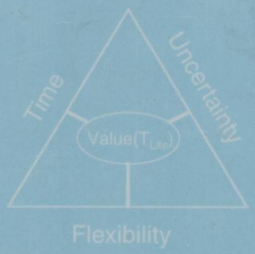
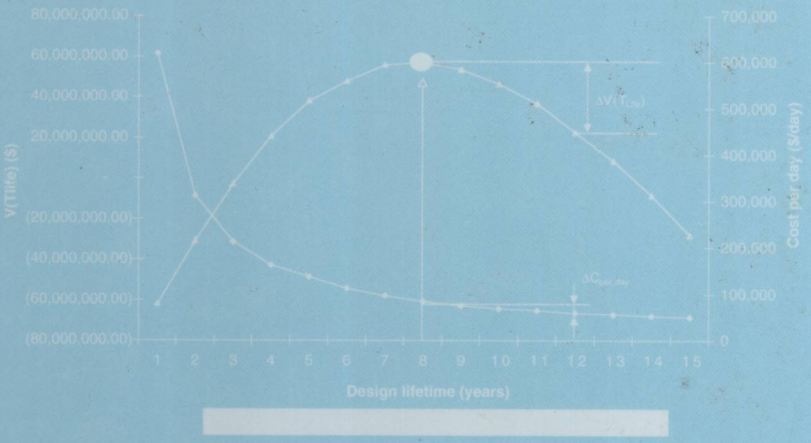
$$T^*_{\text{Life}} = -\frac{1}{r}\ln\left(\frac{C_0\alpha}{u_0 - c_{\text{OM}}}\right)$$



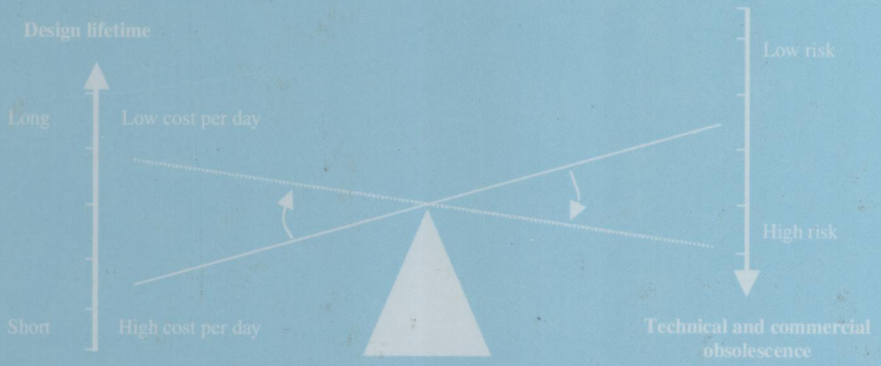


Analyses for Durability and System Design Lifetime

A multidisciplinary approach

Joseph H. Saleh

$$V(T_{\text{Life}}) = \int_0^{T_{\text{Life}}} [u(t) - c_{\text{OM}}(t)] \times e^{-rt}dt - C(T_{\text{Life}})$$



$$\left.\frac{\partial V}{\partial T_{\text{Life}}}\right|_{T^*_{\text{Life}}} = \left\{u_0 \times \exp\left[-\left(\frac{t}{T_{\text{obs}}}\right)^2\right] - c_{\text{OM}}(t)\right\} \times e^{-rt} - \frac{\partial C(T_{\text{Life}})}{\partial T_{\text{Life}}} = 0$$

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A MULTIDISCIPLINARY APPROACH

Joseph H. Saleh

Georgia Institute of Technology

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ANALYSES FOR DURABILITY AND SYSTEM DESIGN LIFETIME

An important issue in engineering design is a system's design lifetime. Economists study durability choice problems for consumer goods, but seldom address lifetime problem(s) of complex engineering systems. The issues for engineering systems are complex and multidisciplinary and require an understanding of the "technicalities of durability" and the economic implications of the marginal cost of durability and of value maximization. Commonly the design lifetime for infrastructure is set between 30 and 70 years, with limited rationale. Satellite lifetimes are also assigned with limited analysis. This book provides a systemic qualitative and quantitative approach to these problems, addressing first the technicality of durability, second the marginal cost of durability, and third the durability choice problem for complex engineering systems with network externalities (competition and market uncertainty) and obsolescence effects (technology evolution). Because the analyses are system-specific, a satellite example is used to illustrate the essence and provide a quantitative application of these analyses.

Dr. Joseph H. Saleh is an Assistant Professor of Aerospace Engineering at the Georgia Institute of Technology. He received his Ph.D. from the Department of Aeronautics and Astronautics at MIT and served as the Executive Director of the Ford–MIT Alliance. His research focuses on issues of design lifetime and how to embed flexibility in the design of complex engineering systems in general and in aerospace systems in particular. Dr. Saleh is the author or co-author of 50 technical publications and the recipient of numerous awards for his teaching and research contributions. He served as a technical consultant to NASA's Jet Propulsion Laboratory and has collaborated on research projects with various aerospace companies.

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To Carl, Mia, Jihad, Abu Ali, Na'ama, and Michal

That they may find fulfillment in a peaceful, diversely rich, and prosperous Middle East

To The Reader

I know that, despite my care, nothing will be easier than to criticize this work if anyone ever thinks of criticizing it. I think those who want to regard it closely will find, in the entire work, a mother thought that so to speak links all its parts. But the diversity of the objects I had to treat is very great, and whoever undertakes to oppose an isolated fact to the sum of facts I cite or a detached idea to the sum of ideas will succeed without difficulty. I should therefore wish that one do me a favor of reading me in the same spirit that presided over my work, and that one judges this work by the general impression it leaves, just as I myself decided, not by such and such a reason, but by the mass of reasons.

Alexis de Tocqueville, *Democracy in America*, 1835

Preface

Time and the ephemeral nature of human life have been major themes for poets, philosophers, and theologians. Every scripture, philosophical writing, and work of art addresses, explicitly or implicitly, issues of time and the human experience of it.

Engineers have also considered and often grapple with issues of time, except that, instead of the human experience of it, they deal with the relationship of engineering artifacts with time. Less profound than the previous subject but equally thought-provoking is the transiency, not only of human life, but also of human artifacts. Through structural or functional degradation, or loss of economic relevance, the hand of time lies heavy on engineering designs. Several terms are used to describe this particular aspect of a product or a system's relationship with time, namely the duration from fielding a system, that is, when it first enters operation, to its final breakdown or retirement. These terms include *lifespan*, *service life*, *durability*, and *design lifetime*, to name a few. This book discusses these issues in the context of complex engineering systems.

More specifically, this book explores an important issue in engineering design that is becoming increasingly critical for complex engineering systems in general, and aerospace systems in particular, namely the selection and implications of a system's design lifetime. Although economists have grappled with the durability choice problem for simple consumer goods, limited attention has been given to the design lifetime problem(s) of complex engineering systems. The issues at stake in selecting a reduced or an extended design lifetime for an engineering system are complex and multidisciplinary in nature; they require a thorough engineering understanding

of the "technicalities of durability" along with the economic implications of the marginal cost of durability and of the value maximization problem in guiding the durability choice problem.

Systems engineers and program managers recognize the increasing importance of the durability choice problem for engineering systems. For example, design lifetime for infrastructure is typically set at 30–70 years, often with limited rationale, and satellite lifetimes are assigned rather arbitrarily or with limited quantitative analysis (cost-based). This book provides a systemic qualitative and quantitative approach to these problems in the form of a triptych addressing, first, the technicalities of durability; second, the marginal cost of durability, along with the economies of scale (in the time dimension), if any, that result from extended durability; and third, the durability choice problem for complex engineering systems in the face of network externalities (competition and market uncertainty) and obsolescence effects (technology evolution). Because the details of the analyses are system-specific, a satellite example is used in several chapters to illustrate the essence and provide a quantitative application of these analyses.

Also addressed is the increasing tension between the design lifetimes of present-day complex engineering systems and the shortening time scales associated with the obsolescence of their underlying technology base. The book ends with a discussion of the need for and growing interest in the concept of flexibility in system design.

The book is intended for graduate students, researchers, and practitioners. Each chapter is self-contained and can be read independent of the other chapters. The six chapters and Epilogue do, however, tell a coherent story that reaches its climax in Chapters 5 and 6, where traditional engineering wisdom and the "economies of scale" argument in system design are challenged and proved flawed under certain environmental conditions; an alternative framework and solutions are provided in Chapter 6.

Finally, it should be noted that this text is but a small book about a broad topic. It does not pretend to be exhaustive in its treatment of durability related issues. Important topics such as product replacement and recycling, for example, have not been addressed. These topics reflect "downstream" issues that define the end of life, or post-service life, of a system, whereas this book deals with the "upstream" problem of the definition and selection of

the intended design lifetime of the system. More specialized texts would do better justice to these subjects of product replacement and recycling than a summary treatment in the present work.

This book is one "panel" of a triptych that consists of two additional books (forthcoming) on flexibility and uncertainty in engineering design. The close connection among time (durability), uncertainty, and flexibility is elaborated in the Epilogue of the present work.

Contents

1 Introduction

On Time

1.1 Sundials and Human Time

This story begins with a sundial. One of France's famed fishing ports, at the lower tip of Brittany, is a medieval walled town called Concarneau. A walk though the old city, as in a few others in France, is a spellbinding experience for the visitor. Here, time does not seem to have taken as heavy a toll as in other places. A sundial on the outside wall of one of the old houses in Concarneau carries the inscription *Tempus Fugit Velut Ombra*, which means "time flies [or escapes] like a shadow." I am very fond of this inscription for many reasons. A casual reading of this inscription suggests that it is a clever indication of the obvious: as the day goes by and the Sun traces its path across the sky, the shadow of the gnomon moves along the surface of the sundial... and time flies, along with this shadow's movement.[1] But the word "like" or *velut* in the inscription, instead of "with" for example, invites the reader to a second, deeper, interpretation: the inscription may be suggesting that, like the shadow, time is elusive and (any presence in it) ephemeral. The inscription, although conveying a sense of fragility, does not decry the destructive side of time, nor does it succumb to the traditional view of time as the destroyer of all things. *Tempus edax rerum*, time the devourer of all things, cried the Roman poet Ovid. This theme found echo in many

[1] It is interesting to note that around 400 C.E., when Saint Augustine wrote his *Confessions*, he wrote of "the drops of time" as a metaphor for the water-clock or time measurement device, not the fleeting shadows of sundials.

works of art of later periods. Shakespeare, in the *Rape of Lucrece*, spoke of time as the

> *carrier of grisly care,*
> *Eater of youth [. . .]*
> *Thou nursest all and murder'st all that are:*
> *O, hear me then, injurious, shifting Time!*
> *Be guilty of my death [. . .]*

None of that on our sundial in Concarneau. The power of its inscription, *Tempus Fugit Velut Ombra*, is also in its seemingly unfinished state; like an invitation, it incites the reader to reflect on the consequences of its observation and answer the "so what?" question. How is one to use or spend time given its fleeting nature? The inscription leaves open the possibility of a positive interpretation of time as a provider of opportunities and a "space" for creative endeavors.

That sundial in Concarneau offers a window into much broader and more general questions of time, its meaning, perception, and usage. It also reminds us not to forget the immense influence of time measurement on the history of civilizations.[2] There is a vast literature on the subject. The following pages will touch briefly on some of the issues in order to position the discussion on product durability and system design lifetime in the broader context of human reflections on time in general.

Time and the ephemeral nature of human life have been major themes for philosophers, theologians, and artists. "The human experience of time is all-pervasive, intimate, and immediate" (Fraser, 2003), and, not surprisingly, almost every scripture, philosophical writing,[3] or work of art addresses, explicitly or implicitly, issues of time and the human experience of it. Time

[2] Mumford (1967) suggests that "the clock, not the steam engine, is the key-machine of the modern industrial age." Furthermore, Landies (2000) argues that it was time measurement, along with navigational imagination, that "opened the world," and that "without [a common language of time measurement] and without a general access to instruments [of time measurement], urban life and civilizations as we know it would be impossible" (Landes, 2000).

[3] From the Greek philosophers Plato, Aristotle, Plotinus, and others to the 20th century's most influential work by Heidegger, "Being and Time."

remains a deep and thought-provoking mystery.[4] Saint Augustine asks, What is time?[5] in Book XI of his *Confessions*. "Provided that no one asks me, I know; if I want to explain it to an inquirer, I do not know . . . yet what do we speak of, in our familiar everyday conversation, more than of time?" In other words, the knowledge and understanding of (the word) time is instinctive when it is used in a given context, but it becomes difficult when it is looked at in isolation: "The word then becomes an unfathomable enigma" (Miller, 2003).

Physicists realized that the laws of mechanics, in which time is a fundamental coordinate, require a separate implicit assumption of an exogenous flow of time. "We have to assume that there exists a mathematical flow of time," declared Newton. And with this he by-passed the question of the nature of Time. Philosophers, in contrast, posited that time is an experience of the human mind (or soul), which is granted the awareness of time intervals through memory and perhaps some other faculties, and the awareness that the movement of physical bodies in themselves does not constitute time.

But beyond the issues pertaining to its nature lie questions related to the experience of time and the various ways of communicating it. Consider literature, for example: "all literature is about time," writes J. Hillis Miller (2003) in his brief survey of the subject.[6] A number of secondary sources and analyses tend to support Miller's assertion.[7] Similarly, a myriad of human behaviors and creative endeavors finds the original impetus for their existence in an individual's relationship with time. Whitrow (1972), in his account of the nature of time, writes "the mental and emotional tension resulting from man's discovery that every living creature is born and dies,

[4] One ancient religion, or more precisely, one branch of the Zoroastrian religion that flourished under the Sasanian empire (circa 226–651 C.E.) was called Zurvanism, from Zurvan, which in Middle Persian (or Pahlavi) means Time. Time, according to Zurvanism, was considered a stronger force than Good (Ahura Mazda) and Evil (Angra Mainyu) and transcended both of them.

[5] The question should not be confused with "what time is it?" More seriously, time measurement raises a set of issues separate from those related to the nature of time. Saint Augustine writes, "I measure time and yet I do not know what I am measuring." Time is not identical with the units by which it is measured.

[6] "The study of time in literature [means] the investigation of the way literary works present in one way or another the human experience of lived time" (Miller, 2003).

[7] For example, George Poulet, "Studies in Human Time," and Paul Ricoeur, "Time and Narrative."

including himself, must have led him intuitively to seek some escape from the relentless flux of time." The classical theme of *ars longa, vita brevis*, which came to mean that art[8] is longer-lasting than the life of the artist,[9] is probably one reflection of an approach to (partially) escaping the flux of time in Whitrow's account. Nietzsche, for example, in *Twilight of the Idols* (1888), illustrates this approach to some extent when he claims that by writing he seeks "to create things on which time tests its teeth in vain; to endeavor to achieve a little immortality in form and in substance – I have never yet been modest enough to demand less of myself." In a similar vein, but unlike Nietzsche, Shakespeare often sought a "little immortality" for his lover through his sonnets. Consider the following, for example:

> *Devouring Time, blunt thou the lion's paws,*
> *And make the earth devour her own sweet brood; [. . .]*
> *O, carve not with thy hours my love's fair brow,*
> *Nor draw no lines there with thine antique pen; . . .*
> *Yet, do thy worst, old Time: despite thy wrong,*
> *My love[r] shall in my verse ever live young.*[10]

In summary, every person has concerned himself or herself with time one way or another, and Landes (2003) is probably right in stating that "all cultures and civilizations have concerned themselves with time, if only to give cues and set bounds to social and religious activities." For the individual, it may be that we are governed by time, just as "we are [physiologically] the children of gravity, which we cannot see or touch, but it has guided the evolutionary destiny of every species, and has dictated the size and shape of our organs and limbs."[11] So perhaps are many of our psychological dispositions,

[8] Including artifacts that are not necessarily *artistic* in nature.

[9] Although this is probably a misreading of the original expression ascribed to the Greek physician Hippocrates, in which he probably meant that learning the art of medicine is a long process . . . but life is short.

[10] I also like the following sonnet, which adds another dimension to our present subject:

> *If I could write the beauty of your eyes*
> *And in fresh numbers number all your graces,*
> *The age to come would say "This poet lies: [. . .]"*
> *But were some child of yours alive that time,*
> *You should live twice; in it and in my rhyme.*

[11] D. Newman. "Human Spaceflight from MIR to Mars." AIAA-SF June 2000 Dinner Meeting. Sunnyvale, CA.