Supply and Demand in Engineering and Management

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ABSTRACT

All successful infrastructure products and processes exemplify the collaboration of engineering and economics in space and time. In their respective domains, the two specialized professions optimize supply and demand (S / D) of energy and money. If their priorities diverge, structural and economic failures result. The various stages of a bridge lifecycle and the transitions between them are examined as vulnerable nodes and links where diverging constraints of supply and demand must be reconciled. Robustness, resilience and sustainability are considered as properties which, if sufficiently defined, can model realistically the cost-effective performance of the infrastructure under varying conditions over extended lifecycles.

1 Introduction: supply / demand (S / D) in economics and engineering

The Industrial Revolution channeled the social transactions and acquisitions of intelligence, information, money and energy in increasingly specializing professions. Concurrent technological and economic schools of thought evolved as a result. In the dimensions of physics, natural information / energy and time / space are integrated. In the dimensions of economics, social ones are distinct. Economics and engineering process and produce tangible social assets, however they operate in social and natural time / space, respectively. Engineering harnesses natural information and energy into relatively more permanent products. The universally valid laws of thermodynamics underly all design of engineering products. Economics specializes in more dynamic processes in terms of money, whose value is local and transient. Engineered structures demonstrably supply strength superior to the service demands. Demands exceeding supplies energize social development. As a result, engineering solutions attain a higher level of determinacy in the natural environment than do those of economics in society. Von Neumann and Morgenstern [1] acknowledge: "Our knowledge of the relevant facts of economics is incomparably smaller than that commanded in physics at the time when mathematization of that subject was achieved". In Eq. 1 – a and – b the defining contrast between the two fields is reduced to the supply / demand (S / D) equilibria governing them:

$$\begin{aligned} \text{Economic processes: } S < D \text{ } [\$] & \quad (1-a) \\ \text{Engineering products: } S > D \text{ } [\text{Energy}] & \quad (1-b) \end{aligned}$$

The inequalities of Eq. 1–a and –b express opposite dynamics in incongruent dimensions. They reflect the varying unsatisfied demand inherent in all economic processes and the invariable satisfaction supplied by all engineered structures. Economics improves the process of supply S to meet the greater demand D. Engineering perfects the oversupply S in products creating future demand D. Economics maximizes by indeterminate negotiations under the restraint of money. Engineering optimizes by deterministic calculations under the constraint of energy. Both utilize the instruments, tools and methods of art and science. In both, reversing the governing inequalities of Eq. 1 produces failures. With luck, the claims of 're-engineering government' and 'economical structures' remain overreaching fantasies. Drucker's [2] statement is quantifiable in engineering dimensions: "Everything degenerates into work". Managers also agree that bottom lines crystalize in money.

Table 1 presents a comparison between the specialized domains of economics and engineering. The two systematically mingle and borrow from each other. The processes and products of the transportation infrastructure are optimized when they integrate. The inherently different restraints and constraints on the supply and demand in the two fields are briefly examined, in order to qualify and quantify the terms of their collaboration.

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Table 1. Economics and engineering

	Economics	Structural Engineering
Domain	Society	Nature
Instrument	Politics	Physics
Preferred models	Probability, Statistics	Determinism, Mechanics
Type of equilibrium	Dynamic, unstable	Static, stable
Method	Negotiation	Calculation
Dimensions \$,	Time	Energy, Space
Bounds	Adopted restraint	Imposed constraint
Supply / Demand	$S < D$	$S > D$
Outcome	Process Transaction	Product Acquisition

2 Supply and demand (S/D) in economic processes

Von Neumann and Morgenstern [1] begin by stipulating that “there exists at present no universal system of economic theory” and “if one should ever be developed, it will probably not be in our lifetime”. Hence, they obtain mathematically rigorous solutions for games representing “the endeavor of the individual to obtain a maximum utility, or in the case of the entrepreneur, a maximum of profit”. In that reduced domain demand exceeds the available supplies ($S < D$) and players *win / lose* or minimize their losses / maximize benefits.

Social models assuming $S \geq D$ reduce all non-negotiable constraints to optional restraints. If they were attainable technologically and psychologically, a stagnant indifference, analogous to entropic death might result. Hence, the various schools of economics differ primarily on the optimal $S/D < 1$ ratio and on the constructive means to influence it. From Adam Smith (1723 – 1790), Anne Robert Jacques Turgot (1727 – 1781) and Henri de Saint-Simon (1760 – 1825) to Friedrich Hayek (1899 – 1992) and John Maynard Keynes (1883 – 1946), on to Milton Friedman (1912 – 2006) and John Kenneth Galbraith (1908 – 2006), complementary, contradictory, and conflicted views on the need for ground-up and / or top-down regulation of the economy have evolved and are still in progress. As Von Neumann and Morgenstern state [1], the empirical evidence amassed over centuries remains insufficiently homogeneous and much too subjective to be conclusive. A hopefully realistic expectation is that the top-down / ground-up regulation schools might integrate into an optimal dynamic hybrid. Thus far, the two agree that ‘social engineering’ of the type championed for example by Auguste Comte (1798 – 1857) and Karl Marx (1818 – 1883) is not that hybrid. As a by-product of that conclusion, reached over three centuries of free market research, engineering and economics have specialized in acquiring products in space, and transacting processes in time, respectively.

3 Supply and demand (S/D) in engineering products

In physics, as in economics, a unified theory remains elusive. Von Neumann and Morgenstern [1] point out that “It happens occasionally that a particular physical theory appears to provide the basis for a universal system, but in all instances up to the present time this appearance has not

lasted more than a decade at best.” As in Game Theory, engineering achieves its stated objectives by defining the limited domain over which they apply. Engineered products supply services exceeding known present and expected future demands in terms of quantifiable information and energy. A structure is built to resist greater loads than expected. A new transportation facility is designed to accommodate present and anticipated numbers of users. The material ‘oversupply’ is dimensioned in time and energy, under various names, such as ‘safety factor’, ‘reliability index’, and ‘performance index’. It is perpetually reviewed and refined. When the constraints are rigorously defined, the process becomes optimization.

During the 20th century physics gained critically important intelligence about the transactions and acquisitions of information and energy in the natural world. The S/D relationship in engineering evolved accordingly, as documented in the many editions of the Bridge Design Specifications by the American Association of State Highway Transportation Officials (AASHTO). The Allowable Stress Design (ASD) evolved to Load Factor Design (LFD), and (thus far), to Load and Resistance Factor Design (LRFD), now in its 8th edition [3]. The relationship between the demand of loads Q and the supply of structural resistance R is stated in Eq. 2–a, –b, and –c, and illustrated in Fig. 1:

$$\text{ASD (1928): } R \geq S.F. Q \quad (2-a)$$

$$\text{LFD (1960s): } \phi R \geq \sum \gamma_i Q_i \quad (2-b)$$

$$\text{LRFD (1994): } \phi R \geq \sum \eta_i \gamma_i Q_i \quad (2-c)$$

where: R – structural resistance;
 Q_i – demand of load i ;
 $S.F.$ – safety factor;
 ϕ – resistance factor;
 γ_i – factor of load i ;
 η_i – modifier of load i .

Figure 1. Distribution of load demand Q and structural resistance R , recommended by AASHTO LRFD Bridge Design Specifications

The parameters of Eq. 2 are physically quantifiable. However, they also qualify socially evolving views. Engineering supplies resistance R , constrained by material properties, to meet the demands the economically restrained design loads Q .

Equation 2 and Fig. 1 are fundamentally deterministic, but they acknowledge the different uncertainties in the socially restrained demand D for service loads and the naturally constrained supply of structural resistance R . Material strength and reliability are consistently improving. So are the quality and quantity of information about all pertinent variables. Thus, the supply S of engineering

resistance R approaches the demand D of the loads Q (as ever from above). Both however, are prone to different uncertainties, which in turn are treated by widely diverse probabilistic models. The entailed professional challenges are addressed for example in Yanév [4]. Higher quality and reduced quantity of materials have produced tallest towers, longest bridges, largest aircraft, and further-venturing spacecraft. The concurrent trends in lifespans and implied safety margins might benefit from a more far-sighted economic assessment, again recognizing the probabilistic and deterministic constraints of its modeling.

4 Supply and demand (S/D) in economics / engineering management

Drucker [2] wrestled with the vagueness of the management process as follows:

"Management is a practice rather than a science. In this, it is comparable to medicine, law, and engineering. It is not knowledge but performance. Furthermore, it is not the application of common sense, or leadership, let alone financial manipulation. Its practice is based both on knowledge and on responsibility."

The economics and engineering 'knowledge and responsibility' in Drucker's rumination differ. Long-term, both should tend towards maximizing social benefits, however under the opposed constraints of $S < D$ [\$] and $S > D$ [energy], respectively, short-term priorities diverge. Economics and engineering do not anticipate convergence to $S = D$ but they approach that equality by a lower and an upper bound path, respectively.

As financial restraints govern most contemporary management, decisions related to the infrastructure at the highest levels are taken 'top-down' by economists, lawyers and ultimately, politicians, whereas engineers deliver assets 'ground-up'. Figures 2-a and -b illustrate the evolving engineering and management chain of supply and demand. Figure 2-a depicts a bi-lateral relationship between comprehensively resourceful manager and competent builder. From the pyramids, the Code of Hammurabi (1730 - 1685 B.C.), and the Roman aqueducts to some modern 'signature' structures, such exclusive interactions have supplied outstanding products, respecting natural constraints, and selective about social demands. Between 1928 and 1964 the fortuitous collaboration of master manager Robert Moses (1888 - 1981) and master designer Othmar Ammann (1879 - 1966) produced the unique network

of record – breaking spans in New York City. The demands for preserving that network today compete with other services for restrained funding supplies.

Figure 2 – b depicts a typical modern democratic chain of infrastructure management responsibilities. The levels of responsibility, the competences, the constraints, and their dimensions are different throughout the various stages of the process. The S/D restraints on money and constraints of energy are implicit. As the number of links and nodes increases, so do the potentially vulnerable transitions where S/D dimensions change and priorities reverse. Economics adjusted to the scientific and technological advances, by shifting its priorities from static acquisitions to dynamic transactions, dimensioned in time, energy, and money. Ground-up at the bottom of the chain in Fig. 2 – b, structural engineering supplies products exceeding the performance demands.

The accelerated pace of social transactions has affected the longevity of structural acquisitions. Whereas old bridges have lasted for centuries, AASHTO currently recommends a useful life of 75 years, and contemporary bridge decks often serve only 30 years. The trend reduces the supply of services by the engineered product but expands demands in the economic process. Therefore, infrastructure management must reconcile ostensibly opposed economic and engineering views and dimensions. Particularly sensitive are the stages involving the disparate sets of actors, with their incongruent dimensions of supply / demand.

In a letter to the author, dated 10/6/1993 President Bill Clinton wrote:

"I agree with you that America must address the problems of its vast network of bridges and highways if we are to remain a strong nation during the next century."

However, on 10/23/1993, Chief Highway Administrator (later Secretary of Transportation) Rodney Slater specified the restraints as follows:

"Needs typically exceed the means available to address them. ... Clearly if funds were unlimited, we would do more."

No profession can compete with engineering in the design and construction of the infrastructure. In management however, engineering must collaborate with economics. The first step in meeting that demand is to model the products constrained in space and energy also as processes restrained in time and money. Bridge management initiated that transition in the U.S. and worldwide during the 1990s. It is reflected for example in [5-8]. Yanév [9] expands the static snapshot of a bridge management operation shown in Fig. 3-a to the dynamic presentation of a bridge lifecycle shown

Figure 2. Supply and demand at different levels of management and engineering

in Fig. 3–b. The intelligence, information, money and energy, demanded and supplied at each stage of the lifecycle differ, satisfying different S/D ratios, obtained and measured by different means. In a typical transportation network, all stages are concurrent, demanding complementarity and collaboration of the diverse competences.

Lifecycle costs: present worth (PW) versus annualizing

Economics and engineering tend to assess future supply and demand by the present worth (PW) and annualizing methods, respectively. The PW of future costs and benefits is a function of a selected discount rate i , according to Eq. 3–a and –b.

$$i = (1 + cc) (1 + fr) (1 + pi) - 1 \quad (3-a)$$

where: cc = 'real' opportunity-cost of capital

fr = required premium for financial risk associated with the considered investments
 pi = anticipated rate of price inflation

Neglecting the higher order terms is justified by their relatively small values and reduces Eq. 3–a to the following:

$$i = cc + fr + pi \quad (3-b)$$

The present worth of an amount A occurring N years into the future is reduced by the factor $1/(1+i)^N$. The aggregate present worth of amounts a occurring annually during N years from the present is equal to:

$$a \sum_{n=1}^N 1/(1+i)^n = a (1 + 1/i) [1 - 1/(1+i)^N] \quad (4-a)$$

$$\lim_{N \rightarrow \infty} a \sum_{n=1}^N 1/(1+i)^n = a (1 + 1/i) \quad (4-b)$$

Figure 3. The Bridge Management lifecycle: a: Cross section, b: Plan

Hence, i determines a finite discounted present worth of the infinite series ($a, a, a, \dots$). The ratio of the discounted sums of a finite N and n tending to infinity is equal to:

$$a(1 + 1/i) [1 - 1/(1 + i)^N] / a(1 + 1/i) = [1 - 1/(1 + i)^N] \quad (5)$$

Given a discount rate i , a period of N years can be selected such that the neglected remainder of the infinite sum would not exceed an acceptable error ε , as follows:

$$N = -\ln \varepsilon / \ln (1 + i) \quad (6)$$

Yanev [9] shows that, at a discount rate $i = 4\%$ and a period $N = 75$ years (the bridge useful life recommended by AASHTO), the remainder of the infinite sum is 5%. The truncated 'attention span' of the *PW* method moved Leeming [10] to conclude:

"Future maintenance costs are regarded as visionary while capital costs are real. ... If maintenance of our bridge stock is to remain a fixed percentage of the total governmental expenditure on construction, then there is an argument for a zero-discount rate in calculating the net present value of maintenance."

Annualizing distributes all lifecycle costs equally over the structural life. Whereas economics considers infrastructure assets over a limited time, new engineering facilities permanently alter geographic space. Hence, annual maintenance costs can be expressed as a relatively constant percentage of the renewal cost, changing proportionally over the years. If services are tolled, the annual maintenance can be expressed as a percentage of the revenue. For infrastructure facilities requiring periodic maintenance and replacements, De Gramo et al. [11] recommend *perpetuity*, e.g. a uniform series of indefinitely running payments.

In order to provide for annualized payments X , a principal P must be set aside at annual interest $in\%$ (interest $\neq$ discount rate), such that $P in = X$. If the payments are not annual but arise at k periods, the relationship becomes:

$$X = P [(1 + in)^k - 1] \quad (7)$$

where: P = the capitalized value of X .

Under the diverse engineering and economic assessments of future and even present supply and demand in the domains of money and energy, particularly sensitive are the transitions from one lifecycle stage to the next, when the S/D parameters and their ratios change. Brief descriptions of each follow.

4.1 Design and selection

Codified design supplies structural resistance in acceptable excess over the demands of standard load combinations or states. Barring the rare error, the constraint of $S > D$ stipulated in Eq. 2 is satisfied in terms of forces $R > Q$. For bridges of average size, forces are applied statically or pseudo-statically. The dynamic demands of the service life are acknowledged for example in fatigue and seismic provisions, and in some serviceability recommendations (including displacements). Redundancy and ductility, allowing load redistribution on the global (structural) and local (element) levels are encouraged.

Performance-based design has become a broadly defined subject, ranging over heterogeneous engineering and economic parameters. This is elaborated for example in [12-15]. The perpetually elaborated demands of a performance-based design by far exceed the laconic form of Eq. 2.

Design selection is one of two critical moments in the structural lifecycle which are briefer than the commonly recognized 'stages', and hence, do not appear explicitly in Fig. 3 – b. Assuming that all design alternatives satisfy $S > D$ in terms of $R > Q$, structural costs are restrained by the supply of money, e.g., $S < D$ in terms of $\$ < \$$. Lower first costs are strongly favored, even if they might correspond to higher lifecycle costs. The *PW* method enhances this effect.

Given adequate funding supply, lifecycle costing considerations can justify higher first costs. An owner can require a larger S/D ratio, serviceability, inspectability, maintainability, or other design enhancements.

Peer review is targeted by cost-cutting, whereas Value Engineering has emerged as a process of reconciliation between the two opposed constraints of first cost and lifecycle performance. It has an incentive to produce multiple recommendations reducing the demand of first costs. An owner may implement few or none of them.

Despite the extensive commentary of AASHTO LRFD (2017 and earlier editions), structures supplying $R > Q$ can perform below the long-term and even the short-term demand. Purvis [16] and Yanev [17] are among many arguing that expansion joints fail to satisfy the demand for $R > Q$ in the domain of forces under normal traffic over relatively short periods. Joints are not considered as essential links in the transfer of live loads and hence, are not designed to resist the impact forces of even moderate service. They fracture, but are not fracture – critical and hence, their under-performance affects resilience and sustainability over long service periods more than it does robustness under brief extreme events. If robustness and resilience were qualified and quantified sufficiently for direct reference in design specifications, they could serve as the criteria of lifecycle needs.

4.2 Construction

The constructors and owners manage energy and money in space and time under different and even opposite constraints. Projects materialize after the supply and demand of these constraints are successfully negotiated. In roughly 80% to 90% of the cases, construction is awarded to the lowest bidder, reflecting the strong economic constraint of first costs. The time constraint is negotiated in terms of contractual incentive / disincentive. Both owner and builder have incentive to minimize the time and space of construction. However, the supply / demand of projects and assets differ. The constructor's incentive is to minimize construction time and cost. The asset manager's incentive is to maximize service and time at minimum cost. As a result, the 'knowledge and responsibilities' in Drucker's [2] preceding quote diverge. Quality assurance of the process (QA) and quality control of the product (QC) traditionally ensure that all contract specifications are met, however both are conducted on a spot-check and sample basis. Under diverging constraints, QA and QC can reduce to spot-checks optimized by risk assessment.

The design / build method reduces the project demand for time by merging the two stages. Once again, design and construction prioritize S/D differently. Design transacts abstract intelligence and information, whereas construction acquires real money and energy. As the capabilities of analysis and construction are expanding, so are the design options. Ultimately, the design / build method is likelier to restrain the intelligence and information of design to the money and energy constraints of construction.

4.3 Delivery and Service

Project delivery, as design selection, is a brief but critical moment in the bridge lifecycle, not explicit in Fig. 3. Both the constructors and the future users have incentives to open the structure to service. As a result, the transition from constructed project to asset in service is plagued by haste and incomplete assessment. All construction constraints of space, time and money may be satisfied at delivery without guaranteeing the owner's ability to deliver service over the structural lifecycle. According to certain management practices large infrastructure projects are inspected 10 years after completion. Divergences from the designed performance are attributed to the responsible parties, including owners, designers and builders. A more volatile economy precludes such practice. When, after 40 years of service, the I-35 bridge over the Mississippi at Minneapolis collapsed on Aug. 1, 2007, the designing consultants were no longer active. The critically important design calculations and construction drawings were unavailable.

Whereas the Federal Highway Administration mandates biennial bridge inspections, it only recommends preservation and serviceability, as in AASHTO 2010 [18] and FHWA 2011 [19]. Some recommendations may translate into performance – based design specifications, however with a considerable time-lag.

So long as FHWA funded construction but not maintenance, the supply of service declined and the demand for construction grew. After the policy was rescinded, the funding could meet more diverse demands, within the same restrained supply. If the total deck area A of a bridge network and its condition rating R are relatively constant from year to year, Eq. 8 should reflect the equilibrium between the demand of the annual deterioration r and the improvement, supplied by reconstruction and repair.

$$(A - A_{rec}) r = A_{rec} \Delta R_{rec} + A_{rep} \Delta R_{rep} \quad (8)$$

where:

A - the deck area of the bridge network

A_{rec} - deck area under reconstruction

A_{rep} - deck area under repair

ΔR_{rec} - average annual change of R of A_{rec}

ΔR_{rep} - average annual change of R of A_{rep}

R - bridge condition

r - rate of bridge deterioration in annual increments ($= \partial R / \partial t$)

A cost-effective maintenance should reduce the rate of deterioration r , and hence, the demand for costlier reconstruction and repair. Yanev [9] points out that maintenance and preservation supply unquantifiable benefits over indeterminate lifecycles, whereas their funding demands are immediate and compete with the more attractive capital condition upgrades. The supply / demand (S / D) of service and of structural preservation are easier to 'monetize' at toll structures. By incorporating maintenance into the more general preservation, FHWA 2011 [19] allows the qualifying activities to be planned as discrete projects with quantifiable costs / benefits.

The demands of probable random extreme events are more effective than those of predictably determinate regular maintenance in supporting bridge serviceability demands. Robustness has emerged as a measure of structural performance under unique loading demands over limited time. Resilience and sustainability expand that demand over the recovery and the ensuing lifecycle.

5 Supply and demand S / D in masterpieces and 'signature' structures

The Renaissance separated art and science, predating, and prefiguring the separation of economics and engineering in the Industrial Age. The French language refers to large infrastructure assets as *ouvrages d'art*. A structural masterpiece exceeds lifecycle service demands within economic constraints to such a degree that it becomes a 'signature' of the professional art and science. According to Billington [20] the two fundamental ideas of structural art are efficiency and economy (of both process and product). The author argues that the products of structural artists, such as Eiffel, Roebling, and Freyssinet continually meet service demands, while their process minimized first costs. The Brooklyn, Golden Gate, and George Washington bridges, and the Eiffel Tower have become signatures of their creators and of their localities. If structural masterpieces have established their standing over millennia, 'signature' structures deliver instant gratification. In a reversal, the demand for a 'signature' structure can precede its ability to supply the service within the governing constraints.

Demands for 'signature' structures relax funding restraints. The advanced analysis and construction capabilities can foster the illusion that the energy constraints in terms of $R > Q$ are similarly relaxed. In such instances, the long view of supply / demand in terms robustness, resilience and sustainability introduces a sobering restraint.

'Signature' structures have resulted from individual visions, as well as from popular demand (as in the case of the San Francisco – Oakland East Bay Bridge). President François Mitterand's Grands Travaux burnished his pharaonic image, but over time joined older Paris signatures. At the Viaduct de Millau Lord Norman Foster and Michel Virlogeux designed, and Eiffage constructed a masterpiece, such that $R > Q$. Fifteen years later the structure bears the signature of its authors and of the region.

6 Supply and demand (S / D) in structural failures

Engineering commonly attributes structural failures to a demand of loads equaling or exceeding the supply of resistance in terms of forces ($R \leq Q$). However, most failures can be traced to multiple coinciding supplies falling short of demands ($S < D$) in the dimensions of time and money. The investigation following the failure of the Silver Bridge at Point Pleasant in 1967 found critical deficiencies in all stages of its lifecycle, including design, construction, maintenance, and inspection. One assessment of the collapse in 1994 of the Seongsu Bridge over the Han River in Seoul, found the structure "poorly designed, built, and used". Multiple causes were identified after the failures at the Charles de Gaulle airport in France in 2004 and suspected at the I-35 bridge over the Mississippi in Minnesota in 2007. At each lifecycle stage the S / D relationships imply and reflect different vulnerabilities in the process and the product.

6.1 Design and construction

A restrained supply of money is unlikely to cause deliberate design or construction error however, it can constrain time and thus render the process vulnerable. Since the quantities supplied and demanded in construction exceed those for design, that is when a misplaced $S < D$ ratio is likelier to affect the $R > Q$ ratio adversely. Since QC and QA can add to the cost and delay delivery, their demands

can be viewed as counter-productive and targeted for 'streamlining'.

6.2 Service

It is impossible to estimate how many service failures have been prevented as a result of the bridge management efforts following the Silver Bridge failure, not only in the USA, but worldwide. The main contribution is due to the funding of the National Bridge Inventory (NBI) and the biennial inspections of vehicular bridges. The push for funding of bridge lifecycle extension has been less effective. Among the reasons may be the institutional inertia restraining all 'expense' funding to $S < D$. The funding of large (possibly 'signature') projects is popular, but the continuing preservation of assets is 'streamlined' and eliminated. Thus, each stage of the lifecycle inherits pending demands from the preceding ones and expands them to the next one. Concurrently, it is argued that biennial inspections should be relaxed to a 'risk-based' schedule at the discretion of the owner.

6.3 Management

If failures are expressed as $S \geq D$ and $S \leq D$ by economics and engineering, respectively, they are bound to occur when the processes and products managed by the two domains unduly influence each other. Hence, all failures are failures of management. Just as structural failures are likelier at links transferring loads between elements, so are management failures likelier at transfers of responsibilities. Figure 2 – b illustrates the proliferation of such links. Engineering design delivers redundant products. Economic management 'streamlines' processes by eliminating 'duplication of effort'. As time and money are negotiable restraints in economics and absolute constraints in engineering, most management failures can be traced to unreconciled economic and engineering supply of and demand for time and money.

7 Supply and demand (S/D) for robustness, resilience, and sustainability

Robustness, resilience, and sustainability are relatively new qualifiers (and hopefully, quantifiers) of structural performance during regular service and extreme events. Their many and still slightly vague definitions reveal an attempt to reconcile the diverse S/D restraints and constraints governing the various stages of structural lifecycles. For structures designed to supply $R > Q$, robustness and resilience gain significance when 'adverse' conditions threaten to reverse that inequality. Bruneau and Reinhorn [21] define resilience as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events". Robustness is defined as the ability of a structure or network with an impaired resistance to redistribute its supply to meet the load demand in constrained time, for example during 'extreme events'. Thus, robustness can be dimensioned in space and energy, and resilience – in time and money. The two properties are correlated with structural redundancy and ductility and can be extended from structural design to network management. A resilient network comprises robust assets. A sustainable asset must be a network of robust and resiliently linked elements. In Fig. 4 robustness and resilience are superposed

over the codified strength and stability governing performance-based structural design. The figure illustrates the following stages:

Figure 4. Robustness, resilience, and the structural performance properties currently designed according to specifications

- Performance – based design according to AASHTO 2017 [3] supplies structural strength, stability, ductility, and redundancy to exceed rigorously codified demands, including regular service loads, environmental conditions and 'extreme events'.

- 'Normal' service conditions gradually reduce the as-built levels of the structural properties. The rate of decline is drawn as a range, rather than a line, to represent the implicit uncertainties and variability, as discussed for example in Yanev [4].

- 'Extreme demands' of brief durations reduce the structural supply to an uncertain new level. Any residual supply of structural resistance is a measure of its robustness. The time during which the impaired structure can supply some level of service is a measure of its resilience.

- The rapidity with which the supply of service can be restored to meet and exceed acceptable demand levels is a measure of resourcefulness.

With some qualifications, the reasoning can be extended to networks. If a network's sustainability is quantified by its annualized lifecycle supplies and demands, robustness and resilience can be shown to improve it, in both engineering and economic terms.

8 Conclusions

Under the dynamic social restraints and more permanent natural constraints, the different managers of bridge economics and engineering optimize (or more often prioritize) the supplies S and demands D of different resources, over different time – horizons. The resources of energy and money tend to, but do not reach, $S = D$ by upper- and lower-bound routes. At various stages of their activities, both economics and engineering may apply ratios of $S/D > 1$ and $S/D < 1$ to different parameters under different restraints and constraints. Engineering designs the relatively stable parameters of products such that $R > Q$, but once it adopts time and money as governing constraints (as for example during construction), it too seeks to minimize the supply of services and costs. Thus, engineers and economists may tend to demand and to supply more and less than the necessary funding. Therefore, it must be

recognized whether these ratios are as intended, or due to mismanagement. Economics expects future supplies to meet current demands. Present engineering supplies exceed projected future demands. In all structural achievements economics and engineering have reconciled that difference. They must do so perpetually, as rigorous optimization is not possible. The alternative is failure.

Billington [20] points out that masterpieces create the false impression of courting risks, because they meet demands with minimum supply of material, time and money. In the meanwhile, insufficient supply is blamed for failures. Upon closer examination of an engineered masterpiece, it appears that $R > Q$ is a hard constraint in the domain of ultimate forces, but $S < D$ has been an optimized restraint of the initial resources.

In a market democracy the overriding political management supplies services to voters. Consequently, it is highly risk-averse over its short-term mandate, but has limited long-term incentive and competence in economics, let alone engineering. As a result, S/D optimization can narrow down to risk minimization. Qualifying management and inspections as 'risk-based' signals not a reduction of risk by increasing supply, but a reduction of supply, while trying to control risk. The risk of supplying only the means demanded by hazard mitigation, common in the early days of bridge management, can creep back into it.

From their origin in assessing structural performance under extreme events, robustness, resilience and sustainability are expanding to integrated qualifiers and, potentially, quantifiers of transportation networks in economic and engineering terms. Moreover, they are applicable to management itself, with its nodes and linkages, as illustrated in Fig. 2–b. Sustained robustness over extended periods within the restraints and constraints of the available supplies amounts to resilience. Such a definition expands the design responsibility from the performance of the product under specified loads to the benefits of the process within the social fabric over the time of service. Restraints of money and constraints of energy reconcile. In this expanded view, sustainable design and management can be qualified and quantified for consideration in political debate. Thus far, the design, construction and preservation of robust, resilient and sustainable bridges are recommended. Forthcoming bridge design specifications are addressing this subject in more concrete terms.

The optimal supply and demand of the hard-fought 1.3 trillion \$US (2021) for upgrading the nation's 'hard' infrastructure will require rigorous and authoritative engineering end economic collaboration along the described terms.

References

- [1] Von Neumann, John and Oskar Morgenstern, *Theory of Games and Economic Behavior*, John Wiley & Sons, Inc., New York, N.Y., 1945.
- [2] Drucker, Peter F., *Management*, Harper & Row, Publishers, New York, N.Y., 1973.
- [3] AASHTO, LRFD Bridge Design Specifications, 8th Edition, American Association of State Highway Transportation Officials, 2017.
- [4] Yanev, Bojidar, *Probability and Determinism in Bridge Management, Building Materials and Structures* 62(2019), 3-14. ISSN 2217-8139.
- [5] Purvis, Ron, *Life-Cycle Cost Analysis for Protection and Rehabilitation of Concrete Bridges Relative to Reinforcement Corrosion*, NCHRP Report 377, National Cooperative Highway Research Project, Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.
- [6] Hudson, Ron, R. Haas and W. Uddin, *Infrastructure Management*, McGraw-Hill, New York, N.Y., 1997.
- [7] Hawke, Hugh, BLCCA (Bridge Life-Cycle Cost Analysis), National Cooperative Research Project, NCHRP Report 483, Washington, D.C., 2003.
- [8] Brühwiler, Eugen and B. Adey, *Improving the consideration of life-cycle costs in bridge decision-making in Switzerland*, *Structure and Infrastructure Engineering*, Vol. 1, No. 2, Taylor & Francis Group, Ltd., Abington, U.K., 2005, pp. 145 - 157.
- [9] Yanev, Bojidar, *Bridge Management*, John Wiley, Inc., Newark, N.J., 2007.
- [10] Leeming, M. B. 1993, *The Application of Life-Cycle Costing to Bridges*, *Bridge Management 2*, Harding, J. E., G. A. R. Parke and M. J. Ryall, editors, Thomas Telford, London, UK, 1993, pp. 574-583.
- [11] De Gramo, E. P., J. R. Canada and W. G. Sullivan, *Engineering Economy*, Macmillan Publishing Co., New York, N.Y., 1979.
- [12] Wilson, David C., *Value Engineering Applications in Transportation*, NCHRP Synthesis 352, Transportation Research Board, National Research Council, Washington, D.C., 2005.
- [13] Bell, Michael E. and T. J. McGuire, *Macroeconomic Analysis of the Linkages Between Transportation Investments and Economic Performance*, NCHRP Project 2-17 (3), Transportation Research Board, National Research Council, Washington, D.C., 1994.
- [14] Frangopol, Dan, editor, *Optimal Performance of Civil Infrastructure Systems*, ASCE, SEI, Reston, VA, 1998.
- [15] Furuta, H. et al., *Performance Measures for Bridge Management*, *Proceedings of the International Workshop on Structural Health Monitoring of Bridges*, Sept. 1-2, 2003, pp. 181-186, Kitami Institute of Technology, Japan Society of Civil Engineering, Kitami, Japan.
- [16] Purvis, Ron, *Bridge Deck Joint Performance*, NCHRP Synthesis 319, National Cooperative Highway Research Council, Transportation Research Board, Washington, D.C., 2003.
- [17] Yanev, Bojidar, *Joints: the weak link in bridge structures and life cycles*, *Smart Structures and Systems*, Vol. 15, No. 3, 2015.
- [18] AASHTO, 2010, *Bridge Element Inspection Manual*, American Association of State Highway and Transportation Officials, 2010.
- [19] FHWA, 2011, *Bridge Preservation Guide*, Office of the Infrastructure, Federal Highway Administration, FHWA-HIF-11042, Washington, D.C., 2011.
- [20] Billington, David, *The Tower and the Bridge*, Basic Books, Inc., 1983.
- [21] Bruneau, Michel and A. Reinhorn, *Overview of the Resilience Concept*, *Proceedings of the 8th U.S. National Conference on Earthquake Engineering*, San Francisco, CA, April 18-22, 2006.