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Projecting technology change to improve space technology planning and systems management ☆

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A R T I C L E I N F O

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A B S T R A C T

Projecting technology performance evolution has been improving over the years. Reliable quantitative forecasting methods have been developed that project the growth, diffusion, and performance of technology in time, including projecting technology substitutions, saturation levels, and performance improvements. These forecasts can be applied at the early stages of space technology planning to better predict available future technology performance, assure the successful selection of technology, and improve technology systems management strategy.

Often what is published as a technology forecast is simply scenario planning, usually made by extrapolating current trends into the future, with perhaps some subjective insight added. Typically, the accuracy of such predictions falls rapidly with distance in time. Quantitative technology forecasting (QTF), on the other hand, includes the study of historic data to identify one of or a combination of several recognized universal technology diffusion or substitution patterns. In the same manner that quantitative models of physical phenomena provide excellent predictions of system behavior, so do QTF models provide reliable technological performance trajectories.

In practice, a quantitative technology forecast is completed to ascertain with confidence when the projected performance of a technology or system of technologies will occur. Such projections provide reliable time-referenced information when considering cost and performance trade-offs in maintaining, replacing, or migrating a technology, component, or system.

This paper introduces various quantitative technology forecasting techniques and illustrates their practical application in space technology and technology systems management.

1. Introduction

Quantitative technology forecasting (QTF) can provide insight into the progress of space development, from projecting patterns in exploratory launches to identifying the nexus of technology performance trends and requirements for extended space travel. The quantitative analysis of technology change can improve policy, resource allocation, and investment decisions in all space-related activities, as QTF analysis have advantaged other industries. The application of QTF tools can be a significant strategic element in space technology planning.

2. Background

Quantitative technology forecasting is the process of projecting in time the intersection of social needs and technological capabilities using quantitative methods. For the purposes of forecasting, technology is defined as any

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human creation that provides a compelling advantage to sustain or improve that creation, such as materials, methods, or systems that displace, support, amplify, or enable human activity. It has been shown that rates of new technology adoption and rates of change in technology performance take on characteristic patterns in time.

A quantitative technology forecast includes the study of historic data to identify one of several common technology diffusion or substitution models. Patterns to be identified include constant percentage rates of change (so-called "Moore's Laws"), logistic growth ("*S*"-curves), logistic substitution, performance envelopes, anthropological invariants, lead/lag (precursor) relationships, and other phenomena. These quantitative projections have proven accurate in predicting technological and social change in thousands of diverse applications, on time scales covering only months to spanning centuries.

Invariant, or well-bounded, human individual and social behavior, and fundamental human evolutionary drives, underlie technological change. In essence, humans and technology co-evolve in a trilogy that includes the local environment, our internal physiology, and technology that can be considered simply external physiology.

Carrying out a quantitative technology forecast includes selecting a strategically important technology, gathering historic data related to change or adoption of that technology, identifying candidate "compelling advantages" that appear to be drivers of the technology change, and comparing the rate of technology change over time against the natural characteristic patterns of technology change and diffusion.

3. Methodologies

Quantitative technology forecasting has been applied successfully across a broad range of technologies including communications, energy, medicine, transportation, and many other areas. A quantitative technology forecast will include the study of historic data to identify one of or a combination of several recognized universal technology diffusion or substitution trends. Rates of new technology adoption and rates of change of technology performance characteristics take on common patterns. The discovery of such a pattern indicates that a fundamental trajectory or envelope curve has been found and that reliable forecasts then can be made.

The quantitative forecasting techniques are, to use the words of mathematician and theorist Gregory Bateson "explanatory principles" [1], that is, their applicability is sufficient by their reliability for the purposes of modeling technology diffusion patterns and forecasting technology adoption. Many researchers have attempted to substantiate the commonly found patterns through application of systems kinematics and other advanced systems theories, to varying success and acceptance in the field. The ubiquity of the various patterns has been studied also using systems theory and complexity modeling, such as the complex adaptive systems approach.

Several of the many techniques in quantitative technology forecasting are ideally suitable for projecting technological change and technology sustainability in early stage practicality and affordability studies are introduced here in more detail and illustrated with examples, including possible topics for space-related studies.

3.1. Logistic growth projection

Forecasters had their first significant successes in predicting technological change when they used exponential models to project new technological and social change. See, for example, Malthus [2]. It was deemed only logical that a new technology at first would be selected by one, than perhaps two others, and these people in turn, two others each, and so on, in a pattern of exponential growth. Ultimately however, as in any natural system, a limit or bound on total selections would be reached, leading early researchers next to the logistic (or so-called *S*-curve) to model technology diffusion.

In the late 20th Century, researchers in the United States such as Lenz [3], Martino [4], and Vanston [5], and others around the world [e.g., the very prolific Marchetti (see, for example, Marchetti [6]) refined forecasting methods and showed that the logistic model was an excellent construct for forecasting technological change with virtually universal application for technology adoption and many other individual and social human behaviors. The classical logistic curve is given by

$$P(t)=\kappa/\{1+\exp[-\alpha(t-\beta)]\}$$

This simple three-point curve is defined by κ, the asymptotic maximum, often called the carrying capacity; α, the rate of change of growth; and β, the inflection point or mid-point of the curve.

Fig. 1 illustrates the idealized logistic curve of technology adoption or diffusion.

A popular means to visualize the growth match to the ideal logistic curve is by way of a linear transformation of the data. The Fisher–Pry transform is given by

$$P'(t)=F(t)/[1\text{-}F(t)], \quad \text{where } F(t)=P(t)/\kappa$$

The plot simply is the ratio of per unit complete and per unit remaining. Fig. 2 shows the logistic growth of the

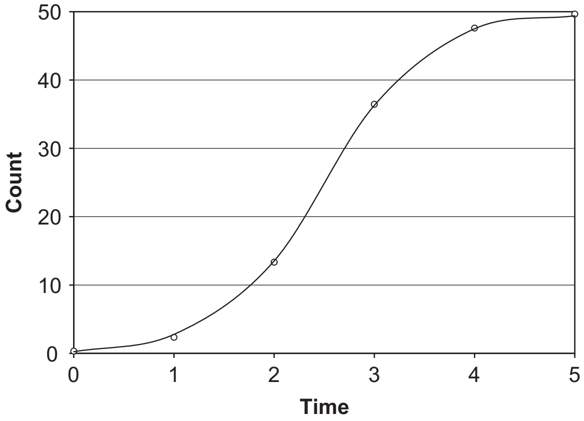

Fig. 1. Ideal logistic growth curve (adapted from Meyer [8]).