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.

behaviors, and actions the children of our experience or relationship with *time* (like gravity, we cannot see it or touch it) and our recognition of the transiency of human life.

1.2 Time and Human Artifacts

Beyond the human relationship with time lie questions related to human artifacts and time. Probably less profound than the discussion in the previous section but equally thought-provoking is the transiency, not only of human life, but also of human handiwork. For example, of all the structures and artifacts of antiquity, only a small number survive today (Terborgh, 1949). Similarly, with regard to more recent artifacts, one often hears about "modern ruins"; abandoned concrete launch pads and steel gantries at Cape Canaveral, remnants of the Mercury, Gemini, and Apollo lunar programs, or the Aerospace Maintenance and Regeneration Center[12] (AMARC) in the Arizona desert, better known as the aircraft graveyard, where over 4,000 aircraft lie moldering in the sun. These modern ruins of engineering systems stand as a reminder that nothing is permanent: through physical or functional degradation, or loss of economic usefulness, the hand of time lies heavy on human artifacts.

Several terms are used to describe this particular aspect of a product or an engineering design relationship with time, namely the span of time from fielding a product to its breakdown or retirement. These include a product's or a system's *lifespan*, *service life*, *durability*, or *design lifetime*, to name a few.[13] This book discusses these issues in the context of engineering systems.

1.3 Two Broad Categories of Questions Regarding Durability

Durability is an important multidisciplinary concept. It is traditionally used to describe both an artifact's lastingness, or the extent of its permanence in

[12] The AMARC provides storage, regeneration, reclamation, and disposal of aircraft and aircraft parts.
[13] There are differences among these terms, and they will be discussed shortly.

time, and its capability of withstanding use, decay, or wear (*Oxford English Dictionary*). This definition is adequate for the purposes of this introductory chapter. However, in the following chapter, a distinction will be made between the durability of a product in an ex ante and an ex post sense, as well as the design lifetime of a complex engineering system, and more formal definitions of these three concepts will be provided. These details need not concern us for the time being.

For physicians, social scientists, and engineers, a host of critical issues revolves around the notion of durability. Medical doctors and surgeons, for example, are concerned with the durability of living tissue grafts and of prosthetics and implants (a heart valve, for example). Political scientists are interested in the durability of cease-fires, interstate disputes, military regimes, or coalitions in parliamentary democracies. Economists are interested in the choice of durability of durable goods under various market conditions (e.g., monopoly and competition). Engineers are concerned with the durability of structures, concrete, steel bridges, or with the durability of a coating material, of polymer bonds, or of toxic waste after disposal. This is a short list of a few concerns with durability in a variety of settings. Interest in product durability or system design lifetime generally falls under two broad categories of questions, the technicalities of durability and the choice of durability:

1. **The technicalities of durability**: The first category of questions is concerned with the identification and control of parameters affecting durability: What governs durability? What drives the deterioration processes? What limits an artifact's durability, and how can it be made to last longer? For instance, in the case of concrete structures, one can ask: How durable is concrete? How does cold climate affect the durability of concrete? And how can one make concrete more durable, by careful selection of materials, by adjusting mixture characteristics or mixing procedures, or by adding a protective coating? These concerns are generally addressed under the heading of "design for durability" in the civil and structural engineering community. Although the details are discipline-specific, the quest for identifying, understanding, and, to the extent possible, controlling the parameters affecting an artifact's

durability is prevalent in all disciplines (e.g., how to build a more durable bridge, how to make a graft last longer, or how to design a satellite that will remain operational on-orbit longer).

2. **The durability choice**: The second category of questions related to durability is less technical than the previous category and more normative in nature. These questions include the following: How long should artifacts be made to last? What is the purpose of an artifact's durability and what metrics are to be optimized – maximized or minimized – through this choice? In the case of consumer goods, for example, how do manufacturers select product durability under various market conditions (e.g., monopoly and competition)? Or, in the case of industrial goods, for example, what should customers ask or require that the manufacturer or contractor provide as a system's durability?

Questions related to the choice of durability have received significant attention from economists, but little attention has been given to these questions from the technical or engineering community. This limited interest may in part be due to the fact that engineers often view durability as a constraint rather than as a choice. Engineers often strive to create products with the longest durability technically or practically achievable. Engineering efforts in various cases can often be interpreted as (1) pushing the boundary of the technically achievable durability of a product or a design or (2) reducing the cost at which the current durability is achieved. In other words, engineers to date have been more interested in the technicalities of durability questions.

There are important and subtle durability choice questions that are by no means fully addressed yet. For example, because "infinitely durable" components or systems do not exist, durability specification requires choices and tradeoffs. System engineers and program managers, in deciding how much durability is needed, must assess how much durability is worth and how much customers are willing to pay for it. This theme will be further developed throughout this work. But although the technicalities of durability have received significant attention in the engineering literature, limited attention has been given to the durability choice problem in engineering systems. Systems engineers and program managers are beginning to recognize the importance of the durability choice problem for engineering systems. Consider the following observation from a civil engineer:

> Design service lives for infrastructures are set typically at 30–70 years often with very limited rationale. Definition of design service life [is], in principle, a choice to be made by designers and owners, based on life-cycle costs and benefits. Most typically, no such analysis is conducted. (Lemer, 1996, p. 155)

A similar mindset can be found in the space industry:

> In principle, we would like to obtain a graph of a spacecraft cost versus design lifetime. . . . In practice, [such analyses] are almost never done or at best, are done qualitatively. The mission duration is normally assigned rather arbitrarily. . . . Thus, there may be a push to produce spacecraft lasting five or ten years because people believe these will be more economical than ones lasting only a few years. Doing [these analyses] provides a much stronger basis for determining whether we should push harder for longer spacecraft lifetime or back off on this requirement. (Wertz and Larson, 1999, pp. 17–18)

The purpose of this book is to identify and discuss what some of "these analyses" cited by Wertz and Larson are or should be and to contribute an analytical framework toward a rational choice of durability for engineering systems, from a customer's perspective, and in the face of network externalities and obsolescence effects.

1.4 Why the Interest in Product Durability and System Design Lifetime?

It is likely that questions of durability were raised and became of interest to academics as soon as the notion of a durable good was conceptualized. A *durable good* is an economic term that designates a set of products that provide utility or a flow of service over a period of time, as opposed to products that are immediately consumed on first use. Consider the two ends of the product durability spectrum. At one end are goods that never wear out – sometimes referred to as perfectly durable goods. At the other end, we have nondurable goods that are totally consumed when used once. Real world durable goods occupy the space between these two ends of the durability spectrum. Questions of durability, both technical and economic, are bound to arise, as soon as one realizes that durable goods are durable to some extent: To what extent are they or should they be made durable? How is the durability choice made, and what needs to be taken into account in making this choice? How does it impact a manufacturer's profits? And subsequently, how does an industry structure impact the choice of durability?

There is a popular belief that manufacturers of durable goods often deliberately reduce the durability of their products to increase sales and profits. There are interesting case histories in the electric lamp, razor blade, and vacuum tube industries that suggest that producers of these durable goods may have colluded to limit the durability of their products, or had a concealed policy of deliberately limiting their products' life, in order to increase their sales "when customers' interests were generally thought to be better served by [products] of much longer life" (Avinger, 1968).

The discussion in the previous paragraph is meant to serve two purposes. First, it introduces three main stakeholders who should be taken into account in analyzing issues of product durability and system design lifetime. These are (1) the customers, (2) the manufacturer, and (3) society at large. Second, the previous paragraph indicates a tension between the stakeholders above, as each is affected differently by an extended or reduced product lifetime, and shows that the interests of one are not necessarily aligned with the interests of the others. One should therefore recognize that, in exploring the issues at stake in reducing or extending a product durability, it is necessary to first specify from which stakeholder's perspective the analysis is carried out, as the interests and tradeoffs can be substantially different.

Durability became a contentious issue,[14] and the practices alluded to above heightened the interest of academics (mainly economists) in durability choice under various market structures. They asked: Will durability choice be different under different conditions of competition and monopoly? Empirical or anecdotal evidence seemed to suggest that monopolists would indeed produce goods of shorter durability than competitive markets. Starting in the 1960s, the economic literature saw a proliferation of studies on durability.

[14] This is further discussed in Chapter 3.

In summary, both the engineering and economic issues associated with product durability and system design lifetime continue to offer a rich field of investigation for academics and industry professionals. The implications for selecting a reduced or extended product durability are complex and multidisciplinary in nature; they demand careful consideration and require much more attention than they have received to date in the engineering and economic literature, as their impact is substantial and can ripple throughout an entire industry value chain.

1.5 Book Organization

This book, as mentioned previously, deals with issues of durability and system design lifetime, with a focus on engineering systems rather than consumer goods. Although the arguments in each chapter build on those of the previous chapters,[15] they are nevertheless designed to be self-contained. Although this makes it easy for the reader to read and understand any one chapter from the book without reading the previous chapters, it implies that there is a bit of overlap between chapters. The reader who wishes to go through the whole book in one sitting can easily skip through the overlapping parts.

Chapter 2 explores the qualitative implications associated with reducing versus extending a product's durability or a system design lifetime, as seen from the perspective of the customer, the manufacturer, and society at large. This chapter shows that the implications of selecting a reduced or an extended product durability are complex and multidisciplinary and affect an entire industry value chain. One should not reduce the subject, as is often done in the economic literature, to the study of revenues or profits for the manufacturers.

Chapter 3 provides a narrative of development of economic thought on durability. This chapter also discusses the present limitations in the economic literature on durability and provides a background against which the remaining chapters can be contrasted.

[15] With the exception of Chapter 3, which is an overview of economic thought on durability.