An Engineering Philosophy for the Next Wave of Infrastructure Renewal

Steven G. Pudney, Lin Ma, and Joseph Mathew

Abstract—**This paper examines engineering philosophy in relation to the renewal of aging or outdated infrastructure. The authors test hypotheses concerning standardisation, obsolescence and operational risk using option-pricing models. The results of our study indicates engineering for infrastructure renewal that:**

- **is standardised,**
- **remains relevant for the longest period and**
- **has the lowest operational risk profile when implemented,**

has a higher inherent value than engineering that does not follow such principles when all other factors remain the same.

We conclude that infrastructure renewal guided by the principles of standardisation, obsolescence reduction and operational risk mitigation has a higher value than that without such guidance. We also demonstrate evidence of synergy between the three guiding principles through some examples.

Index Terms—**Engineering obsolescence, Engineering standardisation, Infrastructure renewal, Operational risk assessment.**

I. INTRODUCTION

The modern era has been characterised by development of large-scale, centralised infrastructure that supports the energy, water, waste removal, transport, security and communications needs of our societies. Much of the infrastructure in the developed world, constructed during the post Second World War boom, is rapidly aging [1], [2] and is declining in its relevance.

The values of developed nations are changing and there will be significant costs associated with realignment of current operating practices with our new values. Consequently, the costs of operating existing infrastructure systems are increasing rapidly and this will eventually precipitate fundamental and widespread changes to infrastructure design, installation, renewal and operation. Additional costs in operating existing infrastructure that we see emerging are mainly on two fronts, namely, the cost of greenhouse gas emissions and the cost of insurance. These issues are discussed separately.

A. *Cost of Greenhouse Gas Emissions*

There is recognition by the governments of developed nations that greenhouse gas emissions have had, and will have a significant impact on global warming. The Garnault Climate Change Review [3] commissioned by the Australian government found that “there are advantages in aiming for an ambitious global emissions mitigation target in order to avoid some of the high-consequence impacts of climate change”. Virtually all developed nations have accepted this notion and have introduced or plan to introduce an Emissions Trading Scheme (ETS) to manage the reduction of greenhouse gas emissions.

The European Union has an ETS and is already trading carbon credits, Australia is planning the introduction of a cap and trade ETS, the United States has indicated its willingness to begin emissions trading and has plans to begin a non-mandatory ETS in 2009, Japan has introduced a voluntary ETS and although Canada is struggling with the implementation of a domestic ETS, several of its provinces are planning emissions trading with the US. All developed countries except the United States have committed to their Kyoto emission targets. There will be significant emission related costs associated with the operation of existing infrastructure such as coal fired power generation systems, long-range electricity and water distribution systems and transport systems that are heavy users of carbon based fuels.

B. *Cost of Insurance*

The risk tolerance of infrastructure boards and their insurers has changed substantially in recent years. The high cost and unavailability of insurance has resulted in cases where self-insurance has become necessary. There are many cases where large-scale, centralised infrastructure projects have failed catastrophically with dire consequences. Some examples include:

The 1993 contamination of Milwaukee’s drinking water with cryptosporidium that resulted in more than 400,000 residents being infected and the premature deaths of over 100 people with compromised immune systems [4]. Subsequently, the city of Milwaukee spent US$89 million on upgraded water treatment facilities [5].

The 1998 Auckland power crisis in which four separate power cable failures resulted in the inability of Mercury Energy Limited to supply power to the central business district of Auckland. The power supply was virtually non-existent for 3 weeks and subject to major restrictions for a further month. The Inquiry into the Auckland Power Supply Failure [6] lists lack of awareness of cable condition and “as built” design as well as Mercury Energy’s risk

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management, contingency planning and asset management practices as factors contributing to the failures. It was estimated that Mercury Energy spent NZ$120 million on new infrastructure and compensation [7].

The 1975 failure of the Banqiao and Shimantan Dams in China and subsequent failure of another 60 downstream dams that resulted in the deaths of as many as 230,000 people [8]. An abnormal weather event caused overtopping failure of the first two dams. Those dams were unable to expel water fast enough through their sluice gates and spillways to prevent overtopping.

C. *Objective of this Paper*

The cost of emitting greenhouse gases and the cost of insurance of infrastructure are already having an impact on the financial viability of infrastructure in developed countries. In the future, these factors are likely to have an even larger adverse effect on viability. Yet there appears to be a business-as-usual approach to continue operating, servicing, supporting our current infrastructure and building like-for-like replacement infrastructure. In fact, the renewal and expansion of existing infrastructure using “old world” principles, is about to increase rapidly with the deployment of some large-scale economic stimulus packages across the developed world.

Our current engineering practices are based on old thinking patterns and need to be challenged lest we overlook a better way. The objective of this paper is to propose and validate an engineering philosophy for infrastructure renewal that is relevant to our current circumstances and will serve to guide us judiciously into the future.

II. THEORETICAL BACKGROUND

A financial option is the right, but not the obligation, to buy or sell a financial asset such as shares at an agreed price. A real option (viz. engineering option) is the right, but not the obligation, to undertake different courses of action in relation to real assets.

In this paper, we consider the engineering for infrastructure renewal to be a real option on an infrastructure renewal project. By taking an engineering option, we can be flexible in the face of changing circumstances, choosing to implement the engineering (renew the infrastructure) when circumstances are most suitable or not at all if there is a change to the requirements for that infrastructure.

The value of an engineering option can be calculated using an Option-Pricing Model (OPM). Such OPMs are used to calculate the theoretical trading price of financial options and to calculate the value of real options.

OPMs can be categorised as closed form models (which are computationally efficient but can be inaccurate depending on assumptions) and numerical models (often highly accurate but can be computationally inefficient). OPMs can further be categorised as either “European”, which means the option can be exercised only on maturity or “American” which means the option can be exercised at any time up to maturity.

In 1973, Fischer Black and Myron Scholes developed a closed form option pricing model [9]. The Black-Scholes Option Pricing Model (BSOPM) shown in equations (1) to (3) is used for pricing European options.

$$C = S \cdot \Phi(d_1) - X \cdot e^{-rT} \Phi(d_2) \tag{1}$$

$$\textit{such that} \quad d_1 = \frac{\ln(S/X) + \left(r + \tfrac{1}{2}\sigma^2\right)T}{\sigma\sqrt{T}} \tag{2}$$

$$\textit{and} \quad d_2 = d_1 - \sigma\sqrt{T} \tag{3}$$

Where C is the European call option price. S is the stock price, X is the exercise price, r is the risk free interest rate, σ is stock price volatility and T is the time to option expiry.

In deriving this model, Black and Scholes’ assumptions were that:

1. The stock price can be described in the form:
$$S_t = S \cdot \exp\left\{\left(\mu - \tfrac{1}{2}s^2\right)t + Z_t s\right\} \tag{4}$$
such that μ and s are drift and volatility terms respectively and Z_t is a standard Brownian motion with expectation $E_0[Z_t] = 0$ and variance $E_0[(Z_t)^2] = t$. In our case, μ translates directly to being the risk free interest rate (r) and s becomes the stock price volatility (σ).
2. The risk free interest rate is constant.
3. It is possible to borrow the price of the stock (at the risk free interest rate) to buy or hold that stock.
4. There is no dividend or distribution paid by the stock.
5. The option cannot be exercised until maturity.
6. Other assumptions with respect to perfect, frictionless markets. That is, no transaction costs in buying or selling the stock or option, no penalties or transaction costs in short selling the stock.

Merton [10] has shown that the value of a European option is always greater than the value it would have if it were exercised immediately. A rational investor would never exercise an American option before maturity, and so the value of an American call option is the same as the value of a European call option.

From the late 1970s a number of people began to see an analogy between financial options and real options and that financial option pricing models could be used to determine the value of real options. Leslie and Michaels [11] suggested an analogous relationship between financial options and real options (table I). We use this analogy in calculating the value of engineering options for infrastructure renewal.

The following definitions are used in conjunction with terminology used in this paper:

Engineering: Designs, specifications, drawings, budgets, plans, schedules and programs that are sufficient for the complete manufacture, procurement, construction and commissioning of a physical asset.

Engineering option: Engineering for a given project or projects that may or may not be implemented.

Engineering value: The theoretical price of an engineering option for a given infrastructure renewal project calculated using an option pricing model.

TABLE I: THE SIX LEVERS OF FINANCIAL AND REAL OPTIONS

Financial Option Value Levers	Equivalent Real Option Value Levers
Time to option expiry (T)	Time to real option expiry
Stock price (S)	Present value of expected cash flows
Volatility in stock price movements (σ)	Volatility in expected cash flows
Dividends	Value lost over duration of option
Risk free interest rate (r)	Risk free interest rate
Exercise price (X)	Present value of project fixed costs

III. DESIGN OF THIS STUDY

In our study of engineering infrastructure renewal, we propose three hypotheses. The hypotheses are tested, results are analysed and conclusions are drawn.

The hypotheses chosen were derived from discussions with colleagues with wide ranging experience in engineering management covering several engineering disciplines. Our hypotheses are as follows:

Standardisation. Engineering capable of multiple uses has a higher value than single use engineering when all other attributes of that engineering and the application remain the same.

Obsolescence reduction. Engineering that is relevant for a longer period has a higher value than engineering with relevance for a shorter period when all other attributes of that engineering and the application remain the same.

Operational risk mitigation. Engineering that gives rise to lower operational risk has a higher value than engineering giving rise to higher operational risk when all other attributes of that engineering and the application remain the same.

Both the *Standardisation hypothesi*s and the *Operational risk mitigation hypothesis* are tested using deductive reasoning assuming that the BSOPM adequately represents the value of an engineering option.

For the *Standardisation hypothesis*, we assume multiple use engineering results in the reduction of fixed costs for implementation (X) because of synergy between like projects. We also assume all other variables in the BSOPM remain unaffected by standardisation.

For the *Operational risk mitigation hypothesis*, we assume lower operational risk results in higher project cash flow. Once again, we assume all other variables in the BSOPM remain identical.

Under the *Obsolescence reduction hypothesis*, we assume engineering that becomes obsolete (or irrelevant) sooner results in an engineering option that has a shorter time to expiry. We assume all other variables in the BSOPM remain identical.

The obsolescence hypothesis is tested using the BSOPM and Monte Carlo simulation software. Ranges chosen for each variable are broad enough to cover all likely and many unlikely scenarios. We use uniform distributions within the ranges for each variable and set the number of trials to 100,000. The ranges set for each variable are as follows:

TABLE II: VARIABLE RANGES FOR OBSOLESCENCE HYPOTHESIS TEST

Variable	Description	Range	Units
S	Present value of project cash flows	10 to 100	Currency
S/X	Benefit / Cost ratio	0.5 to 20	Nil
T	Time to engineering option expiry	1 to 50	Years
r	Risk free interest rate	1 to 20	% / year
σ	Volatility	10 to 100	% / year
T_a/T_b	Time to expiry ratio (project a/b)	1.0001 to 10	Nil

IV. RESULTS

The *Standardisation* hypothesis is accepted with the limitation that it applies to projects for which the present value of cash flows is greater than or equal to the present value for project implementation. Our reasoning for acceptance is detailed in Appendix I. Acceptance of this hypothesis implies the acceptance of the *Standardisation* principle. That is, ***Engineering capable of multiple uses has a higher value than single use engineering when all other attributes of that engineering and the application remain the same.***

The *Operational risk mitigation* hypothesis is accepted with the limitation that it applies to projects for which the present value of cash flows is greater than or equal to the present value for project implementation. The reasoning for acceptance is found in Appendix 1. Acceptance of this hypothesis implies the acceptance of the *Operational risk* principle. That is, ***Engineering that has lower operational risk has a higher value than engineering with higher operational risk when all other attributes of that engineering and the application remain the same.***

The *Obsolescence reduction* hypothesis is accepted on the basis that all of the 100,000 simulation trials support the proposition. Acceptance of this hypothesis implies the acceptance of the *Obsolescence reduction* principle. That is, ***Engineering that is relevant for a longer period has a higher value than engineering with relevance for a shorter period when all other attributes of that engineering and the application remain the same.***

These results are combined into an engineering philosophy that is proposed as applicable to the next wave of infrastructure renewal.

V. ANALYSIS AND DISCUSSION

On first inspection, the principles appear to be common sense and provide no new guidance. However, when extrapolated to the logical end, these principles lead to radical changes to our current infrastructure designs.

A. *Standardisation*

The *Standardisation* principle has been in use almost as long as human kind has been producing manufactured objects. The obvious advantage of standardisation is that it enables the cost of design to be spread over many applications. It results in economy of manufacture because tooling and other set-up costs can be spread over many items. A less obvious advantage of standardised designs is that component parts of a standard design can be interchanged and spare part inventories to replace those components that are prone to failure become economic.

If standardisation is taken to its extreme it leads to large scale sharing of engineering solutions. There are local standards for many individual engineering components such as fasteners, flanges and steel section sizes but the extension of this principle demands much more in order to gain the most leverage from our designs. Generic designs that transgress country borders (where one set of standards arbitrarily takes over from another) become a natural solution. Designs that are available for use by any end user are implied. In many ways, this is the engineering equivalent to open source architecture in information technology.

Standardisation with respect to infrastructure naturally leads to many small duplicated solutions rather than singular large specialised solutions. In the case of power generation, for example, standardisation logically points to many local power stations of the same design rather than fewer unique power stations. Following this principle, it makes sense for many houses and small businesses to have a wind generator of the same size and design with some having a generator that is significantly over-designed for the requirement. Alternatively, solar cell energy production coupled with batteries may be applicable in those places where wind speed is too low or too variable. Another example is the use of standardised condensation devices at each house for extracting water from moisture-laden air rather than a dam with pump-stations and water distribution piping.

There is a point of optimisation between the cost of supporting a bigger range of designs and the savings to the customer in matching the design more closely to requirements. We acknowledge this but leave it for others to research.

Barriers to full implementation of engineering standardisation include the desire for protection of intellectual property, country specific standards, differences in units of measure between countries, differences in terminology and language, trade restrictions and the natural desire of designers to match the design to each individual application.

B. *Operational risk mitigation*

The *Operational risk mitigation* principle sounds like common sense. Surprisingly, there are many cases where this principle has been given a low priority. The introduction section of this paper gives some examples of operational failures that have occurred. Obviously, in the examples given, the infrastructure wasn't intended by its designers to fail but it actually did fail and failure was on a grand scale. Why is this so? The answer lies in the fact that the infrastructure is large scale and has a centralised structure.

If we are to mitigate risk, we must choose strategies that work in our favour. We must choose easy and reliable ways to achieve our objective. Infrastructure that is based on a network structure with inbuilt redundancy and backup rather than large-scale centralised infrastructure has an inherently lower operational risk profile. With the network model, if failures occur, they are small and can often be bypassed quickly and easily. Small, localized solutions that are networked rather than large centralised infrastructure enable catastrophic risk to be minimised.

Let us return to the examples of the wind or solar generators and water condensation devices discussed earlier. These can easily be networked to mitigate the risk of failure in any single household. There is much less risk of widespread service interruptions, less risk of widespread water contamination and no risk of dam failure.

Interestingly, networked infrastructure solutions seem to naturally support the standardisation principle in that networked systems can be made up of many interconnected standardised wind generators, solar generators or condensation plants. So the Standardisation principle and the Operational risk mitigation principle could be considered complementary, at least in the examples we have reviewed.

C. *Obsolescence reduction*

The *Obsolescence reduction* principle also sounds like common sense. Of course we would like our infrastructure designs to be relevant for the longest possible time frame. However, we must consciously work to achieve this outcome and not assume that it will naturally follow with any given design.

Addressing obsolescence in the long term requires a return to simplicity, reliability and classic design using readily available, renewable materials that are safe to handle, easy to fabricate and create little or no waste or pollution. Obsolescence is typically associated with the use of rapidly evolving technology, dangerous materials or polluting processes. Use of smaller scale standardised local infrastructure solutions that can be duplicated rather than larger, purpose-built solutions support the reduction of obsolescence. Implementation of long-term planning based on constancy of purpose increases the life of infrastructure designs and enables standardisation to flourish. Reduction in obsolescence requires planning that encompasses a long-term vision about use of renewable resources and non-polluting solutions for the provision of services.

The principle of obsolescence reduction could easily be used to override technical improvements in the design. To prevent this, design changes must be managed in such a way that interfaces with other equipment or systems are rarely if ever changed. Sometimes the principle of obsolescence must give way to superior designs. This must happen when the advantage of a new technology outweighs the disadvantage of obsolescence of the old design.

We return to our examples of wind generators, solar cells, and condensation plants, this time from the perspective of reducing obsolescence. Our proposed equipment makes use of renewable resources (wind, solar energy and moisture in the air) in satisfying their respective functions. This is a good start for minimising obsolescence since we are not likely to incur future costs associated with non-renewable resources that create pollution. However, there are ways in which the Standardisation principle complements the obsolescence principle. It seems natural that standard equipment is less likely to become obsolete than non-standard equipment. Furthermore, a design that is easy to manufacture, operate and maintain is less likely to become obsolete. Therefore, a wind generator or solar electricity generation plant that can be easily operated and maintained by the average householder is in the best interests of reducing obsolescence. Likewise a condensation device that is easy to maintain with standard replacement filters supports the reduction of obsolescence.

D. Value of the Solution

The value of infrastructure engineering has been calculated using an OPM but what comment can we make about the value of the renewed infrastructure itself? Does a higher value option (engineering) automatically imply a higher value solution? Real Option Valuation (*ROV*) of the renewed infrastructure in terms of the Net Present Value (*NPV*) of the project and the option value (*C*) is given by equation (5).

$$ROV = NPV + C \tag{5}$$

Note that *NPV* for a project is given by:

$$NPV = \sum_{t=0}^{T} \frac{S_t}{(1+r)^t} \tag{6}$$

In the case of standardisation, we have shown in Appendix I that *C* increases but *NPV* also increases because the fixed project costs reduces (hence the cash flow *S* increases) and everything else remains the same. Hence, *ROV* must increase when the standardisation principle is applied.

In the case of obsolescence reduction, we have shown that with an increase in the time to engineering expiry, *C* increases and everything else remains the same. The *NPV* remains the same but since *C* increases, *ROV* must increase when the obsolescence reduction principle is applied.

In the case of operational risk mitigation, we have shown in Appendix 1 that *C* increases but *NPV* also increases due to a reduction in operational risk costs. Everything else remains the same so *ROV* must increase when the operational risk mitigation principle is applied.

VI. SUMMARY AND CONCLUSIONS

Many developed countries are in the midst of a period of significant infrastructure renewal together with significant change in societal values. The engineering philosophy for the next wave of infrastructure renewal needs to be re-evaluated with close reference to our current societal values.

This paper tests hypotheses about the value of engineering for infrastructure renewal under different circumstances using the Black Scholes Option Pricing Model. The results of our hypotheses tests reveal that engineering for infrastructure renewal that:

- is standardised,
- remains relevant for the longest period,
- has the lowest operational risk profile when implemented,

has the highest inherent value and hence provides the best return on investment when all other factors remain the same.

The results support the corresponding engineering principles of standardisation, obsolescence reduction and operational risk mitigation. We have found, through examination of some examples, that standardised, small scale, networked infrastructure solutions based on simple designs that are easy to operate and maintain and make use of readily available and renewable resources align closely with these principles. We have also found that there is synergy between the proposed principles in the case of the examples we have examined.

REFERENCES

[1] Burns P., Hope D. & Roorda J. (1999) Managing infrastructure for the next generation. *Automation in Construction*, 8.

[2] Pudney S.G., Ma L., Mathew J. & Y S. (2004) A High-level Asset Management Model for the Water Utility Industry. *Proceedings of the Asia Pacific Conference on System Integrity and Maintenance*, New Delhi.

[3] Garnault R. (2008) The Garnaut Climate Change Review. Melbourne: Cambridge University Press.

[4] Blair K. (1995) Cryptosporidium and public health. *Journal of Environmental Health*, 58(2), 34.

[5] Kaminski J.C. & P.W. P. (1996) Milwauki's ozone upgrade. *Civil Engineering*, 66(9), 62-64.

[6] Rennie H., Turner K. & D. S. (1998) Inquiry into the Auckland power supply failure.

[7] Sinclair Knight Merz. (1998) The Auckland CBD Power Failure.

[8] McCully P. (2001) Silenced rivers : the ecology and politics of large dams. London: Zed Books.

[9] Black F. & M. S. (1973) The pricing of options and corporate liabilities. *Journal of Political Economy*, 81(3), 637.

[10] Merton R.C. (1973) Theory of rational option pricing. *Bell Journal of Economics and Management Science*, 141-183.

[11] Leslie K.J. & M.P. M. (2000) The real power of real options. *The McKinsey Quarterly*(3), 1-23.

APPENDIX I

1) The Standardisation hypothesis

Let C_a be the call option value for which there is multiple use of engineering and C_b the call option value for which there is single use engineering. We assume multiple use engineering results in the fixed costs for implementation (X) being lower than the case for single use engineering because of synergy between like projects. We also assume all other variables remain unaffected by standardisation.

$$C_a = S \cdot \Phi(d_{1a}) - X_a \cdot e^{-rT}\Phi(d_{2a})$$

and $C_b = S \cdot \Phi(d_{1b}) - X_b \cdot e^{-rT}\Phi(d_{2b})$

Proof:
If, as assumed, $X_a < X_b$ and all other variables remain the same,
then, $\ln(S/X_a) > \ln(S/X_b)$
and

$$\frac{\ln(S/X_a) + (r + \tfrac{1}{2}\sigma^2)T}{\sigma\sqrt{T}} > \frac{\ln(S/X_b) + (r + \tfrac{1}{2}\sigma^2)}{\sigma\sqrt{T}}$$

Then, by substituting equation (2),

$d_{1a} > d_{1b}$.

It is also true that

$$S \cdot \Phi(d_{1a}) - X_a \cdot e^{-rT}\Phi(d_{1a} - \sigma\sqrt{T})$$
$$> S\Phi(d_{1b}) - X_b \cdot e^{-rT}\Phi(d_{1b} - \sigma\sqrt{T})$$

or

$$S \cdot \Phi(d_{1a}) - X_a \cdot e^{-rT}\Phi(d_{2a})$$
$$> S\Phi(d_{1b}) - X_b \cdot e^{-rT}\Phi(d_{2b})$$

or
$C_a > C_b$
whenever $S \geq X$ and r and T are both positive.

Note that S must be greater than X for the project to be financially viable. Since financial viability is a prerequisite for the majority of projects, it is a reasonable limitation. Also note that r and T cannot be negative.

Hence, the standardisation hypothesis can be accepted whenever S exceeds X.

2) The Operational risk mitigation hypothesis

Let C_a be the call option value for a project with lesser operational risk (project A) and C_b the call option value for greater operational risk (project B). We assume project A has a higher present value of cash flows (S) due to the smaller expected impact of operational risk. We also assume that all other variables remain identical.

$$C_a = S_a \cdot \Phi(d_{1a}) - X \cdot e^{-rT}\Phi(d_{2a})$$

and $C_b = S_b \cdot \Phi(d_{1b}) - X \cdot e^{-rT}\Phi(d_{2b})$

Proof:
If, as assumed, $S_a > S_b$ and all other variable remain the same,
then, $\ln(S_a/X) > \ln(S_b/X)$
and

$$\frac{\ln(S_a/X) + (r + \tfrac{1}{2}\sigma^2)T}{\sigma\sqrt{T}} > \frac{\ln(S_b/X) + (r + \tfrac{1}{2}\sigma^2)}{\sigma\sqrt{T}}$$

Then, by substituting equation (2)

$d_{1a} > d_{1b}$.

It is also true that

$$S_a\Phi(d_{1a}) - X \cdot e^{-rT}\Phi(d_{1a} - \sigma\sqrt{T})$$
$$> S_a\Phi(d_{1b}) - X \cdot e^{-rT}\Phi(d_{1b} - \sigma\sqrt{T})$$

or

$$S_a\Phi(d_{1a}) - X \cdot e^{-rT}\Phi(d_{2a})$$
$$> S_b\Phi(d_{1b}) - X \cdot e^{-rT}\Phi(d_{2b})$$

or
$C_a > C_b$
whenever $S \geq X$ and r and T are both positive.

Hence, the operational risk hypothesis can be accepted whenever S exceeds X