**Notes on Project Evaluation**

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# Note on Infrastructure Costs

This note addresses the major factors that relate to the cost of infrastructure.

## Cost of a Component

The production cost of a component depends upon the size and shape of the component, the materials, and the production process. The quality of the component – however measured – will be a different function of the same factors. The quality of structural components could relate to both engineering and aesthetic parameters, including strength, durability, susceptibility to wear or corrosion, fatigue life, ease of transport, ease of construction, appearance when new and appearance over time. The production process can be important in terms of the material properties of the completed component, the quality control (i.e. probability of defects in the completed component), and the cost of production. For commonly used components, there may be great economies of scale in production, so that the costs of materials and transportation will dominate; for specialized components, there may be a high cost related to design or specialized production techniques.

The production cost of a component is not the only cost that is of interest. It is also necessary to consider how long the component will last, how it might fail (and the consequences of failure), how will it will stand up to the environment and to usage, and how and why it will eventually have to be replaced. The costs of a component over the life of a project will therefore reflect maintenance, safety, and operating concerns. The lifecycle cost can be calculated as a net present value or as an equivalent uniform annual cost; the equivalent uniform annual cost will be easier to use for comparing infrastructure costs with operating costs and revenues.

The major cost elements that may be considered will be as follows:

1. Purchase of materials
2. Transport of materials to production facility
3. Production of components
4. Transport of components to project site
5. Construction costs
6. Inspection costs
7. Maintenance costs
8. Rehabilitation costs
9. Replacement costs
10. Failure costs

The first four items comprise what might typically be thought of as the elements determining the unit price of the components, whether gravel, structural steel, or highly polished marble that is delivered to a construction site. Gavel is widely available, cheap, and transportation costs tend to dominate all other factors. Steel is manufactured at very large mills, and the quality of the steel may be very critical; transportation costs are a much smaller fraction (10-20%) of the product cost, so supplies may be obtained from many different places around the world. Beautiful marble, suitable for use in the lobby of a major building, will be very expensive, require specialized work forces, and be available only at a few locations; material costs and skilled labor will therefore dominate.

Construction costs aren't normally considered as a component cost, but ease of construction is certainly a factor in the selection of components. Composite materials may be favored in certain projects because they are as strong as and much lighter than steel, and therefore cheaper to install.

The last five items are all interrelated. The nature and frequency of inspections is driven by the risks associated with component deterioration or failure. If these risks are negligible, then inspection may not be necessary. If it is necessary to conduct routine maintenance to avoid rapid deterioration, then periodic inspections will be part of a normal maintenance management program. If failure of a component is likely to lead to loss of life or severe disruption in operations or living conditions, then inspection at "safe" intervals will be essential. The purpose of the inspection is to determine if there are:

- Any hazards that require immediate attention: a broken rail on a railroad line or a crack in an important bridge component or a leak in a pipe.
- Sufficient deterioration in components to require maintenance or replacement prior to the next inspection interval.

The frequency of inspection must be sufficient to ensure an acceptable level of safety. This requires the interval between inspections to be short enough that defects that are not observable to an inspector are "unlikely" to have time to cause failures prior to the next scheduled inspection. On a railroad, it is possible to use ultra-sonic inspection to identify internal defects within the rail. These defects generally are small cracks that begin at a point where there is some kind of contaminant or microscopic gap within the steel rail. The rail industry has long experience and considerable research that helps them estimate the amount of traffic that can move over the track before the crack grows large enough to break the rail. Theoretical and laboratory studies can be conducted to formulate models of crack initiation, crack growth, wear, corrosion, or other kinds of deterioration.

In general, there will be some kinds of deterioration that increase as the component ages and some kinds of potential failures that become more likely as the component deteriorates. Thus, there will be an increasing probability of some kinds of failure and eventually something will have to be done to preserve a safe operating environment. For railroads, the interval between ultrasonic inspections is related to the traffic volume and the nature of the traffic (because heavier cars cause more fatigue damage). The potential consequences of a failure determine what probability of failure is acceptable. A railway that handles high-speed passenger trains is at much greater risk than one that handles only coal and grain; high-speed passenger lines might therefore have daily inspections, whereas coal lines might have monthly or less frequent inspections.

Even if no safety hazards are identified, inspection may lead to maintenance or replacement of components. Maintenance may be justified in terms of its effect on a) future deterioration of the infrastructure or b) its effect on the performance of the infrastructure. It makes sense to patch cracks in highways before they grow into large potholes, and it makes sense to fix leaks in pipes in order to avoid wasting clean water that is moving toward cities.

Some components will be “maintenance-free”, i.e. they can be expected to remain in service without requiring inspection, maintenance or replacement over the life of a project. Most components will not be maintenance free, and their life cycle costs will include most of the factors listed above. The choice of the components will therefore require what may be rather complex trade-offs concerning initial cost, infrastructure performance, and operating performance. The basic approach to selecting components will be to determine the initial costs (as described above), and the expense and frequency of inspections and maintenance activities over the life of the component.

Component life may be determined by failure, risk, economic factors, or availability of new technology. New components may be so much better that it is justifiable to replace existing components. This will occur if the EUAC (equivalent uniform annual cost) for maintenance and operations over the remaining life of the existing component is higher than the EUAC for a new component (over the expected life of the project or of the new component, whichever is shorter).

The expected life is a key element for estimating the lifecycle cost. In general, the expected life of a component will be the expected time until:

- It fails
- It is replaced as a safety hazard
- It is replaced to avoid reducing facility performance
- It is replaced to reduce annual maintenance costs
- It is replaced to avoid reduced system performance
- It is replaced by superior components
- The project or facility reaches the end of its useful life

Engineering relationships can be developed for each of these (as function of materials properties and usage parameters), and the most likely limits for each component can be studied in great detail. Based upon models or experience, it will be possible to establish the inspection and maintenance activities over the expected life of the component. This information can then be combined with the initial price to obtain a NPV or EUAC for any component under any type of load and annual usage.

The result will be something like this:

NPV(C) = $Inst + ☒NPV(insp(t) x $I) + ☒NPV(maint(t,i) x $Mi) + ☒NPV((fail(t) x $F))

Where:

$Inst = Unit cost of component, including transportation to site and installation

$I = unit cost for inspection

$Mi = unit cost for maintenance activity i

$F = expected consequences of failure

insp(t) = inspections at time t

maint(t,i) = maintenance activity i ocurring at time t

fail(t) = probability of failure at time t

The net present value of all inspections and maintenance activities needs to be calculated for everything that is expected to occur over the life of the facility, where the life is estimated separately, as described above. Given the NPV, it is then straightforward to determine the EUAC over the life of the component and to compare the EUAC for various components that might be used.

This obviously can get quite complex. However, it can be done, and it can be very helpful in designing and managing infrastructure to understand these relationships. There are some useful insights that can be gained from this structure:

- If a component is going to be subjected to a great deal of use, then the benefits of using better components will be clear, even if there is a much higher initial cost.
- If a component is going to be subjected to only modest use, then initial cost will dominate.
- R&D efforts will be devoted toward improving those components with the highest costs or the highest risks.
- Improved inspections can reduce risks of failure and thereby extend the life of components.

Salvage values and the costs related to decommissioning are other factors that can be important for infrastructure costs and design.

## Element Design

For a road, a railroad, an aqueduct, a dam, and many other types of infrastructure, it makes sense to look at the combination of components and elements that define the system. The terms "components and elements" are used to suggest the hierarchical structure of infrastructure: a system is composed of various elements, and each element is composed of various components. For example, a rail system includes terminals, track, turnouts and interlockings (locations where routes cross or diverge), bridges, trestles, signal systems, and maintenance facilities. The track structure's major components are rails, fasteners, ties, ballast, and subgrade. A highway system includes intersections, bridges, rest areas, signs, and signals as well as the roadways. Each roadway has elements similar to those of the railway: a layer of pavement, plus several layers of gravel and subgrade. Both highways and railroads have ditches for drainage.

The choice of components and the way they are combined determine the engineering capabilities of each infrastructure element. For example, the typical cross-section of a railroad is defined by the following:

- The weight, shape, and metallurgy of the rail (which together determine the strength, wear life, and fatigue life of the rail).
- The weight, shape, and materials used for ties (which may be standard wood ties of various dimensions or they may be made of concrete, plastic, or steel).
- The spacing of ties.
- The fastening system (e.g. spikes and tie plates or premium fastening systems).
- The materials used for ballast.
- The depth of the ballast.
- The possible use of geotextiles or an asphalt layer to deal with wet or weak subgrade.

Over many decades, railroads have developed stronger materials, mechanized techniques for installing track, and automated techniques for inspection and maintenance. The result has been to create a track structure that has lower life cycle costs and also can handle heavier trains.

The capacity and cost of the railroad also relate to the gauge (the width between the rails) and the clearances (both vertical and horizontal). Similar design features apply to highways, canals, pipelines, and airport runways. A wider roadbed allows larger trains or trucks, but also requires greater cost.

Another design feature is the number of lanes for a highway or the number of tracks for a railway. This aspect of the design will have a great impact on service capabilities, e.g. speed, daily capacity, peak loads, etc.

Since each element is made up of many components, it is possible to develop a cost model for each element by combining cost models for the components. Once this is done, it will be straightforward to use standard designs to obtain standard costs for, say, a mile of track that can handle coal trains or a 4-lane divided highway in rural areas.

A building is a different type of infrastructure, but the same general approach will work. A building requires various components, and it is possible to determine the cost and performance of the various components and to count the number of components required for an element – which might be a hallway or a room or a floor of a multi-story building or a single-family house.

As with a railroad or a highway, it is possible to use standard designs using standard components to come up with easily-used cost estimates for buildings. The construction industry often expresses building costs in terms of the "cost/square foot" by type of building, because the size of the facility is probably what is of most interest to the client. The contractor needs to prepare cost estimates that easily relate to designs and measures that are meaningful to the client. Therefore, even though costs really reflect the nature and number of the elements and components that make up a building, it is useful to calculate "cost/square foot" for an existing design or an existing building and to use that as a rough estimate for future buildings.

Large contractors often develop specialized experience with specific types of infrastructure, e.g. electric power plants, off-shore oil-drilling platforms, or transit systems. Experts in these areas may think in terms of the cost/megawatt of capacity, the cost per platform, or the cost per station and per route mile – but at some level they will be building upon knowledge of the costs of components, trade-offs related to intial cost and durability, design of elements, and design of the system. The lifecycle costing approach described here will be fundamental for any type of infrastructure.

## Network Design

Infrastructure often takes the form of a network. A transportation network consists of a set of routes, intersections, and terminals. Similar networks are needed for energy distribution, water supply, waste-water collection and treatment, and for transmitting information. Design issues for infrastructure networks include the selection of the elements for each location as well as the layout of the network and its affect on accessibility and service capabilities. Capacity, cost, accessibility, and service capabilities are all relevant concerns. When the networks are first put in place, the main benefits will be in terms of new services – mobility, cheaper energy, cleaner water, or cheaper communications. Once the network is established, further projects will be needed either to maintain service capabilities (maintenance and renewal), to improve service capabilities, to provide additional capacity, or to reduce the negative impacts of the infrastructure (e.g. provide noise barriers for highways or re-route a road around environmentally sensitive areas.)

The network is a collection of elements, so the cost of the network can be built up from the cost of the elements. The only complication is that new types of elements (complex interchanges or high capacity elements) may be needed.

At a network level, system cost will be easier to estimate than system benefits. The design questions will at first relate to the feasibility of constructing any portion of the network.  It may be possible to start some networks with a single route (this is how the rail systems were initially built), but in others, a complex, but locally constrained network may be needed (cable TV).  Given a network, there will constantly be proposals to extend it to new regions, to upgrade it to provide better service, or to increase the capacity.  It is beyond the scope of this note to go into any further detail concerning infrastructure networks – suffice it to say that the issues become very interesting and that estimating both costs and benefits are continuing concerns.