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Technical paper

The supply and demand of infrastructure robustness, resilience and sustainability – Part II

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ABSTRACT

Engineering and economics seek equilibria in the disparate dimensions of money and energy. In Part I of the present development [1] the mechanical instability of conservative systems in the domain of energy was compared to the five typical stages of events considered crises in any field, including those dimensioned in money. In that view, the economic, and engineered stability of the built infrastructure can be qualified, and to an extent quantified in terms of robustness, resilience, and sustainability. It is expanded herein with details and examples.

1 Introduction

Simply stated, *a structure* (or any system) *is stable if a small change in the initial conditions* (input) *leads to a small change in the solution* (output, response). The foregoing definition of stability, due to Lyapunov (1892), is generally used in all fields – not only structural mechanics, but also biology, economics, etc. [2].

In 1637, René Descartes [3] concluded that "the diversity of our opinions does not arise from some being endowed with a larger share of reason than others, but solely from the fact, that we conduct our thoughts in different ways and do not fix our attention on the same objects". The Cartesian *Méthode* sought to streamline the thought process. More modestly, the present objective is to identify the fundamental differences between the engineering constraints and economic restraints governing infrastructure, and in particular, bridge management. Energy is viewed as the rigid constraint of engineered products, whereas money is regarded as a negotiable restraint of economic processes. Hence, infrastructure management must reconcile the supply of and demand for structural performance under rigid physical constraints, dimensioned in energy, and negotiable, largely monetized economic restraints, subject to political priorities. As a result, the balancing of supply (R) and demand (Q) in economics and engineering can diverge. Fig. 1 is one way of illustrating the contrast between the respective governing priorities.

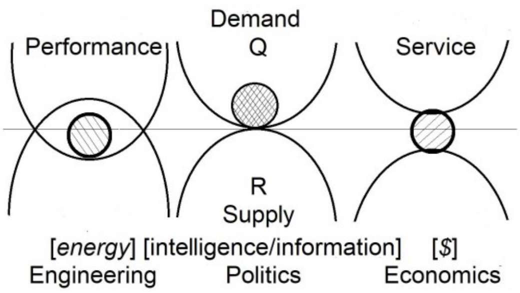

Figure 1. The supply(R) and demand (Q) in engineering, economics and politics

At least since Sir Isaac Newton professed induction, the deductive / inductive methods, more recently referred to as top-down / ground-up, have constrained engineering in the domain of energy. In [4], they are described as follows: "It must be realized that deductive justification is based on quantities and concepts determined inductively." Engineered products must supply performance R (in terms of energy) exceeding the demands Q of service and extreme events by codified load, resistance, and serviceability factors. In [4, 5] the latter are denoted by γ, φ, and η, respectively, according to Eq. 1.

$$\varphi R \geq \eta_{1,2,3} \sum \gamma_i Q_i \quad (1)$$

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In contrast, competing and even conflicting interests and schools of thought negotiate on the public, academic, and executive levels of economic processes in terms of money over strategically and tactically diverse time horizons. Except in the extreme high- and low- income areas, where social programs and philanthropy may reverse the general pattern, service demands exceed the supply by an indeterminate degree, thus motivating social progress. The diverging engineering constraints and economic restraints are reduced to Eqs. 2 – a and – b [1], as follows:

Engineering products: $R > Q$ [*Energy*] (2–a)

Economic processes: $R < Q$ [*$*] (2–b)

Thus, since the Industrial Revolution, engineering has improved the production of assets, whereas economics and politics are perfecting the process of transacting them. Social development depends on a reconciliation between the disparate political-economic restraints on public funds and engineering constraints on physical energy. Herein is extended the argument proposed in [1] that this reconciliation requires new terminology, coherent in the domains of engineering, economics, and politics in the 3-D space of energy, time, and money. The long-governing standards of engineering design, including structural strength, stability, and durability do not reach far enough into the economic aspects of bridge management. If defined to the satisfaction of all concerned, robustness, resilience, and sustainability can serve those management criteria, as they more or less implicitly have been serving engineering design.

2 Bridge conditions

In the interest of completeness, the evolution of the bridge condition database in the US is briefly reiterated from [1] herein. Following the collapse of the Silver Bridge at Point Pleasant in 1967, the Federal-Aid Highway Act of 1968 [6] mandated biennial inspections of highway bridges, thus initiating their nation-wide and, by extension, worldwide management. The National Bridge Inventory (NBI), established by the Federal Highway Administration (FHWA), rapidly built a database of 230,000 highway bridges, eventually expanding it to nearly 650,000. A vehicular tunnel database was launched in 2015. Incorporating more than 220,000 railroad bridges is pending. Milestones in that process were the introduction of the LRFD Bridge Design Specifications by the American Association of State Highway Transportation Officials [5] and the AASHTO Bridge Element Condition States [7].

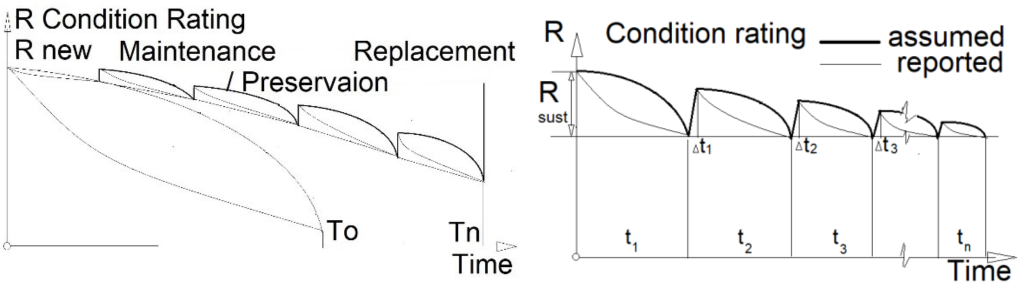
The biennial inspections update the NBI with descriptive and prescriptive assessments. The original 10 – level condition ratings [6] were essentially descriptive. The four element-level condition states [7] supersede them by combining the descriptive opinions of qualified engineers with quantitative measurements and, at the lowest level 4, by prescribing corrective actions. Also prescriptive are the 'flag' reports of potential hazards according to the New York State Department of Transportation (NYS DOT), defined in [8, 9]. Based on its bridge inventory, NYS DOT also recognizes a number of vulnerabilities, such as steel details, concrete details, seismic, hydraulic, collision, overload, and acts of destruction. The vulnerability to overload was withdrawn. Advanced technologies are offering a rapidly expanding variety of non-destructive testing and evaluation (NDT & E) techniques [20], allowing for the quantification of previously purely qualitative assessments.

The prescriptive, quantified assessments can help with budgeting for future needs, while the descriptive, qualitative assessments can help with long-term predictions of, if not actual conditions, then at least the ratings of conditions for each bridge and network. As the data accumulated, both deterministic and stochastic methods were used, yielding generally coherent results. Theoretical models tended to assume convex *condition* deterioration paths, whereas inspection records indicated concave *condition rating* histories. S – shapes (inverted either way) have been suggested as both more adaptable and realistic. Yanev [11] argued that in large networks where both bridge age and conditions are normally distributed, a linear model can be sufficiently accurate for rough estimates. Typical forecasts based on the condition ratings obtained by the biennial inspections conducted according to [6, 8] are illustrated in Fig. 2. They could not be generated directly based on the element condition states of [7, 9].

Stable bridge networks ought to demand a relatively constant level of annual preservation activities, consisting of reconstruction, component rehabilitation, and maintenance. Thus, over a large network, the pattern in Fig. 2(b) should converge to a near-constant level of annual expenditures, adjusted for inflation. (New construction is viewed herein as network expansion, to be planned on a comprehensive socio-economic level with all its long-term implications.)

Let T_o and T_n be the estimated life-cycle durations with and without preservation interventions. Let R be the bridge condition rating assessed by one or more methods of Table 1 and *Rsust* be the sustainable level maintained by periodic preservation actions at times t_i up to a declining t_n, when full rehabilitations and replacements become more cost-effective. The durations of preservation actions are denoted by Δt_i. They are associated with costs C_i (direct and indirect) and, contrary to Δt_i, tend to grow longer and costlier. Yanev [11, 12] argues that money expenditures cannot measure structural and social benefits with sufficient rigor. Moreover, the costs and benefits of capital reconstruction are more readily monetized than those of 'preservation' and its constituent 'routine maintenance'.

Engineering plans discrete condition upgrades at times t_i to prevent demands from becoming critical. Economics funds them as corrective actions responding to such demands. Economic processes are not only dynamic but also subject to divergent assessments. Thus, engineering and economic views of risk and stability are contrasted. Economic expansion is expected. Engineers study product failures in controlled tests. The 'market adjustments' favored by economists imply localized process failures. In a market democracy, economic restraint governs infrastructure management. Hence, process instabilities can eventually affect product performance. The proliferation of potential hazards [8] in New York City (NYC), discussed in [1, 12], is an instructive example. In a bridge network managed according to the models in Fig. 2, potential hazards ought to be the exception. However, between 1988 and 1992, their number in NYC increased from 180 to 3071.



a b

Figure 2. Hypothetical effect of periodic preservation interventions on extending the useful life of a bridge and a network

Figure 3 [1] pertains to approximately 690 vehicular (including the 4 landmark East River and 25 movable) and 100 pedestrian bridges in NYC. The following five periods are discernible:

A – B : 1982 –1 987 Apparent equilibrium following initial adjustments;

B – C : 1987 – 1992 Increase reaching an annual factor of 2;

C – D : 1992 – 1996 Peaking approximately 24 times above the initial level;

D – E : 1996 – 1999 Annual decrease by a factor of approximately 1.24;

E – : 1999 – 2006 Apparent equilibrium at approximately 10 times the initial level (sustained into the 2020s).

Similar 5-stage patterns are common to crisis histories, such as the developments of the Covid-19 epidemic and the financial crisis of 2008. The stages of grief comprise a comparable sequence of denial, anger, bargaining, depression, and acceptance. The ultimately constructive 'Future Tech Hype Cycle' includes analogous innovation, exaggerated expectations, a trough of disillusionment, enlightenment, and a plateau of productivity. Common to the described processes are the occurring instabilities. The inverted outline of Fig. 3 and similar histories of crises parallel energy behavior during mechanical instability, in particular those of the 2-bar von Mises truss, strain-softening materials, and bodies retained by friction [2].

3 The stability analogy

Bažant and Cedolin [2] illustrate the snap-though and snap-down instability modes of the von Mises truss, as shown in Fig. 4. The typical stages A-E of Fig. 3 and similar crises loosely fit as shown into the path of P on Fig. 4-b.

Reiterating [1] for completeness, Bažant and Cedolin [2] state: "The question of stability may be most effectively answered on the basis of the energy criterion of stability, which follows from the dynamic definition if the system is conservative." The authors present catastrophe theory as a "strictly qualitative viewpoint," analyzing the stability of conservative systems by energy methods as follows: "[Catastrophe theory] seeks to identify properties that are common to various catastrophes known in the fields of structural mechanics, astrophysics, atomic lattice theory, hydrodynamics, phase transitions, biological reactions, psychology of aggression, spacecraft control, population dynamics, prey-predator ecology, neural activity of the brain, economics, etc. Simply, the theory deals with the basic mathematical aspects common to all these problems." Parrochia [13] takes a similar view. Both [2, 13] refer to René Thom's [14] demonstration that in a conservative system with one control parameter, only one type of catastrophe is possible (the limit point or snap-through), with two independent control parameters, the fold and the cusp types

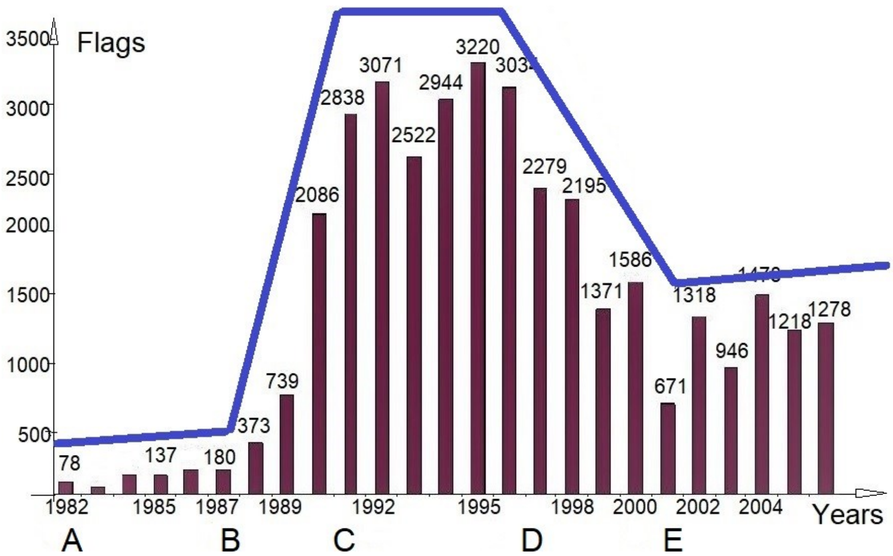


Figure 3. Bridge – related potential hazards in NYC, 1982 – 2006

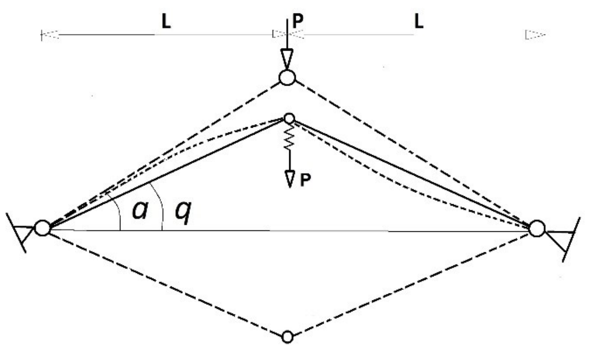
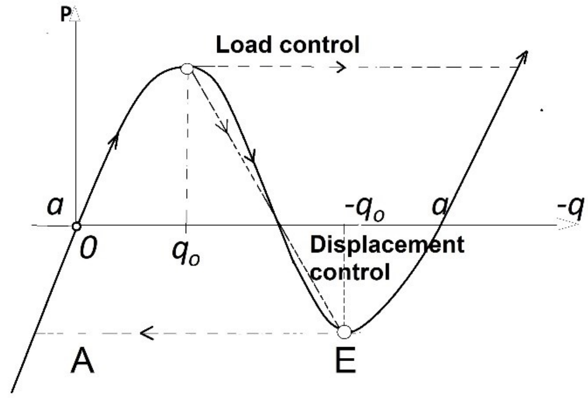


Figure 4 – a. The Von Mises truss



– b. Snap-through and snap-down equilibrium paths

of catastrophes are possible (asymmetric and symmetric bifurcation). For systems with three control parameters, five types of catastrophes become possible; and systems with up to four control parameters allow at most seven types of catastrophes. The seven types of catastrophes are called 'elementary'.

Under load control [2, Section 4.4], the bars with area A and length L do not buckle locally. A global snap-through instability occurs when the potential energy $\Pi(q)$ of the elastically deformed system reaches a critical value. The equilibrium condition for the potential energy $\partial\Pi / \partial q = 0$ obtains Eq. 3, where α and q are the initial and deformed angles of the inclined bars. The truss is unstable for $-\alpha/\sqrt{3} \leq q \leq \alpha/\sqrt{3}$.

$$P = EAq(\alpha^2 - q^2) \quad (3)$$

Under displacement control [2, section 4.8], the bars of the von Mises truss can buckle locally in a snap-down mode. A snapback is possible under certain constraints. Critical loads and displacements can coincide. Interacting buckling modes and the inevitable 'passive' system imperfections strongly influence near-instability behavior, adding further indeterminacy. The authors stress that "there are buckling problems that are inherently nonlinear and cannot be linearized, even if the deflections are very small". Despite its non-redundancy, the von Mises truss can fail in a number of ways. Either bar can fail in compression or tension. The system snaps 'through' globally and snaps 'down' locally. More than one mode can coincide.

Damage-related material instabilities, including strain-softening and friction, discussed in [2, Ch. 13], provide another applicable analogy. Particularly relevant are the possibility of material rehardening (after strain-softening) and the drop of the static friction force F_s to a smaller dynamic one F_d as initial friction is overcome. Both phenomena correspond to the behavior of structures and networks gradually losing their original resistance, as shown in the inset of Fig. 5.

Infrastructure networks, with their broadly estimated multi-parameter dynamic equilibria of vaguely quantified and qualified supply and demand, do not qualify for rigorous stability analysis. Nevertheless, the patterns of Figs. 3 and 4-b, as well as those of other crises, share important features. To those already enumerated in [1] can be added the following:

– An equilibrium of supply and demand, dimensioned in energy, is essential to both conservative mechanical systems and infrastructure networks.

– Adding the non-conservative parameter of money recalls that it is the social equivalent of energy. Treating the money supply as potentially unstable allows for identifying the potential crises precipitated by budget shortages.

The energy constraint governs Peter Drucker's (1909-2005) view that "everything degenerates into work.". The economic restraint drove Napoleon (1769-1821) to conclude that "all politics is money." If energy and money were viewed as the two active parameters controlling the bridge network, each could cause its own type of instability, expanding the near-unstable domain. For four control parameters, for example, if intelligence and information were regarded as additional parameters (e.g., the inevitable political restraints), the possible types of catastrophes would increase to seven [2, Table 4.7.1., p. 300].

4 Robustness, resilience, and sustainability of products and processes

The definition of a new category requires the introduction of at least one new term. Henri Léon Lebesgue (1875-1941)

The position herein is that abrupt discontinuities in engineered and economic products and processes are preceded by a gradual buildup (or depletion) of effects in overlooked dimensions. Therein lies the relevance of mechanical stability, where force equilibrium alone overlooks the relationship between energy accumulation and structural form in space. Quantifying in terms of forces (energy), the product's resistance (supply), and the service demand according to Eq. 1 similarly overlooks stability. That is addressed separately, along with ductility, redundancy, and importance under the general umbrella of serviceability. The traditional scope of designing and managing engineering products and processes in energy and space-time is illustrated in the inset of Fig. 5 herein. Inverting the contour obtains a crisis pattern similar to that of Fig. 3 with comparable stages A-E. Yanev [12] correlated bridge-related potential hazards with element condition ratings, enabling anticipating their proliferation into 'extreme events'. Network performance instabilities, however, cannot be fully anticipated absent the money dimension. The potentially catastrophic structural conditions, illustrated in Fig. 3, were preceded by political and economic instabilities. (In the late 1970s, New York City narrowly avoided bankruptcy.) The argument advanced herein is that engineering, economics, and politics can manage a sustainable (i.e., stable) infrastructure network only jointly in an integrated 3-D space defined by energy, money, and time, as illustrated in Fig. 5.

The inset of Fig. 5 [1] represents a possible lifecycle of the engineered asset(s) in the plane of *energy and time* under 'normal' demands and an extreme event. It illustrates the following sequence:

The bridge strength, stability, ductility, redundancy, and importance prescribed by current specifications deteriorate over time at variable rates, depending on many external and intrinsic factors. Eventually, the accumulated decline disrupts sustainability. To represent sustainability, robustness and resilience must reflect the condition of the network in the domains of energy and money over time. At both project and network levels, they imply redistributing a constrained supply of resistance in response to an expanded demand, as do structural redundancy and ductility. Inverting that history obtains the crisis pattern already familiar from Figs. 3 and 4, with discernible, although differently spaced, points A, B, C, D, and E.

In order to capture all parameters controlling the product and process depicted in the *Energy / Time* plane, Fig. 5 combines Figs. 5 and 6 of [1]. The *$* axis expands the plane into a 3-D space. The lines drawn in the plane of *Energy / Time* expand to surfaces in *$ / Energy / Time*. Second, the axes of *Robustness*, *Resilience*, *Sustainability* are introduced in the 3 planes of *Energy / Time*, *Energy / $*, and *$ / Time*, respectively. In keeping with the engineering practice of reducing problems to actionable tasks, the 3-D model can be examined in three constitutive planes. Those planes, however, can be defined by *$ / Energy / Time*, as well as by *Robustness / Resilience / Sustainability*. The advantage of the latter is to demand, respectively, the collaboration and cooperation of economics and engineering [*$, energy*], politics and engineering [*time, energy*], and economics and politics [*$, time*]. Restraining economics to the dimension of money [*$*] makes it (arguably) the only one of the three disciplines whose models can be formulated entirely within (although they should not be necessarily limited to) a social construct. Contradictory top-down economic models are notoriously resilient over extended time periods by ignoring the ground-up constraints of robustness and sustainability. By integrating energy, time-space and money, the new 'control parameters' of social and physical performance restrain engineering, economics and politics into collaborating. The implicit 'control parameters' of intelligence / information account for the occasional contradictions between engineering, economics and politics.

Consistently with Lebesgue, sustainability is treated as a 'new category' requiring (at least) the new terms of robustness and resilience. FHWA [15] has advanced bridge management towards the standardizing and codifying of their assessments. Thus far, robustness is defined as the ability of a possibly impaired structure or network to retain functionality under the demands of 'extreme events' in constrained time. In the explicit forms of redundancy and ductility, robustness redistributes and sustains the load demands in the defined space of the asset and time of the event. According to [16], resilience describes lifecycle network performance under typical and extreme conditions as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events". Deterioration reaching a point of system instability (e.g., state of emergency) is qualified herein as an extreme event. Resilience pertains to the process of network response, not only in terms of energy but also in terms of money and extra-monetary considerations over extended but nonetheless foreseeable time periods. Simplifying, robustness quantifies essentially the product, and resilience qualifies and quantifies the process.

Politics, economics, environmental protection, and so on discuss the noun 'sustainability' in purely qualitative terms, ultimately reducing their interpretations of qualitatively 'sustainable' policies to quantifiable affordable budgets. To narrow down the scope, [1] proposed the *sustainability factor* (*SF*) of Eq. 4. It should estimate the affordability of an infrastructure network under the governing social restraints and physical constraints of money, energy, and time as follows:

$$SF = \Sigma\ benefits / \Sigma\ costs \tag{4}$$

Constraining sustainability in time, Eq. (4) must be amended to Eq. 4 – a.

$$SF = \Sigma\ (benefits / costs) / time \tag{4–a}$$

Recognizing the qualitative and quantitative differences between the three major contributors to Eq. 4 – a, it can be further expanded to Eq. 4 – b.

$$SF = d\ \Sigma\ (benefits / costs) / time_{direct} + u\ \Sigma\ (benefits / costs) / time_{user} + e\ \Sigma\ (benefits / costs) / time_{environ.} \tag{4 – b}$$

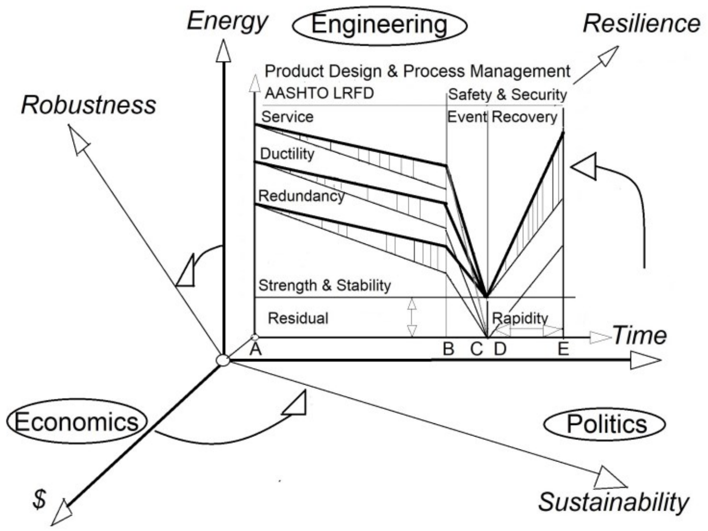


Figure 5. Robustness, resilience and sustainability in engineering, economics, and politics

where: $time_{direct}$; $time_{user}$; $time_{environ}$ are the timespans for assessing direct, user, and environmental costs and benefits, and

d, *u*, and *e* are weights designating the relative importance of each term, respectively.

The *direct*, *user*, and *environmental benefits / costs* and *times* differ as (partially) follows:

- *Direct*

- *costs*: They are relatively straightforward, particularly as the majority of infrastructure assets are publicly owned and, hence, subject to stricter accountability. However, reconstruction and maintenance can be funded by national and local budgets, respectively, restrained by different priorities. In the US, such differences partly contributed to local preferences for capital construction over maintenance from the 1960s to the 1980s. Government policies aside, the costs of maintenance activities are much harder to trace, particularly if some preservation activities are privatized whereas others are performed in-house. Yanev [11] argued that the notoriously delinquent bridge painting can be managed effectively only as capital reconstruction. That policy is currently standard.

- *benefits*: They can be estimated only tentatively over long periods, thus reflecting intractable user and environmental influences. The value of a bridge network is monetized in terms of its replacement cost, which is subject to inflation and other fluctuations. The cost evolution of major capital projects in the US suggests that construction costs have been rising for the past century at an annual rate of approximately 5%. For example, the George Washington Bridge in New York City was completed in 1931 for $US 50 m, and its lower deck was added in 1951 for $US 4 billion. At present, a comparable bridge could realistically cost $US 4 billion. Yanev's [12] correlation of maintenance costs and their benefits in terms of bridge conditions stressed both the value and the limitations of that model.

- $time_{direct}$: Since the 1990s, the time for assessing infrastructure asset performance has been its useful life. If a network deteriorates, its depreciation can be monetized in terms of the increased demand for reconstruction and preservation (e.g., maintenance). These demands, in turn, can be expressed as losses of robustness, resilience, and sustainability. Yanev [12] argued that, for a relatively large network in a 'steady state', the average overall condition ought to be near constant. Hence, time horizons for such networks can be based on 'perpetuity'. In contrast, management budgets are annual. Capital construction plans have 5, 10, and 20-year horizons, with the shorter ones typically slipping into the longer ones. Thus, short- and long-term sustainability estimates are appropriate.

- *User*

- *benefits / costs*: They are only tentatively estimated based on the time users spend in the transportation network. The quantitative and qualitative differences between private users and industries are considerable, since the former are passive consumers, whereas the latter (or some of them) are active contributors. Monetizing the costs incurred by large populations due to declining service obtains quantities incomparably superior to the direct ones. The benefits supplied by existing services are linked to taxes only tentatively through the political domain. The relatively constant 'gas tax' in the US is debated perpetually, with structural robustness and resilience informing the arguments only in unquantifiable terms (e.g., the American Association of Structural Engineers rates the condition of the transportation infrastructure as "D" or "C+").

- $time_{user}$: It can be correlated with the corresponding $time_{direct}$, for short- and long-term sustainability estimates.

- *Environmental*

- (*benefits / costs*) / $time_{environ}$: Sustainability is directly addressed, as robustness and resilience apply better to built infrastructure than to the natural environment. Hence, the debates are conducted under disparate standards and currencies. Some consensus is attainable on long-term global considerations, however short-term local ones inevitably reduce to economy and politics. Engineering is well qualified to lead by creating a more sustainable infrastructure, however, political decisions govern the largest projects. Quantifying an environmental sustainability factor is even harder than the user one, at even larger magnitudes. Its presence in Eq. 4-b is qualitative but essential. Milton Friedman (1912-2006) [17] argued that "neighborhood effects" are *circumstances* where "the actions of individuals have effects on other individuals for which it is not feasible to charge or recompense them". The sustainability of infrastructure management strategies should be qualified and, to the extent possible, quantified based on such effects, e.g., those affecting environmental resilience.

As the times over which direct, user and environmental benefits and costs are accrued and sustained differ, *SF* of alternative strategies must be compared over similar short- and long-time windows. Certain options could be disqualified for failing to address one or the other. This would render the Present Worth (PW) method and its somewhat arguable discounting moot.

Robustness, *Resilience*, and *Sustainability* can be modeled as functions $f(\$, energy, t)$, $\psi(\$, energy, t)$, and $\theta(\$, energy, t)$ in various ways (e.g., continuous, piece-wise continuous, convergent, divergent, and so on) for forecasting purposes. They can have positive projections on the original axes of *$*, *Energy*, and *Time*, as illustrated in Fig. 6-a, or they can coincide with reduced consumption of *Energy* and *$*, as in Fig. 6-b. In more realistic representations, the axes need not be rectilinear, orthogonal or similarly oriented.

In Fig.7, the different possible scenarios are reduced to the planes of expenditures and sustainability with respect to time. If the ratios in Eq. 4-b were continuous functions with respect to time, hypothetical cycles might evolve as shown in Fig. 7. Physical and social randomness render actual processes discontinuous. The period shifts and first derivative sign reversals of $time_{direct}$ and $time_{user}$ can be tentatively assumed or deduced from statistical data. The cycles of $time_{environ}$ would have much longer periods at higher costs. Given the enumerated differences between the three contributors, a compound 'sustainability' would be fraught with speculation. If, however, such a 'sustainability' were assumed, several elementary possibilities might arise. In Figs. 8-a, -b, and -c they are illustrated as follows:

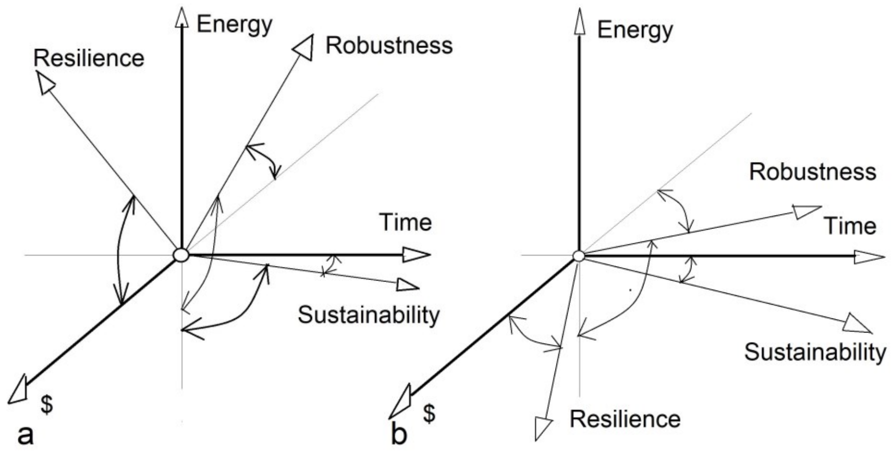


Figure 6. Possible 3-D rotations of Robustness, Resilience and Sustainability with respect to Money, Energy and Time

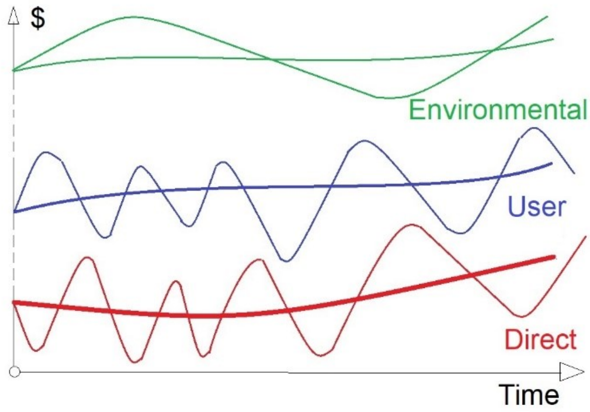


Figure 7. Hypothetical cycles of direct, user and environmental costs

a) Initial costs are low, sustainability is perceived as high. Over time, costs increase, sustainability declines, and cycle periods and amplitudes stretch. This is typical of infrastructure networks built at a low initial cost and, hence, an apparently favorable short-term sustainability, as well as of low-maintenance long-term practices. The A-E stages of Fig. 3 are discernible. Increasing demands for network maintenance and inflation are considered correlated, but the causality is bilateral. Both provoke the customary lament for the 'good old days' when current conditions and circumstances would have been 'unacceptable'.

b) Initial costs are high and sustainability is low. Over time, costs decrease, sustainability increases, cycle periods and amplitudes drop. This can reflect more cost-effective asset design and management and reduced user and environmental costs. Networks serving more energy-efficient modes of transportation (including pedestrians and bicycles) are expanding. Given the expanding populations and demands for services, this is not a very likely scenario.

c) Costs and sustainability can increase or decrease concurrently, with decreasing or increasing cycle periods and amplitudes, respectively, representing improving or declining infrastructure performance. Examples of benefits increasing with added costs include the elimination of environmentally harmful materials such as lead from bridge construction and preservation and deicing salts from roadways. Considerations of economic sustainability motivate the policies favoring local suppliers.

Figures 7 and 8 remind that, whereas cost cycles are considered routine, the energy cycles of robustness and resilience implied in sustainability alternate between stable and unstable paths. Combinations of the various idealized scenarios are more likely.

5 Examples

In [18], Albert Einstein stated: "So far as the laws of mathematics refer to reality, they are not certain, and so far as they are certain, they do not refer to reality". Several familiar examples are reviewed in terms of their robustness, resilience, and sustainability in order to test the realism of these terms.

- Brooklyn Bridge (1883) East River, New York City, John (1806-1869), Washington (1837-1926), and Emily (1843-1903) Roebling (Fig. 9).

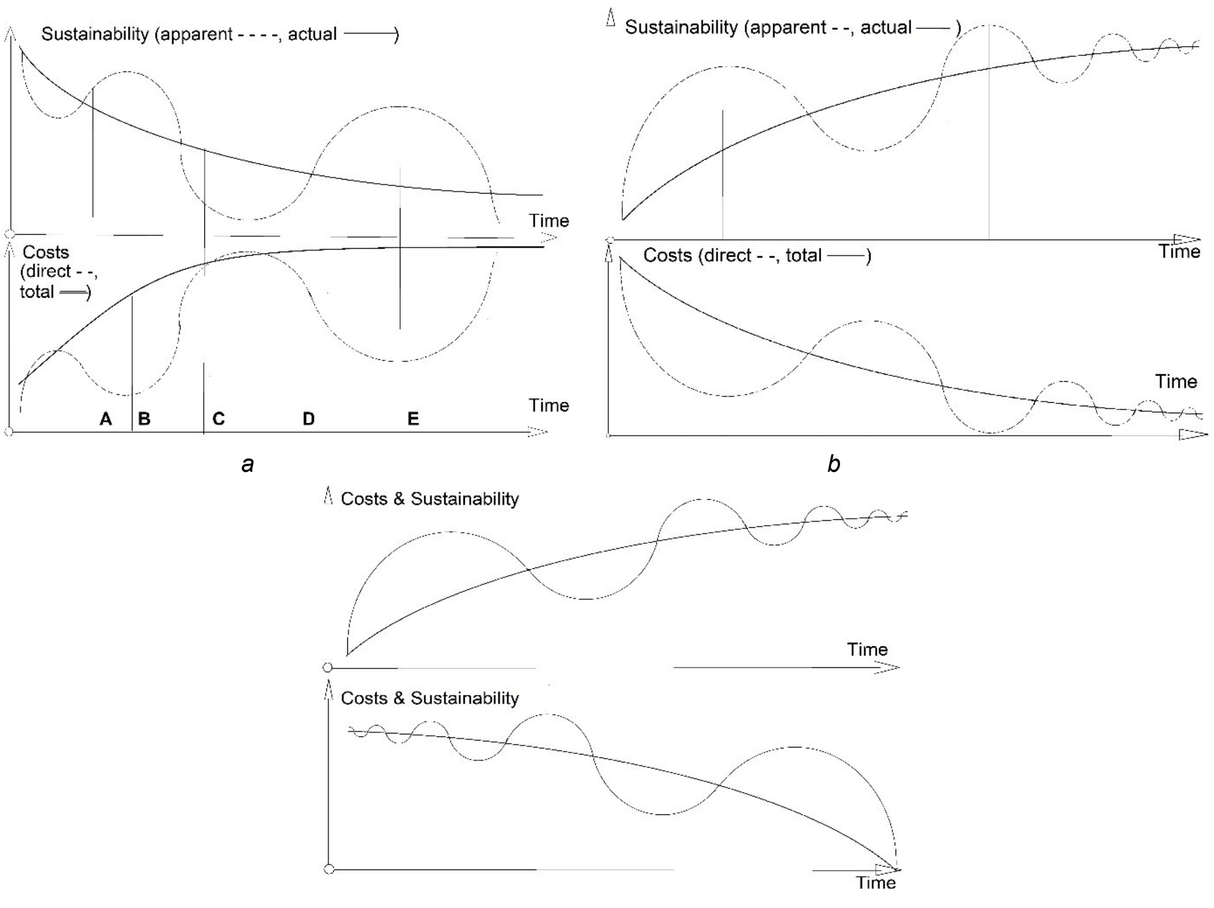


Figure 8. Possible costs / sustainability cycles

Figure 9. Brooklyn, Manhattan and Williamsburg Bridges across East River, New York City

With a main span of 486 m, the bridge was the longest in the world. The structure is a hybrid, combining a suspension system with four main cables, multiple diagonal stays, and four stiffening trusses (Fig. 9). John Roebling famously stated that if one of the three systems malfunctions "the bridge may sag but shall not fail". This integration of robustness and resilience was occasionally criticized as "belt and suspenders". It allowed the bridge to survive a deterioration of the stays and the suspenders, culminating in a suspender rupturing in 1981. The ensuing replacement of all stays and suspenders was conducted without traffic interruption. The bridge, which once served carriages and tramways, today carries four automobile lanes, a bicycle, and a pedestrian path. The bridge demands relatively high maintenance, however, its indispensable service and landmark status make it eminently sustainable. Deicing salts were eliminated from all East River bridges.

- Williamsburg Bridge (1903), East River, New York City, Leffert Lefferts Buck (1837-1909) (Fig. 9)

The bridge carries four traffic lanes and two subway tracks. The 488-m main span was the longest suspended structure at its completion. The side spans were not suspended. In 1998, two strands in one of the four main cables, each consisting of 208 high-strength wires, were found to have ruptured due to corrosion. As the inspection progressed, many more wires were found to be broken or severely damaged. The bridge was closed to traffic pending evaluation, impacting city traffic severely. The subsequent investigations ultimately concluded that the structure could be rehabilitated. The prohibitive traffic interruptions rendered a replacement unsustainable. The original 'factor of safety' in the four main cables had been approximately 4, and the estimated corrosion damage had reduced it to approximately 3. The robust 'overdesign' saved the bridge. In contrast, cable resilience was poor because the high-strength wires had not been galvanized. The reasoning (primarily motivated by the desire to eliminate the weight of the zinc coating) had been that the cables should be kept dry and, hence, did not need galvanization. As it turned out, cable wrapping failed, water penetrated, and the wires corroded. The double protection 'belt and suspenders' policy would have been more resilient and sustainable. The rehabilitation with partial traffic closures took more than 10 years at a cost exceeding $US 1b. The Williamsburg Bridge crisis demonstrated conclusively that investing in bridge robustness and resilience benefits long-term sustainability. The events inspired Japanese engineers of the Honshu-Shikoku Bridge Authority to develop a dehumidification system for their many record-length suspension cables, as at the Akashi-Kaikyo and Kurushima bridges. The system has been adopted by other long-span bridge owners. The improved resilience and, hence, sustainability offset the added maintenance cost. That, however, also supplies an argument for reducing cable robustness, e.g., to factors of safety approaching 2, as at the record-holding Çanakkale Bridge across the Dardanelles.

- George Washington Bridge (1931, 1956) (Fig. 10), Hudson River, Othmar Ammann (1879 – 1965)

At its opening, the main suspended span of 1067 m was the longest in the world. Its 8 traffic lanes were the heaviest. Originally, the bridge had no stiffening trusses (reducing the construction costs), but its weight rendered it sufficiently robust and resilient. The design anticipated a lower level carrying either trains or vehicles, depending on the demand. In 1956, the lower deck with six traffic lanes was added, improving robustness, resilience, and sustainability. The bridge links the states of New York and New Jersey and currently earns more than $US 3 million in tolls daily. Suspenders and roadways have been replaced.

- Tacoma Narrows Bridge (1940), Washington State, Leon Moisseiff (1872-1943)

With a length of 835.4 m, the main span of this vehicular bridge was the third longest in the world (after George Washington and the Golden Gate). The traditional stiffening trusses were replaced by innovative girders on the reasoning that the reduced stiffness would attract reduced stresses. The structural lightening presumably improved initial sustainability. Robustness was consciously reduced. Resilience proved immediately inadequate under normal traffic. On November 7, 1940, moderate wind caused a torsional failure ultimately attributed to flutter. The dynamic vulnerability of the bridge was repeatedly analyzed, advancing subsequent designs, however, in the simplest terms, the structure lacked the robustness and resilience consciously built into the earlier examples. The costs, including those of the following replacements, would render short-term sustainability very low. The transportation link was clearly necessary, and the long-term sustainability of the two replacement bridges should prove superior.

Sliver Bridge (1928), Point Pleasant, West Virginia

The suspension vehicular bridge at Point Pleasant had a main span of 213 m and two equal sidespans of 116 m. It was designed as a two-cable suspension bridge, but the bid was changed to a two parallel eye-bar suspension system, with two eyebars per panel point. On December 15, 1967, it collapsed due to a corrosion fatigue-induced brittle fracture of one eyebar. The subsequent investigation found a flaw in the metal, however, the structure's non-redundancy doomed it. The event kicked off mandatory bridge inspections in the US, even though no visual inspection could have spotted the fatal defect. In addition to the global non-redundancy, replacing the cables with pairs of eyebars further eliminated the structural internal robustness and resilience. In recognition, a similar bridge was deemed unsustainable and demolished promptly. Structural redundancy, alternate load paths, load redistribution, and ductility became performance-based design criteria, amounting to robustness and resilience.

Mianus River Bridge (1958), Interstate I-95, Greenwich, Connecticut

On June 28, 1983, a 30-meter- long span of the east-bound steel girder bridge over the Mianus collapsed. A pin and hanger linkage supporting the span had failed due to the accumulation of debris and corrosion. As with the Silver Bridge eyebars, such linkages are non-redundant and next to impossible to inspect. The standard design at the time lacked both robustness and resilience, and hence, long-term sustainability. Details of this type were designated as fracture-critical, requiring 100% hands-on inspection, and scheduled for retrofit and replacement. The NBI enabled the rapid identification of similar structures, demonstrating that infrastructure management is unsustainable without an up-to-date inventory. The FHWA established the need for Bridge Management Systems (BMS). Inspectability, maintainability, and minimizing lifecycle costs, essential to sustainability, became design criteria.

Figure 10. George Washinton Bridge across Hudon River between New York City and New Jersey

Schoharie Creek Bridge (1954), Amsterdam, New York

The bridge consisted of five spans, simply supported on four piers, two of which were in the main river channel. On April 5, 1987, scour caused by severe flooding resulted in the collapse of piers ##3 and 2, carrying spans 3, 4, and 2 with them. The early design had considered longer spans but had rejected them due to higher construction costs. Apart from the need for diving inspections and maintenance of underwater pier footings, the incident underscored that 33 years are insufficient for assessing the sustainability of a bridge design. A similar conclusion was reached after 40-year-old levees designed for lesser storms failed during Hurricane Katrina in August 2005.

Sunshine Skyway (1954) Tampa Bay, Fla., and Queen Isabella Causeway (1974) South Padre, TX

Sunshine Skyway was a twin multi-span, 6.82 km structure crossing Lower Tampa Bay. The multi-span Queen Isabella Causeway connects South Padre Island to Port Isabel for a length of 3.82 km. Each lost a concrete pier and the adjacent spans due to vessel impact on May 9, 1980, and September 15, 2001, respectively. In both cases, constructing piers sufficiently robust to resist vessel impact or to survive a lost pier would not have been feasible. The Sunshine replacement was a much longer cable-stayed signature bridge. The causeway added more buffers. Both employ supplementary warning signals and other protection systems. Thus, sustainability was improved by reducing the risk by means of a new structure or by augmenting the management of the existing one.

I – 880 Cypress Viaduct (1957), Oakland, and I-240 Embarcadero (1968), San Francisco, CA (Figs. 11-a and -b)

The two multi-span, two-level prestressed concrete structures failed during the Loma Prieta earthquake of October 17, 1989, in strikingly different ways. The Cypress Viaduct collapsed over a length of 3 km, causing 41 fatalities. Among the contributing causes were structural discontinuity between the lower and upper levels, inadequate column reinforcing ties, and foundations on deep piles. Attempts to improve the structure's seismic robustness and resilience had been in progress. At Embarcadero, the column reinforcing ties were similarly inadequate, but the two-level columns were continuous. The severely damaged structure withstood the ground motion, by all estimates, very narrowly. Robustness had been lacking, but resilience prevented a catastrophe. Both structures were deemed unsustainable, structurally and aesthetically, and replaced by traffic on grade. AASHTO and FHWA followed up with comprehensive upgrades to seismic research and design.

Mississippi River Bridge I-35 (1964), Minneapolis, Minnesota, Sverdrup & Parcel

The main bridge structure was a 3-span (81 m, 140 m, and 81 m) non-redundant steel arched deck truss. On August 1, 2007, the central span collapsed, precipitating a global failure. The investigation identified 16 inexplicably thinner gusset plates with inadequate load-bearing capacity. Similar bridges drew immediate attention but did not exhibit such a deficiency. Inspections had observed a buckling in the thinner fracture-critical gusset plates, but the condition had not been sufficiently prioritized. Gusset plates had not been addressed adequately in AASHTO design specifications. The 43-year service of the structure prompted speculation that other factors, including a pier shift and new construction loads, might have contributed. As in multiple modes of instability, multiple causes typically contribute to global failures. A structure built without basic robustness and resilience had appeared falsely sustainable over an extended period. The bridge was replaced in 11 months by a prestressed concrete box-girder structure, abundantly instrumented with performance monitoring equipment.

The World Trade Center, New York City (1973), Minoru Yamasaki (1912-1986), Leslie Robertson (1928-2021)

The Twin Towers were signature representatives of the tubular design, associated also with Dr. Fazlur Khan (1929-1982) and Skidmore, Owings, & Merrill. On February 26, 1993, a bomb exploded in the parking garage, gutting four underground floors of the South Tower and knocking out one

Figure 11 – a. Cypress Viaduct, Oakland *– b. Embarcadero, San Francisco*

diagonal of the outer bearing wall. The tower structure proved abundantly robust, loads were redistributed, and all damage was localized and promptly repaired. The perception of robustness and resilience improved the popularity and, hence, the sustainability of the usually under-occupied towers. Then, on September 11, 2001, passenger planes struck both towers (Fig. 12).

Figure 12. World Trade Center, New York City, Sept. 11, 2001

Both resisted the impact robustly, as the design had anticipated, deflected, and regained their original positions. The South Tower was struck relatively low. With the weight of 30 floors above the damage, it might not have survived for long even without the ensuing intense fire, which brought it down in 56 minutes. The North Tower was struck much higher, around the 91st floor. Its floors lacked the necessary resilience, and in 1hour, 38 minutes, the fire caused a cascading collapse. Since then, the resilience and sustainability of tall buildings (tubular and otherwise) have been revisited under normal and previously unanticipated extreme circumstances, such as fire. Sustainability against aircraft and vessel collisions cannot rely solely on structural robustness and resilience without adding the tools of prevention.

The sustainability of the long-span bridges, designed for a 100-year useful life without major rehabilitation, demands economic and engineering planning taking into account the reconfigured local geography. Over the course of a century, the traffic link they provide becomes permanent. The demand for their services and, hence, their needs can only increase, adding to the owners' responsibility.

Globally, from an environmental viewpoint, it has been argued that the energy footprint of densely populated areas is more sustainable than that of sparsely populated ones, for example, because of the reduced demand for long-distance commuting.

San Francisco-Oakland East Bay Bridge (2013) T. Y. Lin Associates (Fig. 13) and Viaduc de Millau (2004) Norman Foster, Michel Virlogeux (Fig. 14)

After a 15-meter span of the old East Bay truss crossing failed during the Loma Prieta earthquake (1989), a replacement was determined to be preferable to a retrofit. Much less expensive cable-stayed, viaduct, and even pontoon proposals (the shallow channel is not essential to navigation) were rejected in favor of a unique structure with a self-anchored 385-meter main span, elevating the construction cost to $6.5 billion. Legal ramifications, involving Governor Arnold Schwarzenegger, technical corrections, and the need for provisional supports throughout the construction extended the latter to 11 years.

The certifiably unique completed structure is visually striking and attracts artistic lighting displays. Its 78.74-meter width qualifies it as the world's widest bridge. No major earthquake has tested it to date, but the nearby Hayward Fault is considered active.

Viaduc de Millau is an 8-span, 2,460-meter cable-stayed bridge above the Tarn Valley in southern France. The unique design elevated the autoroute traffic high above the terrain as an environmentally more sustainable option. The then mayor of Millau, Jacques Godfrain, recalls an inquiry by representatives of then California Governor Schwarzenegger about the design selection process. Mr. Schwarzenegger may have been more interested in rejecting rather than approving a project on sustainability grounds. The seven bridge pylons are constructed of concrete up to the deck and of prefabricated steel above. The tallest one reaches 336.4 meters. The prestressed concrete deck segments were not extended (as usually) from the towers on successive cable stays. Instead, the construction company Eiffage launched the deck on temporary steel tower midspan and brought the steel pylon tops onto it. The construction took three years and cost €394,000,000. The design useful life is 120 years.

Figure 13. New East Bay Bridge under construction (2011)

Figure 14. Viaduc de Millau (2015)

Both structures are tolled, rendering their management more coherent. The East Bay crossing was designed to become a “signature bridge”. The design of Viaduc de Millau produced one by achieving its purpose brilliantly. Short- and long-term sustainability considerations can be neither ignored nor fully monetized. A similar reasoning applies to all signatures and record-breaking bridges. Fashionable and competitive attitudes can be stimulating, but they benefit from recognizing the restraint of sustainability. David Billington [19] stresses that great structural artists, such as J. Roebling and G. Eiffel (1832-1923) realized their projects on time and on budget. Their signature structures remain highly serviceable (and profitable) more than a century later.

6 Conclusions

The authors of [2] state : “The prediction of failures due to structural instability requires equations of equilibrium or motion to be formulated on the basis of the deformed configuration of the structure.” Although the infrastructure is neither a conservative system nor dependent on uniquely defined control parameters, it is prone to instabilities. In both the domains of energy and money, instabilities occur when and because they are ignored. They would be easier to anticipate and possibly avoid if they were modeled in terms of robustness, resilience, and sustainability. If they are to be adopted as ‘control parameters’ of infrastructure performance, integrating the restraints and constraints governing the design and management of engineered products and economic and political processes, they must be quantified and qualified to the satisfaction of all concerned.

The terms have been seeking recognition for decades, as have the policies that promote them. Sustainable development was the subject of an international conference in Rio de Janeiro in 1992 and a World Summit in Johannesburg in 2002. The US Report [20] addressed sustainable development in chemicals, transport, mining, waste management, and sustainable consumption and production. In 2011, the Office of Sustainable Development at the United Nations (UNSOD) established 17 goals (SDGs), prioritizing least-developed countries (LDCs). In order to advance the subject from commendable thinking to actionable tasks, ‘sustainability’ must be defined in consistent and generally accepted qualifiable and quantifiable terms. As that objective enters national and international politics, it recedes into the future. Practical application becomes more likely within the reduced scope of managing the transportation infrastructure. Therein, ‘robustness’ and ‘resilience’ emerge as appropriate qualifiers and quantifiers of sustainability. In 2021, the US Congress allocated $US 1.3 trillion to rebuilding the national ‘hard’ infrastructure. ‘Shovel-ready’ projects (deemed by former President Barak Obama non-existent) are to be favored. The ultimate objective of these funds should be long-term sustainability, defined in terms of robustness and resilience within the 3-D space of energy, money, and time.

The disparities and complex relationship between the direct, user, and environmental components contributing to the sustainability factor proposed herein should not discredit its usefulness. They parallel the engineering, economic, and political constraints and restraints jointly determining the management of the public infrastructure assets. Energy consumption governs global sustainability considerations in general and the engineered infrastructure in particular. Nevertheless, whereas engineering deals with energy directly, economics and politics tend to monetize its benefits and costs. A 3-D space in which the three fields can operate in coherent terms is as essential to infrastructure sustainability as stability is to structural stiffness analysis. Robustness, resilience, and sustainability can frame such a space.

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