could have been used to prioritize, such as road safety indicators, travel time, accessibility levels, vehicle operating cost, environmental gas emissions, etc. Further information on how to use these measures can be seen in Chap. 6.

5.2.3 *Optimization*

Prioritization techniques improve the worst-first and ranking method in several aspects; however, still some limitations can be identified:

- In real cases, we have many assets while different scenarios could be implemented for each one. Thus, it means many alternatives and scenarios that are challenging to handle manually.
- As it was discussed, developing a multi-year plan is critical. Thus, decision-making would be more and more complex.
- Solving multiple treatment strategies would be much more complex.
- Even multi-year prioritization models disregard the impact of decisions for long-term objectives and can only capture medium-term consequences.

Like all other scientific problems, the rationale behind using optimization tools is enabling us to find the optimal solution for complex models with unlimited alternatives (i.e., many variables, several objectives, and constraints). For infrastructure with many assets and maintenance alternatives, long-term planning for 20 or 30 years is complex decision-making and a computing-intensive process that requires optimization techniques for its formulation and its solution.

5.2.3.1 Decision Variables

As the main base of the optimization model, variables link decision alternatives to the model. In IAM, typically assets are variables that may or may not be selected for intervention. Thus, the next year's decision-making problem for infrastructure with 100 assets includes 200 (100*2) variables while each asset can be given two variables of 1 and zero (Eq. 5.4).

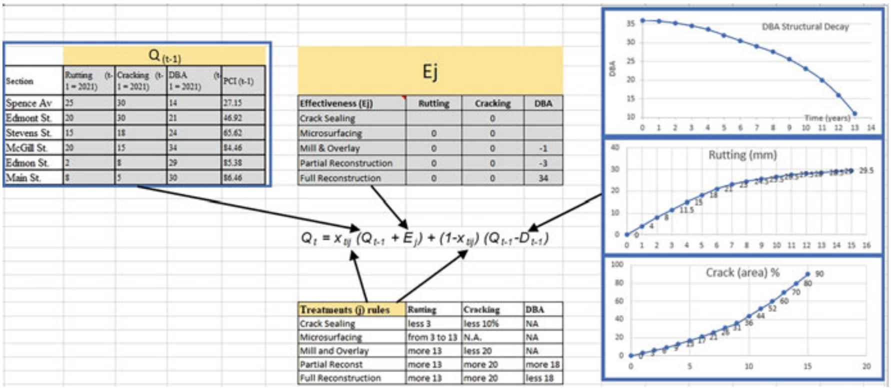
$$X_{s,t} = \begin{cases} 1 & \text{if action is taken on asset } s, \text{in year } t \\ 0 & \text{if no action taken on asset } s, \text{in year } t \end{cases} \tag{5.4}$$

It should be clarified that the total number of alternatives is usually much more than the number of variables. For the same example, if we assume that the budget forces asset managers to pick only 10 from 100 assets, then the total number of alternatives only for the first year would be 1.7×10^{13}. This number goes up if more than one feasible action can be selected for a single asset at the same time. For this reason, computer-based mathematical optimization would be a feasible solution to solve such problems.

5.2.3.2 Dynamic Link

The formulation of the path that asset follows across time requires a dynamic link to connect each year with the following one, similar to the recursive formulations used in economics. Consider the asset "i" with a condition "Qi" on any given period of time "*t*" and the previous period "$t-1$" (often in terms of years); a simple decision variable of "yes" = 1 and no = 0 is used to represent the decision to provide the maintenance selected as per the decision rules (i.e., Table 5.12). If the maintenance is deployed, the asset will improve according to the effectiveness of the treatment "E", but if the decision is made to do not provide maintenance, the asset will deteriorate "D" (Fig. 5.8). This time dynamic is captured by the equation shown in Fig. 5.9.

If the maintenance happens on any given year "$t-1$", the variable x_{tij} takes on the value of 1 and only the first term of the equation survives $(Q_{t-1} + E_j)$ and reports back a value of condition "Q_t". If the decision is made NOT to do the maintenance, then only the second portion of the equation survives and reports back a value "Q_t". This equation is the foundation for the formulation of the path of each asset for the entire analysis period, progressing forward from the current year through time until the last analysis year, opening branches of the decision tree, such as the one illustrated in Fig. 5.7, but for much more than 2 years.



	$Q_{(t-1)}$			
Section	Rutting (t-1 = 2021)	Cracking (t-1 = 2021)	DBA (t-1 = 2021)	PCI (t-1)
Spence Av	25	30	14	27.15
Edmont St.	20	30	21	46.92
Stevens St.	15	18	24	65.62
McGill St.	20	15	34	84.46
Edmon St.	2	8	29	85.38
Main St.	8	5	30	86.46

Ej

Effectiveness (Ej)	Rutting	Cracking	DBA
Crack Sealing		0	
Microsurfacing	0	0	
Mill & Overlay	0	0	-1
Partial Reconstruction	0	0	-3
Full Reconstruction	0	0	34

$$Q_t = x_{tij} (Q_{t-1} + E_j) + (1-x_{tij}) (Q_{t-1} - D_{t-1})$$

Treatments (j) rules	Rutting	Cracking	DBA
Crack Sealing	less 3	less 10%	NA
Microsurfacing	from 3 to 13	N.A.	NA
Mill and Overlay	more 13	less 20	NA
Partial Reconst	more 13	more 20	more 18
Full Reconstruction	more 13	more 20	less 18

Fig. 5.8 Dynamic link and its connection to the effectiveness, deterioration, and decision variables

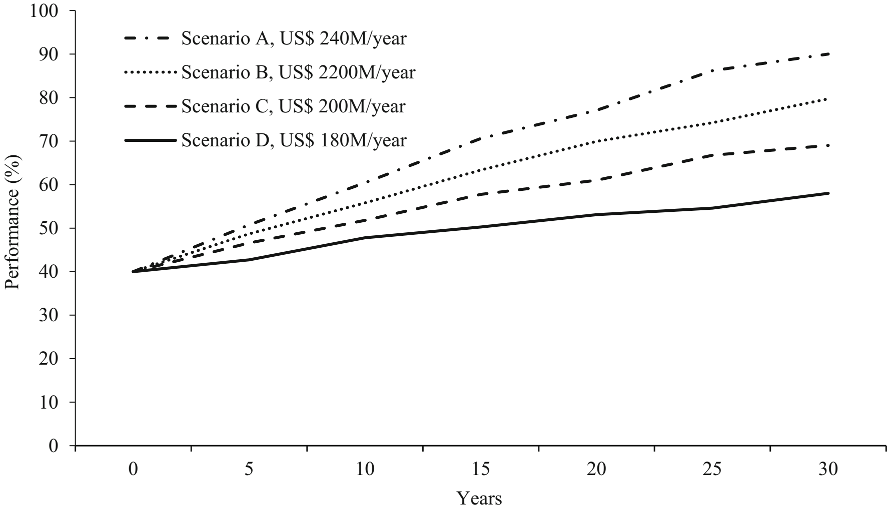


Fig. 5.9 A sample long-term plan

5.2.3.3 Objective Function

The next element necessary for any optimization is the objective equation. Simply put, the objective function establishes an expression that uses the decision variable to obtain either the minimum or maximum network-level aggregated values for a given key performance indicator.

Consider for instance the decision to maximize the level of DBA condition for the entire network or minimize the level of rutting or cracking for the previous example. Such objectives require a summation function and of the decision variable applicable for each asset, segment, or component candidate to receive maintenance, rehabilitation, upgrade, or reconstruction.

Let us continue with the previous example of road pavement sections, and write down the expression to maximize the DBA condition.

$$\max \sum_{i=1}^{n} \mathrm{DBA}_{tij} = \max \sum_{i=1}^{n} x_{tij}\left(\mathrm{DBA}_{t-1} + E_j\right) + \left(1 - x_{tij}\right) \times \left(\mathrm{DBA}_{t-1} - D_{t-1}\right) \quad \forall t \tag{5.5}$$

However, the previous expression could lead to an annual optimization for every year t. Instead, we need to attempt the maximum value for the whole analysis period as well, therefore expanding the expression as follows.

$$\max \sum_{t=1}^{T} \sum_{i=1}^{n} \sum_{j=1}^{J} x_{tij}\left(\mathrm{DBA}_{t-1} + E_j\right) + \left(1 - x_{tij}\right)\left(\mathrm{DBA}_{t-1} - D_{t-1}\right) \quad \forall t \tag{5.6}$$

Extending the previous equation to other indicators requires a simple replacement only. Of more interest will be to minimize the total cost for the whole network. This is based on the unitary cost (C_{tij}) on year "t" of treatment "j" for asset "i"; and the size (S_{tij}) on time "t" of asset "i" receiving treatment "j", which will be written for an annual basis as follows:

$$\min \sum_{t=1}^{n} x_{tij}\ C_{tij} S_{tij} \quad \forall t \tag{5.7}$$

To simplify formulation, a common assumption is considering a single treatment option for each condition (or age) range during asset lifecycle. For instance, as Fig. 5.9 shows, crack sealing will be implemented only when rutting is less than 3. Therefore, there would be only one treatment (j) at the same time, which means this J sigma can be removed from the formulation. This assumption is in line with best practices approaches and reflects reality.

Decision-making for IAM could be multi-objective, and different methods of goal programming or weighted average have been used by scholars to run optimization models. Chapter 6 provides some examples of multi-objective optimization in IAM planning.

5.2.3.4 Constraints

The last piece of the puzzle in the formulation of an optimization problem is given by the constraints. They impose limits on the feasibility of the decision variable. For instance, an annual budget of USD 5,000,000 will be formulated as follows:

$$\sum_{t=1}^{n} x_{tij}\ C_{tij} S_{tij} < 5{,}000{,}000 \quad \forall t \tag{5.8}$$

Another common constraint is the desire to accomplish a minimum or maximum level of a given indicator; for example, average network rutting for time t (RUT_{tij}) to be less than 14 mm would be formulated as follows:

$$\frac{\sum_{i=1}^{n} \mathrm{RUT}_{tij}}{\sum_{i=1}^{n} S_{tij}} < 14, \text{where } \mathrm{RUT}_{tij} = x_{tij}\left(\mathrm{RUT}_{t-1} + E_j\right) + \left(1 - x_{tij}\right)\left(\mathrm{RUT}_{t-1} - D_{t-1}\right) \tag{5.9}$$

5.2.3.5 How to Solve an Optimization Problem

There are two major techniques to solve an optimization problem: (1) Heuristic methods and (2) linear (non-linear) programming. Heuristic methods use an engine to generate values of the decision variable (either 1 or zero) for all possible branches across the decision tree formulated as in Sect. 5.2.2.4. There are multiple engines to do so, being the most simple, the one called genetic algorithm consists of a random binary number generator, a record of the sequence (chain) of binary numbers, and the corresponding value of the objective function and the constraints while eliminating any iteration that produces a violation of the constraints and saving those that do not.

One of the main problems with this approach is that there is no way to ensure one has accomplished the optimal value; always the analyst will end up with a suboptimal value whose quality will depend on the number of iterations and the ability to identify specific binary sequences that produce superior values and implementing some mechanism to control the evolution by keeping those portions of the binary sequence that support the accomplishment of the objective (maximization or minimization) and generating new values for those portions which do not. This approach is called heuristic evolutionary, with specific tactics such as simulated annealing, ant colony, and many others, which the reader can find in optimization books.

For what matters in this book, the heuristic approach is a fast way to obtain results, but the only way to accomplish the true optimal value is by utilizing linear programming. Linear programming uses the simple algorithm in its foundation and visits the feasible space of the problem as delineated by the constraints trying to move in the direction of the objective (maximize or minimize) until the last point of the feasible space is found and such point delivers the binary sequence of the decision variable.

Unfortunately, running linear programming with time dependencies (dynamic) and for a binary variable for thousands of assets and multiple years is computationally expensive and poses a burden on the capability of the computer being used.

For these reasons, the best approach to handle the optimization of infrastructure networks and facilities is to prepare the optimization problem and define the mechanisms for the time dependencies with the dynamic link, the treatment rules, the cost, and the effectiveness of the treatments in the first instance in any desired platform, and handle the solution via commercial solvers (such as MOSEK [Mosek ApS, 2020], LINDO [Lindo System, 2020], CPLEX [IBM, 2020], etc.) or non-commercial (such as Excel solver), which will reduce the problem by eliminating the inferior paths, and those that violate the constraints and solve the problem through advanced matrix algebra techniques, which is out of the scope of this book.

The ideal approach is to run the optimization model for the entire time window (e.g., 20 years). For example, using Eq. 5.6 instead of 5.5 or minimizing the total cost of the whole period of time. However, running an optimization model, in this case, would be more challenging and may need to use commercial solvers and language programming. This should not stop the team to take advantage of optimization and long-term planning. The alternative simplified solution, which can be handled even via non-commercial (such as Excel solver), would be running optimization year by year while each year's decisions depend on the previous year's actions. Still, this approach guides the team toward achieving objectives, however, may not lead to the best scenario. For instance, the final solution to minimize (as an objective) the cost of each year in 20 years plan (running optimization 20 times) can be close but is not necessarily the same as running one optimization to minimize the total costs for the whole 20 years.

5.2.3.6 Optimization Scenarios

The mathematical formulation in optimization models can be defined differently; however, the key factor in selecting the right scenario is respecting organization requirements, constraints, goals, and policy (Amador-Jimenez & Mohammadi, 2020). In the context of IAM, these are the most common scenarios:

Scenario A How much budget do I need to maintain or achieve a non-declining overall condition (Q)?

$$\textbf{Minimize: } Z = \sum_{t=1}^{T}\sum_{i=1}^{I} C_{t,i}.X_{t,i}.L_i \longrightarrow Z_t = \sum_{i=1}^{I} C_{t,i}.X_{t,i}.L_i$$

$$\textbf{Subject to} \quad \sum_{i=1}^{I} Q_{t,i}.L_i \geq \sum_{i=1}^{I} Q_{t-1,i}.L_i$$

$$Q_{t,i} = X_{t,i}(Q_{t-1,i} + q_{t,i}) + (1 - X_{t,i})(Q_{t-1,i} - d_{t,i})$$

$$X_{t,i} = 0 \longrightarrow Q_{t,i} = X_{t,i}(\cancelto{0}{Q_{t-1,i}} + q_{t,i}) + (1 - X_{t,i})(Q_{t-1,i} - \overset{\text{Deterioration portion}}{d_{t,i}})$$

$$X_{t,i} = 1 \longrightarrow Q_{t,i} = X_{t,i}(Q_{t-1,i} + \underset{\text{Gain portion}}{q_{t,i}}) + (1 - \cancelto{0}{X_{t,i}})(Q_{t-1,i} - d_{t,i})$$

where

$Q_{t,i}$ = Overall condition at year t, of asset i after maintenance or do nothing
$x_{t,i}$ yes = 1 and no = 0
L_i = size of the asset
$C_{t,i}$ = Unit cost of treatment on asset i at year t.
B_t = budget for year t
$q_{t,I}$ = Improvement portion of condition from the year $(t - 1)$ to year "t" for asset "i"
$d_{t,I}$ = Dropped portion of condition from the year $(t - 1)$ to year "t" for non-selected asset "i"

Scenario B How much budget do I need to achieve a target overall condition (LOS_n)?

$$\textbf{Minimize: } Z_t = \sum_{i=1}^{I} C_{t,i}.X_{t,i}.L_i$$

$$\sum_{i=1}^{I} Q_{t,i}.L_i \geq (LOS_n) \sum_{i=1}^{I} L_i$$

Term is fixed, constant

$$Q_{t,i} = X_{t,i}(Q_{t-1,i} + q_{t,i}) + (1 - X_{t,i})(Q_{t-1,i} - d_{t,i})$$

And LOS_n = Target level of service for the network, n (when you have more than one network of assets and each has its own target).

Scenario C Given that I have a fixed budget per year (B_t), what is the best overall condition achievable?

$$MAXIMIZE: Z_t = \sum_{i=1}^{I} Q_{t,i}.L_i \quad \textbf{OR} \quad MAXIMIZE: Z_t = \frac{\sum_{i=1}^{I} Q_{t,i}.L_i}{\sum_{i=1}^{I} L_i}$$

$$0 < \sum_{i=1}^{I} C_{t,i}.X_{t,i}.L_i \leq B_t$$

$$Q_{t,i} = X_{t,i}(Q_{t-1,i} + q_{t,i}) + (1 - X_{t,i})(Q_{t-1,i} - d_{t,i})$$

5.3 Asset Management Plan

By completing decision-making, asset managers would be able to extract planning outputs. Asset management plan (AMP) is a typical key report for organizations, which presents the AM path. This document is a tool to define, track, and manage SGR projects communicating internally with various teams including engineering, finance, operation, project delivery, and senior managers. AMP should be an alive and comprehensive report, which includes but is not limited to these sections:

5.3.1 *Goals and System KPIs*

What are the main KPIs and targets to achieve organizational goals? What are the current standing points and what would be the goals for the future?

5.3.2 Assets Portfolio

This section provides a summary of registered assets including the location, quantity, current condition/performance, and RV.

5.3.3 Plans

Different types and layers of plans such as long-term (strategic), medium-term (tactical), and short-term (operational) can be provided in this report. AMP can be updated yearly or longer such as every 3 years base and the plan will be presented accordingly. It is supposed to provide an operational plan including a list of assigned interventions/budgets for selected assets/systems in the coming year/years. At the same time, tactical and strategic plans provide a longer-term view of future investments and achievements respecting KPIs. Figure 5.9 presents a sample long-term plan analyzing different budget scenarios. LOS in this figure can be any type of KPIs (e.g., PCI for pavement, BCI for bridge, and FCI for building), while the impacts of different budget scenarios are investigated. These kinds of analyses are key tools for policymakers to capture the future impacts of current decisions and to select the appropriate approaches addressing all stakeholders' concerns and expectations.

5.4 Exercises

Exercise 5.1

A recent assessment for a city is partially presented in the below table. If you are assigned \$1,500,000 for the first coming year, how do you plan for maintenance?

A. If you don't care about traffic
B. Considering traffic as a weighting factor

Note: Construction team recommended to do minor maintenance for $60 \leq \text{PCI} < 90$ (\$10,000 per kilometer per lane), major maintenance for $40 \leq \text{PCI} < 60$ (\$50,000 per kilometer per lane) and reconstruction for PCI < 40 (\$200,000 per kilometer per lane) (Table 5.13).

Exercise 5.2

A road agency recently built a highway, and experts suggested three different scenarios for maintenance. The AADT is predicted to be 85,000, and inflation could be neglected. The cost for minor maintenance, major maintenance, and reconstruction are \$10,000, \$50,000, and \$200,000 per lane per kilometer, respectively. The interest rate is 5% annually. Scenario 1 includes doing a minor after every

Table 5.13 Exercise 5.1 dataset

Segment	AADT	Current PCI	Length (km)	Number of lanes
A	353	66	6.5	2
B	450	88	5	2
C	7000	45	3	3
D	3500	50	3	3
E	21,000	69	2.5	4
F	15,500	52	3.25	4
G	9900	75	4	3
H	18,000	40	2.8	4
I	800	35	3.6	2
J	6000	55	3.56	3

Table 5.14 Exercise 5.3 dataset (1)

Segment	Current condition (PCI)	Length	Deterioration rate
s1	75	5 km	5 points/year
s2	50	10 km	5 points/year

4 years four times. The second scenario would be doing minor after 4 years and then doing major after 8 years from minor maintenance. Finally, doing reconstruction after 16 years. Answer the below question briefly and to the point:

- Which scenario has a minimum life cycle cost ($) (only cost related to maintenance and construction)?
- Which scenario does not look to be a feasible approach? Why?
- Which scenario may provide the highest service for users (ignore feasibility)? Why?
- Which scenario do you pick? Why?

Exercise 5.3

Develop a two-year decision tree for a road network of two segments and answer the below questions:

- What would be the required budget to achieve the highest network PCI?
- What would be the network PCI for a no-budget scenario?
- What would be the best possible achievement (i.e., network PCI) for a total available budget of $ 2,500,000? (Tables 5.14 and 5.15)

Table 5.15 Exercise 5.3 dataset (2)

Treatment	Operation window	Cost per km	Effectiveness
1—Crack sealing	70–90	25,000	Gain 5 points
2—Micro-surfacing	60–69	50,000	Gain 30 points
3—Thin overlay	50–60	200,000	Gain 40 points
4—Reconstruction	0–50	500,000	Brand new
5—Do nothing	91–100	0	None, deteriorates

References

Amador-Jimenez, L., & Mohammadi, A. (2020). Decision making methods to prioritise asset-management plans for municipal infrastructure. *Infrastructure Asset Management*, 1–14.

IBM. (2020). CPLEX software. https://www.ibm.com/

Lindo System. (2020). LINDO software. https://www.lindo.com/

Mohammadi, A., Igwe, C., Amador-Jimenez, L., & Nasiri, F. (2020). Applying lean construction principles in road maintenance planning and scheduling. *International Journal of Construction Management*, 1–11.

Mosek ApS. (2020). MOSEK software. https://www.mosek.com/