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Considering obsolescence in system design

Joshua M. Brock[a]*, Elizabeth R. Payne[a], Paul D. Collopy[a], Owen C. Brown[b]

[a]University of Alabama in Huntsville, 301 Sparkman Drive, Huntsville, AL 35899, United States of America
[b]SSCI, USA

Abstract

Systems developers frequently face urgency in delivering their system. If the system is delivered early, it will be very useful, but if delivered late, it may be worthless. More development time may allow performance improvement or reduced risk, but the systems engineer must trade the performance or risk against the loss of value brought about by delay. This paper develops a formal quantitative approach to making system trades between development time and time deployed before obsolescence. We start with obsolescence events that occur at a particular time in the future, then extend the analysis to events where the timing is uncertain. The logic useful in a large variety of planning and decision-making contexts, from planning rapid system development to planning of military actions.

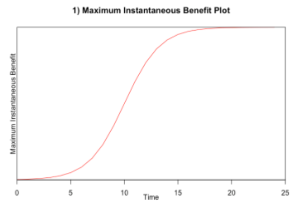
Keywords: Obsolescence, systems engineering, planning

1. Introduction

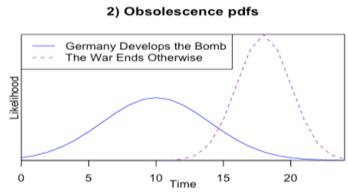
System development programs are plagued with late deliveries. Sometimes the delay itself is the only consequence, but delays often lead to cancellations. We are working on a broad study to develop incentive contracts that can improve system development, balancing the various sources of value in an optimal way. Incentives have been used to accelerate system development, trading a more perfect and lower risk system, delivered later, to a rushed, possibly incomplete, and perhaps riskier system delivered sooner. This paper explores the impact of accelerating development and shows how systems engineers can search for a better balance between speed and

* Corresponding author.
Email: *jmb0030@uah.edu*

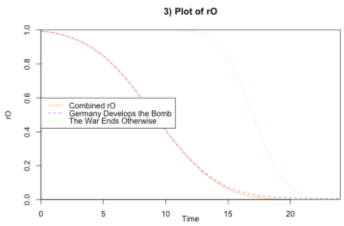
performance facing different types of deadlines, obsolescence threats, and aging issues. It allows planners to develop a picture of the whole project that includes how decisions will impact scheduling and overall benefit. We simplify the threat by positing an obsolescence event out in the future that will degrade or destroy the system's value. Facing obsolescence, how should a system be designed?



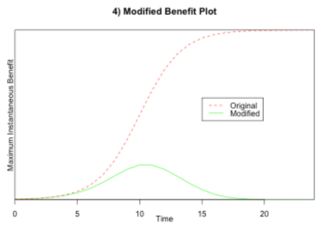
Plot of instantaneous benefit over time during development. The value of the plot at any point in time is the maximum instantaneous benefit that can be achieved were the effort to be deployed at that point in time.



These are the probability density functions (pdfs) representing the likelihood at any given point in time that the obsolescence event will happen. The longer that time goes on, the more likely it is that the event will occur.



This is the plot of $r_O(t)$ according to equation 5. Because we are assuming that t_p is at time t = 0, only the second part of the piecewise function is plotted. This is an assumption made for demonstration; in reality, t_p may begin later or even earlier.



Here is the modified benefit plot, alongside the unmodified benefit plot. The green line is the plot of equation 3, where $r_O(t)$ is as in equation 5.

Figure 1: Modeling Military Obsolescence with Multiple Sources of Obsolescence – The Development of the Atomic Bomb

Examples arise in many domains:

- **Military obsolescence:** An electronic warfare system is being developed to enable an aircraft to detect and evade radar. However, the enemy is researching a new form of radar that will render this system ineffective. Therefore, the electronic warfare system will only be useful up to the time when the new radar is fielded.
- **Commercial electronics:** A top-of-the-line Bluetooth earbud system is being developed. It will be very profitable until the competition releases an even-better earbud.
- **Space science:** A chemical analysis system is being developed for the next Mars rover. If it is delivered in time for the rover launch, it will greatly enhance the science mission. However, if it is late, the rover will be launched without it, so the analysis system will be useless.
- **Disaster response:** After an earthquake levels an apartment building, a rig is designed to safely excavate the rubble. If the rig is operational within 48 hours, people trapped in the wreckage can be saved. However, if it takes longer to design and construct, there will be no survivors to rescue.

There are also less direct contexts, such as political imperative; an example would be the effort to land a human on the moon, where success is less important for its scientific benefits than for the status it generates by being first to accomplish the goal. And these contexts do not stand alone; they can be combined and expanded in various ways, such as the development of the atomic bomb: in World War II if the enemy developed the bomb first *or* if the war ended without needing the bomb, the bomb would lose its value, at least in that immediate conflict. Specifically, we are modeling competitive forces as an *obsolescence event*, the point after which the benefit provided by future effort drops to zero.

We will be modeling obsolescence using methods of net present value analysis, by taking a predicted value stream (which we will call the *potential benefit* of the effort at some point in time) and modifying it according to some discount factor. This will provide us with a means of assessing the future value of that benefit stream, building on mathematics that are familiar to systems engineers. Initially we will examine an example wherein the point of obsolescence is known; later we will expand that to understand what the *expected* benefit could be if the point of obsolescence is unknown, and later still how multiple potential competitive forces can impact that expected benefit.

1. Example 1

In a context where we do *not* know precisely when we intend to expend an effort we have been developing (releasing a product, or executing the search and rescue operation), we can still use this information to plan, since we can trade between further improvements in the *quality* of the effort, once it is executed, and how much time we have to execute it. For example, spending more time in designing a product or training for a rescue operation will (in our assumption) produce a product or effort which has the potential for a higher benefit, but will have less time to generate that benefit (Figure 2, plot 3), assuming a finite end point (which in later analyses will involve our investigation of obsolescence). A product which produces some benefit but is introduced into the situation earlier produces a lower potential value of benefit *per unit time* but is accumulating that benefit for longer (Figure 2, plot 2). Optimizing that trade-off in the context of competition is a potential use of this method in terms of planning. In later examples, we will assume that we do *not* know when the effort will be deployed, and furthermore we will not attempt to demonstrate possible deployment times as we do in this example.

Deployment time will be represented by t_d. When measuring the potential benefit produced by an effort upon its deployment, some means of translating effort to benefit must be employed. We are assuming, at least for the sake of illustration, that the result of this translation is a single term, $b(t)$, the benefit produced by an effort at a particular point in time. Expending very little effort will produce very little benefit, though not zero benefit. For example, pouring the foundation for a house is one of the first steps in actually assembling the house. We cannot find shelter from a storm, or storage for our possessions, in just a foundation. However, a poured foundation on otherwise unimproved land is necessarily an improvement in some measure; the ground is flatter, more stable, less prone to slippage or disintegration. The effort of pouring the foundation has produced *something*, although it is as yet insufficient given the *purpose* of the effort we are expending, i.e., to build a house. This notion of the *purpose* (or mission) of a project is important in this illustration of obsolescence.

Any effort upon which we may embark can be said to follow the same logic. Expending some effort produces some benefit; expending a lot of effort (assuming it is properly coordinated, planned, and efficacious) produces more benefit. A frame for a house makes it easier to add a roof to that house. Eventually, effort expended produces a diminishing return on the value of the project; e.g., we can add more and more to the house, but eventually we will produce rooms that we have no intention of using, and the expense in labor and materials will begin to eclipse the benefit we can derive from the use of the house. We will assume that the benefit embodied in the eventual effort expended in our examination of various contexts of obsolescence will follow the same pattern of diminishing returns (Figure 2, plot 1). As it is this benefit in which we are interested, we will not be modeling effort explicitly, but rather the benefit produced by that effort, both potentially and (in example 1) actually. **This assumption of diminishing returns will be assumed for all further examples.**

The momentary net value embodied in an effort (e.g., a product), v_e can be plotted using a simple benefit-less-cost equation:

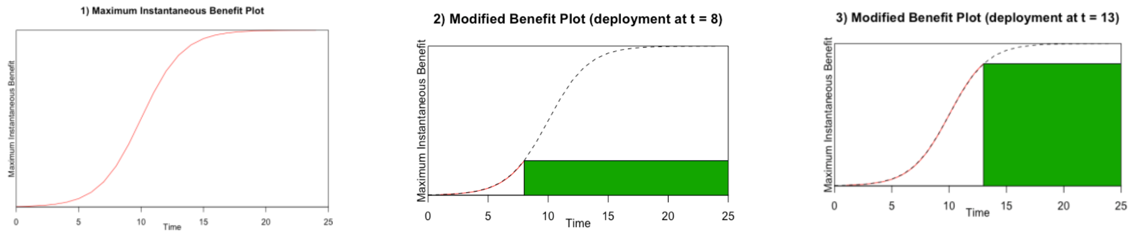
$$v_e(t) = b(t) - c(t) \tag{1}$$

There are also costs associated with the pre-deployment phase, where the effort is developed and planned (for example, in the engineering of a product). In general, because we are concerned here with the impact of competition on potential benefit, we will not be considering costs directly; however, they are an important part of planning, and in practice will be of considerable importance.

Before an effort is deployed, its potential benefit is assumed to rise as a plot of diminishing returns. This, again, is capturing the improvement in benefit that would be received if the effort were given more time to be developed—the product given more engineering time, or the rescue operation given more training time. This allows us to examine the potential accruable benefit in terms of deployment time, by taking the integral under the curve after the moment of deployment (t_d) and up to the moment of stoppage or withdrawal (t_s). We are assuming that deployment represents a maximum potential benefit accruable at any moment in time; in practice, redesign and iteration is a potential option, which produces effects in cost and schedule that are out of scope of this work. With integration, the *total* net benefit equation can be written:

$$v_{e,total} = \int_{t_d}^{t_s}[b(t) - c(t)]dt = B(t) - C(t) \quad (2)$$

Again, we are not considering costs directly in this analysis, but the principle would remain the same. The potential options for deployment are given in the next three plots below.



Plot of instantaneous benefit over time during development. The value of the plot at any point in time is the maximum instantaneous benefit that can be achieved were the effort to be deployed at that point in time.

Plot of instantaneous benefit (red line) with deployment at time = 8. The flat blue line represents the maximum instantaneous achievable benefit. The green box is the *total* benefit that can be accumulated, the area under the blue line.

Plot of instantaneous benefit (red line) with deployment at time = 13. The flat blue line represents the maximum instantaneous achievable benefit. The green box is the *total* benefit that can be accumulated, the area under the blue line.

Figure 2: Example 1 Plots – Options for Deployment and Effects on Accumulation of Benefit (**without** Obsolescence)

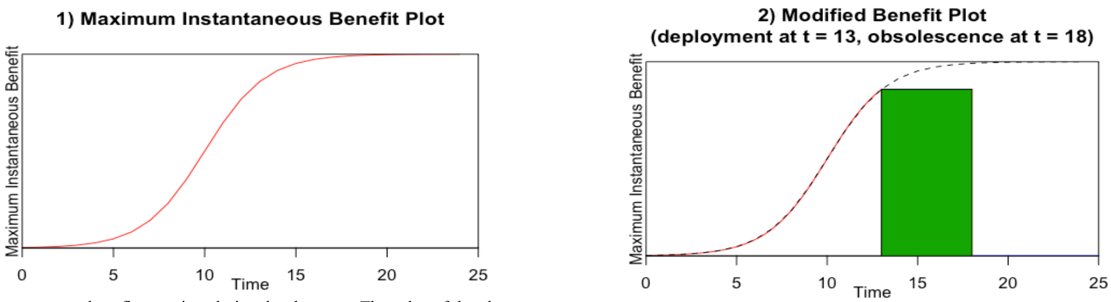
In later examples, we will not know the moment of deployment, so we will not be able to illustrate the potential accrued benefit as directly as in this example. Instead, we will be focusing on the *expectation* of benefit, based on our examination of obsolescence. This is illustrated in the following examples, for various conditions of knowing.

2. Example 2

This example is describing the highest state of knowing with respect to the obsolescence event, when we know exactly when the event will occur. We are using our diminishing returns assumption (Figure 3, plot 1) for the benefit of the effort at a given point in time. At some point (in this example, we know it will be at time t = 18), the future potential benefit of the effort drops to zero (Figure 3, plot 2); this is the moment of obsolescence, t_{obs}. Remember that this is by assumption; it could drop to some lesser, still nonzero value. We can model this using the time-based obsolescence discount factor $r_O(t)$. **This factor only applies to the benefit term, and since we are not considering costs in this analysis we can simply drop that term**, so equation 1 becomes:

$$v_e = b(t) \cdot r_O(t) \quad (3)$$

$$\mathrm{r}_O(t) = \begin{cases} 1, & t < t_{obs} \\ 0, & t \geq t_{obs} \end{cases} \quad (4)$$



Plot of instantaneous benefit over time during development. The value of the plot at any point in time is the maximum instantaneous benefit that can be achieved were the effort to be deployed at that point in time.

In this plot, after deployment at t = 13, an obsolescence event happens at t = 18 such that further deployment produces no benefit. The maximum instantaneous benefit is determined by the red line up until deployment, and the maximum accrued benefit is determined by the area of the green rectangle.

Figure 3: ***Example 2*** (above) - The Limitations of Benefit in the Context of Obsolescence

3. Example 3

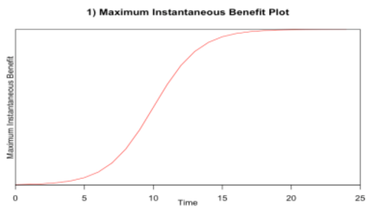
What if we do not know when the obsolescence will even happen? In that case we must plot that moment as a probability density function, to capture that uncertainty. For the sake of demonstration, we will be assuming symmetric normal distributions for these examples, but it would in practice be dependent on context: for example, a rescue operation may be right-tailed to capture immediate threats of weather escalation, while a race to the moon may be left-tailed as the competitors must first work to develop the capability to achieve the goal at all.

For this example, instead of modeling the future benefit as a known function, we will instead model it as a modification of an expected benefit function in order to find the future *expected* benefit. Much as we model a 10% chance of winning $100 and a 100% chance of winning $10 as comparable payoffs (in that case, they are equivalent), we can model the expected benefit as a payoff (the benefit plot) modified by a probability (the probability density function of the moment of obsolescence). This is another place where our notion of net present value discounting applies, by modifying the future value of some value stream (here, the benefit function) by a time-based discount factor. This is a *cumulative* operation, as it is unreasonable to model the discount factor as *increasing* after the highest point in the pdf; the further we go into the pdf's time span, the more likely it is that the obsolescence event is captured in that period of time.

For this example, the obsolescence discount factor $r_O(t)$ is not a single value, but is instead based on the distribution (*pdf(t)*) of potential values for t_{obs}. In order to capture the accumulating nature of the discount, we model it as a definite integral of the distribution *pdf(t)*. Therefore:

$$\mathrm{r_O}(t) = \begin{cases} 1, & t < t_p \\ 1 - \int_{t_p}^{t_f} pdf(t)dt, & t_p \le t \le t_f \end{cases} \tag{5}$$

In this example, we are assuming that the *earliest moment that an obsolescence event is considered to be possible* (t_p) is time t = 0, and the *latest moment that an obsolescence event is considered to be possible* (t_f) is 24; this is by assumption, for the purposes of illustration. Remember that this is cumulative, so the total expected benefit can be found by taking the integral across the modified benefit curve between some potential point of deployment and some potential point of withdrawal. This can be used to optimize deployment and withdrawal schedules, such as time to market, or training versus execution. In plot 3 below, we are plotting r_O as time covers more and more of the pdf.



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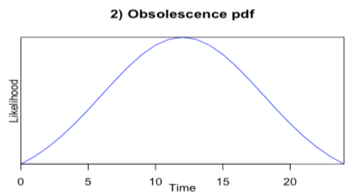
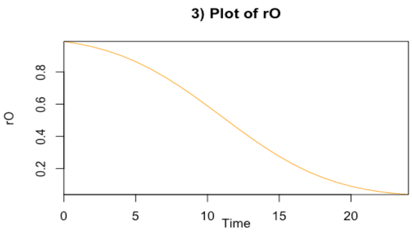


This is the probability density function (pdf) representing the likelihood at any given point in time that the obsolescence event will happen. The longer that time goes on, the more likely it is that the event will occur.



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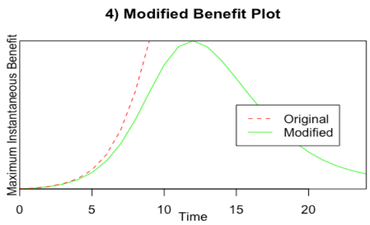


Here is the modified benefit plot, alongside the unmodified benefit plot. The green line is the plot of equation 3, where $r_O(t)$ is as in equation 5.

Figure 4: ***Example 3*** (above) - The Process of Modeling Obsolescence Discounting

4. Example 4

What if there are multiple potential competing forces that could impact the future expected benefit? A historical example—the development of the atomic bomb—can explain. This example is illustrated in **Figure 1 (above).**

There are two forms of competition at play here. The first is a competitor's development of a superior product—in this case, an atomic weapon. The competitor (in this case, Nazi Germany) would be in a position of overwhelming competitive advantage over conventional weaponry were they to develop the atomic bomb before the United States. The second form of antagonistic compatibility is a contextual shift that renders the work of the *project* obsolete, in that the *competitor* is no longer able to develop that product.

The United States thus has three metrics of interest which are subject to probabilistic uncertainty: when the United States would develop the atomic bomb; when Nazi Germany would develop the atomic bomb; and when the United States would, without needing to have the atomic bomb developed, defeat Germany otherwise. The first metric represents the uncertainty associated with the point at which the atomic bomb has been sufficiently developed to allow it to be deployed by the United States; this is part of the initial benefit stream and is not included in r_O (see ***example* 1** for an illustration of the impact of deployment time). The second metric represents the same thing, but for Nazi Germany, and therefore represents the first moment of obsolescence. As for the third metric, defeating Nazi Germany before the development of the atomic bomb is completed would, in that context, render the effort to develop the atomic bomb until that point useless, future applications of the technology notwithstanding.

Mathematically, this is the same as in the previous example, except there are now *multiple* pdfs. Where they overlap, *both* pdfs apply for the discounting effect, since *both* pdfs represent potential sources of an obsolescence event.

5. Example 5

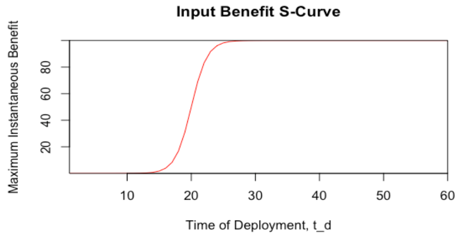
A contemporary example is SpaceX, which received FCC permission to deploy a constellation of satellites for broadband access. However, it did not do so alone; several other organizations have also been granted such permission. SpaceX could use this framework of obsolescence to maximize its total mass of profit by optimizing when to deploy, even if it is ultimately unable to fully realize the deployment of its product.

Let us assume the following: SpaceX's product development follows the same diminishing returns curve used in the previous examples. Their maximum possible momentary value—that is, how good the product is once development has ended—is determined by the height of the diminishing returns curve at the moment of deployment. As in Figure 3 (example 2), if we choose a particular deployment time t_d and a particular moment of obsolescence t_o, we can calculate how much value will be accumulated during that period of time. The obsolescence event has a probability of occurrence along some period of time, and this probability can be used to modify the total value generated between some deployment time and some moment of obsolescence to produce an expectation of that total value. This can be iterated repeatedly, calculating the expectation of total benefit (ETB) for all obsolescence times after a chosen deployment time; these expectations can then be averaged to find the average expectation of total benefit (AETB) for a particular chosen deployment time, which can likewise be repeated to develop a plot of the average expectation of total value as a function of deployment time. This is shown in Figure 5 below. The equation for the Average Expectation of Total Benefit (AETB) for a single value of t_d is:

$$AETB_{t_d}(t_o) = \frac{1}{t_{o,max}-t_d}\sum_{t_d}^{t_{o,max}} B(t_d)(t_o - t_d)\int_{t_d}^{t_o} pdf(t)dt \quad (5)$$

where $B(t_d)$ is the maximum instantaneous benefit at the selected deployment time, t_d (e.g., the height of the diminishing returns curve at t_d). Remember that we are fixing t_d and varying t_o to find the AETB for a particular possible value of t_d and all relevant possible values of t_o. **Note that this is for the case where the deployment time is independently variable and the time of obsolescence is unknown.**

In this example, assuming that the maximum instantaneous benefit of the product changes according to the first plot in Figure 5, and the probability of obsolescence is distributed as shown in the second plot, then the optimal deployment time of SpaceX's Starlink constellation can be seen from the fourth plot—the maximum of the curve. In this case, the optimal deployment time is a little earlier than the flattening of the diminishing returns curve, suggesting that speed is more important than absolute benefit, around that point in time.



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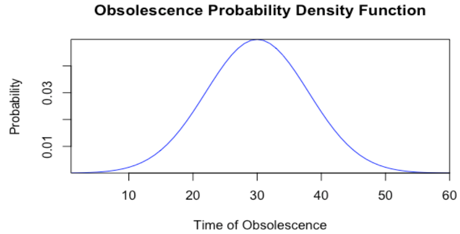
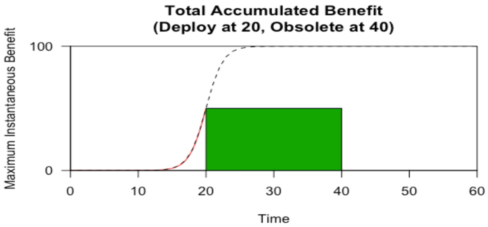
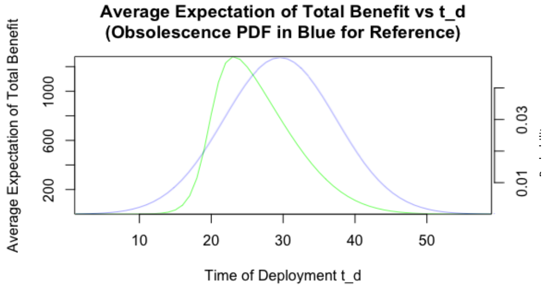


This is the probability density function (pdf) representing the likelihood at any given point in time that the obsolescence event will happen. The longer that time goes on, the more likely it is that the event will occur.



Example of *one* calculation. For each combination of deployment time and obsolescence time, the total accumulated value for that period of time is calculated, then modified by the area under the curve of the obsolescence probability distribution from the deployment time up to the selected time of obsolescence. This produces the *expectation of total value* for that period of time. The *expectation of total value* for each obsolescence time of a particular deployment time is calculated, then averaged to produce the *average expectation of total value* for a particular deployment time.



This is the plot of *average expectation of total value as a function of deployment time*. The optimal time of deployment—the time of deployment for which the maximum average expectation of total benefit should be anticipated—can be seen by inspection: it is the maximum point of the plot.

Figure 5: Example 5 – Application of Obsolescence Modeling

This application of these concepts leverages the same principles of discounting outlined above, only instead of looking at the benefit stream over time, we are looking at the total mass of accumulated benefit and using the probability distribution of obsolescence to find the *average* of our *expectation* of *total* benefit. This allows project planners to better understand and anticipate project needs in order to achieve maximum AETB.

6. Discussion

This approach to obsolescence modeling does more than just allow project planners to optimize for deployment scheduling goals: it provides a framework for understanding trade-offs in cost, scheduling, and product quality. For example, a project manager might ask, "If I can shorten our development time by X time for Y cost, what is the result in terms of our overall benefit?" Or, "If our development time is extended by some amount of time, what is that delay costing us in terms of outcomes?" Understanding the shape of the AETB curve (and the various factors contributing to it) allows for planners to understand the impact of decisions across the whole project period, as well as providing insight on where the project's constraints are and how they might need to be adjusted.

7. Conclusions and Future Work

Obsolescence is a broader concept than merely in system development and deployment. Indeed, concepts of competition and devaluation are relevant across a broad swathe of human activity, even in cooperative efforts such as humanitarian relief and environmental recovery. Being able to model this information probabilistically allows researchers to capture uncertainties and create more rigorous pictures of our own understanding of the situation at hand, and allows project planners to better understand the full scope of their undertaking. This allows us to model expected benefit and produce estimations of overall benefit if particular decisions about deployment time versus development time are made. In future, it may be useful to expand this concept of obsolescence modeling into more complex arenas, especially by expanding the model to capture more complex cost and schedule information than what was assumed in this case to be true (e.g., capturing iterative product re-design and -development after testing and deployment). Additionally, an investigation into the effect this kind of modeling might have in organizational terms (e.g., structure, strategy, culture, etc.) could have interesting results.

This study of obsolescence lays a significant part of the groundwork for a broad theory of system acquisition.

The overall theory will address time, performance, cost (development, production, and operation), and risk. Our team at the University of Alabama in Huntsville and our collaborators at Iowa State University are in the midst of developing this theory, with more results to be announced as we progress.

Acknowledgements

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