Multi-Mode Interaction
Among Technologies

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Abstract

Technological innovation is manifested in the development of new products, processes and techniques such that emerging technologies often substitute for more mature technologies. The interaction between technologies is typically referred to as *competition*, implying a confrontational interaction. The setting of technology strategy is thus often concerned with issues relating to the competition between emerging technologies and the response of mature technologies to the offense from emerging technologies — strategies for attack and defense. In this paper it is argued that the interaction between technologies should be viewed in a broader sense than mere competition, and it is suggested that a multi-mode framework provides a much richer setting for assessing the interaction of two or more technologies. This concept has been successfully applied in biological and organizational ecology, and it is shown that it can be equally useful when applied to the dynamics of technological interaction. It is proposed that the effect that one technology has on another’s growth rate be taken as a classification criterion. Examples are given to illustrate that three major modes of interaction exist, viz. pure competition, symbiosis and predator-prey. In addition, the notion that the interaction between technologies can in general shift temporally from one mode to another is motivated. It is suggested that, since the characteristics of the three modes differ from one another, it is appropriate to develop managerial strategies that apply specifically to each of the three modes, instead of just applying generic “competition” strategies.
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1. Introduction

The process of technological innovation is embodied in technological change and advances. The various ways in which technological change can come about have been widely studied and various schemes of classifying the nature of innovations have been proposed. Distinctions are often made, for example, between radical and incremental innovations, between product and process innovations, between competence enhancing and competence destroying innovations or between architectural and modular innovation, to mention but a few (see for example [1-5]). Irrespective of the way in which one chooses to view the changes that come about, the process of technological innovation involves the creation of something new, whether it be products, processes or techniques.

As a new innovation invades the market, it starts to interact with the established technologies. The interaction is manifested in the degree and rate at which the new technology is adopted when it attempts, and often succeeds, in substituting for the existing technologies. Such interaction between technologies is typically referred to as competition. One frequently encounters the terms “attack” and “defense” in this regard. Foster, for example, speaks of the “attacker’s advantage” [6] and Christensen and Rosenbloom have recently shared some thoughts on “explaining the attacker’s advantage” [7]. Devising strategies for defense and attack is an important part of the management of technological innovation, since the setting of technology strategy is often concerned with issues relating to the competition between new, emerging technologies and the defensive response of mature technologies to the attack from the emerging technologies. Such strategies have been described in some detail by Cooper and Schendel [8], Cooper and Smith [9], Foster [6], Harrigan and Porter [10], Soukop and Cooper [11], Utterback [1] and Williams [12], among others.

The term “competition” implies a confrontation between two entities, in this case technologies. However, there are many cases where technologies interact in a relationship that is not confrontational and where the interaction between technologies is therefore not one of competition in the strict sense of the word. In this paper the argument is made that, in the general case, the interaction among technologies should be viewed in a wider sense than mere
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“competition”. The assessment of the interaction among two or more technologies from a “competition” vantage point can lead to an over-simplified view of the strategic battlefield, which can result in self-imposed and artificial limits to possible strategic options. If technological interaction is considered to occur within a multi-mode framework which allows for various permutations of positive and negative interactions between the interacting technologies, a much richer setting for assessing the interaction and the subsequent plotting of offensive and defensive strategies presents itself. Taking into account the fact that the various modes of interaction (of which pure competition is only one) have different characteristics, and furthermore that the interaction between various technologies can shift from one mode to another with time, it is suggested that strategies that are applicable to each of the modes be developed, in addition to strategies that can be applied to the transition between modes. One has to be wary of deploying generic strategies for attack and defense that are based on the general notion of competition, since the nature of the interaction may in fact be in a mode other than competition, in which case the strategy may be inappropriate.

The general notion of multi-mode interaction is not a new one. Ecologists have for a long time been aware of the fact that different species interact in various modes with one another, be it competition, symbiosis, commensalism, or in a predator-prey mode (see for example [13]). Although interesting and useful analogies can be drawn between biological ecology and technological development, the lessons that can be learnt from organizational ecologists are perhaps more directly applicable here. Population dynamics is an important issue in organizational ecology which relates to the number of firms, and particularly to the rates at which they are born, grow and die (founding and mortality rates). In this article we borrow the concept of multi-mode interaction from organizational ecology, and show how it is also applicable to the interaction among technologies. In order to put the discussion into perspective, it is necessary to elaborate on the differences between the interaction among organizations and the interaction among technologies. This topic is addressed in the next section, followed by a discussion on the notion of growth rate as a criterion for distinguishing between modes of interaction between technologies. Four uni-directional types of interaction among technologies are then discussed, viz. the positive and negative effects that an emerging technology can have on a mature technology’s growth, and vice versa. This leads to the multi-mode framework as applied to
technological interaction, where these influences are combined in three permutations to yield the three modes of the proposed multi-mode framework, i.e. competition, symbiosis and predator-prey interaction. The notion that the interaction between technologies can shift from one mode to another with time is then considered. It is pointed out that this feature differentiates the multi-mode framework as applied to technologies from ecological systems where the nature of interaction between species is fixed. A brief discussion of generic strategies based on the multi-mode concept is given, and the paper is concluded with recommendations and suggestions for further work. An appendix relates the effect that one technology can have on another's growth rate to that of other influences.

It must be stressed that the main thrust of this paper is a conceptual one — particularly to draw attention to the proposed multi-mode framework as a basis for assessing the interaction among technologies in a broader sense than pure competition. Although the development and presentation of the management strategies that are applicable in each of the modes are briefly considered, they are not discussed in any great detail. Instead, the development of appropriate strategies for each of the modes as well as the temporal transition between modes are left as research challenges.

2. The dynamics of technological change and organizational ecology

Many definitions have been offered for “technology”. Even though we shall not attempt to discuss or recall them here, there can be little argument, however, that there is a world of difference between the generic concepts of an “organization” and “technology”, and hence also between organizational ecology and technological ecology (with the latter being closely related to the dynamics of technological change). In one of the seminal works on organizational ecology, Hannan and Freeman state that “...The ecology of organizations is an approach to the macrosociology of organizations that builds on general ecological and evolutionary models of change in populations and communities of organizations” [14]. They emphasize the value of studying evolutionary models of population and community ecology and state that their work is aimed at explaining why there are so many kinds of organizations. In essence, as they put it, “... an ecology of organizations seeks to understand how social conditions affect the rates at which new organizations and new organizational forms arise. the rates at which organizations change
forms and the rates at which organizations and forms die out”. Although technologies and organizations are not the same thing, there are some strong similarities and analogies, just as there are marked differences. Even though these similarities provide a useful opportunity for applying analytical concepts from one field to that of the other, one should be careful not to equate the one with the other.

Some of the characteristics that “technology” and “organizations” have in common, are that both change dynamically and that both often do so in the presence of other “species” — in the one case other species refer to other organizations, whereas in the other case it refers to other technologies. This study essentially focuses on the effect that technological species have on one another’s growth. The term “dynamic” implies that the change occurs in time — be it change in the population or form of organizations or technologies. It is interesting to note that both the population growth of technologies and organizations often follow so-called S-curves. This observation is of course not limited to technologies or organizations, for it is well known that the growth of many animate organisms, whether individually or in populations [15], and social events (such as the number of victims killed by the Red Brigades terrorists, for example [16]), often follow an S-curve as well. However, just as the analogy between biological ecology and organizational ecology has its limits, so does the analogy between organizational ecology and the dynamics of technological change. Whereas population dynamics describes the rates at which organizations and different forms of organizations are founded and perish, the dynamics of technological change deals, inter alia, with the substitution of one technology for another, the diffusion of technologies and the evolution of products and processes (see for example [1-6, 17]).

In addition to the analogies and similarities between organizations and technologies, there are also other links between them which are relevant to this discussion. Technologies are not invented, developed and nor do they get adopted or changed by themselves. These things are done by people, who more often than not, do so within some organizational context. Similarly, technology plays an important role in the evolution of organizations. Manufacturing companies use process technologies to make their products, which in turn, are based on product technologies. Service organizations rely on technology in some way or another to enable them to deliver their services, information technology being a good example. To illustrate the point
relating to the differences between technological dynamics and organizational ecology, let us explore some of the difficulties that arise in deciding upon a unit of analysis when analyzing the dynamics of change in the cases of organizational ecology on the one hand and technology on the other.

The selection of the unit of analysis to describe technological change can be a complicated matter. Finding a useful metric to measure technology itself is not easy, due in part to the problem of defining the term “technology”. As was mentioned before, the literature abounds with definitions for technology and innovations, but for the purposes of measuring technological diffusion and competition, they are elusive entities. In an exercise that focuses on technological forecasting, a technical parameter or combination of parameters is typically selected, such as the speed of aircraft (measured in miles per hour) or the efficiency of lamps (measured in lumens per watt). In the case of substitution, one can argue that the dependent variable should be market share. The complicating issue then becomes a definition of the scope of the market niche to be considered, an estimate of the size of the market niche, determining the market penetration of the technologies and accounting for the fact that the scope and size of the market niche may change with time.

In ecological studies the number of units in a population is a natural and almost intuitive dependent variable to use in growth models. Hannan and Freeman mention cases where, depending on the circumstances, the population, the organization, part of the organization or even the larger environment can be the unit of analysis or observation [14]. The notion of the number of units in a population can be extended with some plausibility when we consider firms that are engaged in the manufacture of use of technology, for example. It is important to keep in mind though, that one cannot generally map a company or even a set of companies on a one-to-one basis to a technology or a set of technologies, particularly not when tracking the dynamic changes that organizations and technologies undergo. A specific company is generally not tied to one technology and furthermore companies will also change their technologies from time to time. Similarly, more than one firm is often involved in the manufacture and use of a specific technology. Although accounting for the number firms involved with the manufacture and use of a technology may be relevant and important from an organizational viewpoint, care should be
taken if the population of technology-related firms in general is to be used as an indicator for technological change. Since the fates of technologies are often tied to the firms that use or develop them, it is sometimes used as a approximate proxy. Loveridge and Pitt make the point that “... technology innovation (as indeed any form of environmental change) affects firms via the mediating action of the competitive or collaborative context of the industry sector in which it operates” [18]. Barnett notes that “... Often there is no clear boundary around an organization’s technology... many technologies can be thought of as systems that cut across formal organizational boundaries” [19]. Technology is often a differentiating factor to distinguish between types of organizations [14], although Williamson contends that technological differences as such are less important than some other factors, typically transaction costs [20,21]. Hannan and Freeman note that “… technological innovation has also played a key role in the creation of new organizations and especially new forms of organizations”, and furthermore that “… New branches of technology are often populated initially by new firms using first mover strategies” [14]. Tushman and Anderson state that some radical technological innovations destroy organizational competence, and hence the term “competence destroying innovation” [2].

Rather than using individual companies as a proxy for technology itself, one might also consider using the industry in which the technology abides to be a more appropriate unit of analysis, specially when considering competition among technologies. Intuitively one would think that using the industry as a unit of analysis would tend to aggregate the idiosyncrasies of the various companies and thus provide a better average. However, as with companies, one finds that there is not a unique mapping between industries and technologies. Moenaert et al., for example, argue that “… industry maturity and technological maturity are two separate concepts and do not necessarily coincide in time” [22]. They point to the substitution of latex foam by polyurethane as an example, noting that the latex foam industry was “… still experiencing strong annual growth, but its mature technology offered little prospect for improvement”.

We now proceed to examine the interaction of technologies within a multi-mode framework. Although a similar framework has been applied to the interaction of organizations, technological change has a different nature than organizational changes (as the discussion above points out) and hence there is merit in examining the multi-mode framework as it applies to the interaction
among technologies. A formal examination of the interaction of technologies within a framework that accounts for multiple modes of interaction is a useful exercise and leads to interesting insights regarding the nature of dynamics of technological change and also to the formulation of technology strategies. Before proceeding to discuss such a framework, it is, however, appropriate to address the notion of growth rate as a metric for classifying the modes.

3. Growth rate as the criterion for classifying the mode of interaction

Whenever the interaction among technologies is described as competition, the meaning and intent of the term competition is generally understood even though an exact description of the term is not usually given explicitly. The nature of the investigation that we are concerned with here, however, demands a definition and classification criterion of the term “interaction” (which encompasses competition) that can be applied more rigorously to offensive and defensive innovation strategies. Borrowing from analogies in the field of ecology, the concept of a growth rate offers itself as a suitable and appropriate criterion for classifying the process of interaction among technologies. In order for a technology to grow to maturity it must have a positive growth rate, at least over a significant period of its life. The multi-mode framework proposed here is therefore based on the premise that other technologies can contribute to a specific technology’s growth rate (together with other factors) by influencing the technology’s growth rate either positively or negatively.

From an ecological viewpoint, the term competition is used to describe the process by which various species or various elements within the same species vie for the same resources, and as a result have a negative influence on one another’s growth rates. Not only is the growth rate a fundamental mechanism whereby the growth in populations is regulated, but it also has the ability to account for the aggregate influence of a multitude of factors. From an economic viewpoint there may also be an incentive to focus on the growth rate as a classification variable. For example, Blackman notes that “... The extent of investment in technological innovation is related to the perceived rate at which a market will develop for the new technology, and the rate of market development is in turn a function of the dynamics of technological substitution” [23]. Cooper and Schendel contend that “... It is not enough to judge that someday a new technology will replace an old one. Rates of penetration must be determined. When the Baldwin Locomotive
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Works was founded in 1831, it would have been of little value to tell the founders that someday their principal product would be obsolete. However, when Sylvania introduced a new line of vacuum tubes for computers in 1957, the rate of improvement of transistors then taking place was extremely relevant” [8]. It should be noted that there are, of course, many factors that can influence a technology’s growth rate in addition to the effect of another technology. This article deals primarily with the effect that one technology can have on another’s growth rate, but for the sake of completeness the effects of other influences and particularly their relation to the effect of another technology's growth rate on the growth rate of the first technology, are discussed in the appendix.

4. Interaction among technologies

The three modes of interaction that make up the proposed multi-mode framework are all based on the notion of the reciprocal enhancement or inhibition of technologies’ growth rate. In order to investigate the characteristics of the three modes, it is therefore appropriate to start by examining the nature of the mechanisms by which one technology can enhance or inhibit the growth rate of another. In the discussions that follow we shall, for the sake of argument, consider the interaction between an emerging technology and a mature technology. In general, this need not be the case, however, and the principles of the proposed multi-mode framework will hold equally well for the interaction of any two (or more) technologies.

In order to introduce the concept, we shall start by considering four uni-directional modes of interaction, where it will be shown how:

- An emerging technology can have a positive or negative influence on the growth of a mature technology; and
- A mature technology can have a positive or negative influence on the growth of an emerging technology.

In the next section, these four uni-directional modes will be combined to yield the three major modes in the multi-mode framework, viz.

- *Pure competition*, where an emerging technology has a negative influence on the growth of a mature technology, and the mature technology has a negative influence on the growth of the emerging technology;
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- Symbiosis, where an emerging technology has a positive influence on the growth of a mature technology, and the mature technology has a positive influence on the growth of the emerging technology;
- Predator-prey, where an emerging technology has a positive influence on the growth of a mature technology, and the mature technology has a negative influence on the growth of the emerging technology; or where an emerging technology has a negative influence on the growth of a mature technology, and the mature technology has a positive influence on the growth of the emerging technology.

The case of an emerging technology having a positive effect on the growth of a mature technology

Consider the case where a new technology emerges in the presence of existing technologies. Intuitively (and without the benefit of the multi-mode framework), one might want to argue that the two technologies are in competition and hence have negative influences on one another's growth rates. However, this is not necessarily so. There are many examples where the mature technology has actually prospered when the new technology emerged. Poznanski, for example, studied the demise of old steel making processes (notably the Bessemer and open hearth processes) in various countries and found that "... the first years of expansion of new production in all countries were accompanied by a stability or increase in open-hearth output" [24]. He also refers to a study by Gold, Pierce and Rosegger [25] who found that "... output from old technologies grew faster than that from the new ones at certain periods of time, not only in the case of open-hearth, but also of by-product coke, coal cutting, and coal washing...". It might well be argued that this growth of the mature technology was not necessarily due to the influence of the emerging technology. There are, however, specific examples to illustrate cases where the emerging technology explicitly enhances the growth rate of the mature technology. In their study of the electronics component industry, Soukop and Cooper found that "... generally the appearance of a new product technology initially has little or no adverse effect on the market for traditional products, and in fact may increase their total sales by stimulating efforts to improve their performance and/or cost characteristics" [11]. This "sailing ship effect" is a well-known phenomenon where the mature technology defends itself against a new emerging...
technology.¹ Once the mature technology realizes that it is under attack, there is often a vigorous effort on the part of the mature technology to resuscitate itself² (see for example Foster [6] and Utterback [1]).

Utterback and Kim state that a technology will often only be optimized with regard to its key parameters after a new technology emerges [26]. This is a well-known response by mature technologies, as is evident in the literature on defensive strategies referred to above. Utterback mentions, for example, efforts by the gas industry to improve the efficiency of gas lighting when attacked by Edison’s electric lamps [1]. Foster refers to the metal manufacturers that have “... limited the use of plastics or ceramics in cars and other products by introducing high-strength, low-alloy steel in metals” [6]. Cooper and Schendel mention several other cases where the sales of the mature technology did not decline immediately after the introduction of the new technology, viz. diesel-electric locomotives versus steam locomotives, discrete transistors versus vacuum tubes and jet engines versus propellers [8]. Anderson and Tushman refer to mechanical typewriters, piston jets, telegraphy and mechanical watches as further examples of technologies which experienced “sharp performance advances in response to technological threat” [3]. Hence one finds evidence that an emerging technology can have a positive influence on the growth rate of the mature technology that it is attacking.

The case of an emerging technology having a negative effect on the growth of a mature technology

Often the new technology enters a niche market rather than the main market of the mature technology, and as such it does not immediately threaten the mature technology. Cooper and Schendel point out that “... some submarkets were insulated from competition for extended periods”, and also that “... The new technology often invaded the traditional industry by capturing sequentially a series of submarkets” [8]. As the emerging technology matures,

¹The term “sailing ship effect” originated from the sailing ship industry that developed fast clipper sailing ships to counter the invasion from steam powered vessels.
² As was discussed above, it is strictly speaking of course not the technology itself that reacts, but the companies and institutions that manufacture, develop and use it. As a figure of speech we shall, however, refer to the technology as the actor.
however, it will expand into other markets that will include the main markets of the mature technology as well as new markets that are not served by the mature technology [1]. Once the new technology enters the main markets of the mature technology, it will often start to have a negative influence on the mature technology’s growth rate as they compete head-on for market-share. Consider for example the case of compact discs (CD). Immediately after the launch of CDs in 1982, this emerging technology started to encroach on the market of long playing records and hence had a very detrimental effect on the latter’s growth [27]. A large number of other examples of new technologies that have replaced mature technologies in the market have been documented (see for example[1,5-8]). There is thus evidence that an emerging technology can have a negative influence on the growth rate of the mature technology it is attacking.

**The case of a mature technology having a positive effect on the growth of an emerging technology**

Let us now examine the effect that a mature technology can have on the growth rate of an attacking emerging technology. Consider again the case where an emerging technology enters a market niche that is not seriously addressed by a mature technology. One can certainly make a case that the emerging technology’s growth rate can be enhanced by the presence of the mature technology. The emerging technology will typically benefit from factors that favor followers and imitators (as opposed to first movers) in an industry (see for example [28-30]). Such factors may include the fact that the mature technology has already established a market, thereby allowing the emerging technology to act as free-rider on the mature technology’s efforts to open a market, educate customers and establish marketing and distribution channels. The emerging technology only has to persuade the customer to “prefer its brand”, since the customer has already bought into “trying the product” [31]. For example, the first generation electronic computers (notably the ENIAC [5]) were originally built with vacuum tubes. A computer industry started developing where the first customers were from the government sector, although commercial, industrial and academic customers soon followed. Academic disciplines supporting the computer industry started developing. By the time discrete transistors arrived on the scene in the 1950s, there was no need to convince anybody that the computer *per se* was a good idea. Discrete transistors had a ready-made market to serve in the computer industry and thus benefited by the presence of vacuum tubes.
An emerging technology can also benefit from the infrastructure that was created to accommodate the mature technology. For example, when diesel-electric locomotives attacked steam locomotives they benefited from the existing railway infrastructure, including tracks, stations, as well as passenger and freight handling systems. When IBM entered the personal computer (PC) market, the market gained significant legitimacy due to the reputation of IBM, a reputation that was established in large part by IBM’s mainframe machines [1]. The PCs thus benefited from the presence of the mainframes. Emerging technologies can also benefit from the mature technology’s efforts to gain regulatory approvals and mechanisms. One can thus argue that a mature technology can have a positive influence on the growth rate of an emerging technology.

The case of a mature technology having a negative effect on the growth of an emerging technology

There are many examples of failed innovations (which is actually a contradiction in terms). Although many reasons can certainly be found for the failures, a case can also be made that some emerging technologies failed because of the negative influence that the established mature technologies had on their growth rates. The QWERTY keyboard had its origins in Sholes’ typing machine of the 1860s, and it became the dominant design in keyboards [1]. Subsequently several alternatives were introduced to try to displace the QWERTY keyboard. One of the most interesting, the Dvorak Simplified Keyboard (DSK), was introduced in 1932 [32]. Many typing records have been held by the DSK, lending some motivation to the contention by some that the DSK is a better keyboard lay-out. Nevertheless, the QWERTY keyboard has held its own against all attackers and is still the dominant design in keyboards [1]. Not too long ago gallium arsenide (GaAs) was hailed as the semiconductor material of the future. Although GaAs has found some applications in certain niche markets, it has yet to succeed in supplanting silicon as the most prominent semiconductor material in electronics. The Wankel engine, also known as the rotary engine, was a contender to replace the reciprocating internal combustion engine in automobiles. The engine was commercialized in NSU and Mazda automobiles in the early seventies; its main claim to fame being that it contained fewer moving parts. However, it never gained large scale market acceptance and its use in commercial automobiles was discontinued.
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Tushman mention the cases of bubble memory, tuning-fork oscillation and the ALCOA smelting process for aluminum as other examples of emerging technologies that could not compete against the established mature technologies [3]. In all of the cases mentioned here, there were mature technologies serving the market niches addressed by the emerging technologies, so that one can surmise that the emerging technologies did not fail because there was not a primary demand for a functional product in that niche. It is more probable that the new technologies failed because they could not compete against the established technologies. One can thus make a case that a mature technology can exercise a negative influence on the growth rate of an emerging technology.

5. A multi-mode framework to assess interaction among technologies

Having laid the groundwork by illustrating uni-directional modes of technological interaction, we can now introduce the multi-mode framework within which to assess the interaction among two or more technologies. By considering the possibility that one technology may either enhance or inhibit another technology’s growth, one finds that three major modes of interaction can exist, viz. pure competition where each of the technologies inhibits the other’s growth rate, symbiosis where each of the technologies enhances the other’s growth rate, and predator-prey interaction where one technology enhances the other’s growth rate of the other but the second inhibits the growth rate of the first.

As was mentioned above, the concept of multi-mode interaction has been proposed in an organizational ecology context (see for example [14]). Brittain and Wholey presents a very useful format [33], albeit one that is borrowed from Pianka [13], who in turn cites Odum [34] and Haskell [35] as his source. However, the use of such a multi-mode framework to model

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3 Brittain and Wholey actually propose the use of six modes (after [13] and [43]). In addition to the modes described above, they also include neutrality, where neither has an effect on the other; partial competition, where A has a negative effect on B, but B has zero effect on A; and commensalism, where A has a positive effect on B, but B has zero effect on A. Pianka uses eight modes, in that he includes parasitism as a weaker form of the predator-prey mode and distinguishes between mutualism and protocooperation as two modes where the interaction is positive, but where association is obligatory and not, respectively [12]. Pianka also uses the terms “mutualism” and “amensalism”, where Brittain and Wholey use the terms “symbiosis”, and “partial competition”. For the purpose of this discussion, we shall dispense with the neutral mode, and consider what is referred to as partial competition and commensalism as special cases of the other modes.
technological interaction, i.e. a framework that integrates the various modes with regard to the technologies per se rather than to organizations, does not appear to have been advanced in the literature. One often finds that, where the literature discusses the interaction of technologies, the discussion is almost always limited to either competition and/or symbiosis. Little research seems to have been done on technological predator-prey relationships from an innovation viewpoint (as opposed to the predator-prey interaction between animate species or organizations, for example).

The multi-mode framework is aimed at providing a setting within which to better analyze and understand the dynamics of technological change and to assess offensive and defensive innovation scenarios and the associated strategies for defense and attack between two or more technologies. It is believed that, in contrast to analyses that are bounded in scope to a single mode (usually pure competition), the multi-mode framework proposed here removes some of the artificial boundaries that are imposed by a single-mode paradigm. Rather than confining the scope of an assessment of the relationship between two or more technologies to pure competition it thus seems fruitful to expand the spectrum of interaction to include predator-prey interaction and symbiosis as well. Not only do the multiple modes give one the flexibility to examine competition in the various circumstances where the different technologies inhibit and enhance one another’s growth, but it also allows an investigation of the transitionary effects as the interaction between the technologies shifts from one mode to another with time. The framework creates the opportunity to consider strategic possibilities and alternatives that are not possible in a single-mode view.

The multi-mode framework is illustrated in Figure 1 for the case of two technologies (even though the framework can, in principle, be extended to any finite number of technologies). Note that, although there are three distinct modes, two possible types of predator-prey interactions can occur within the predator-prey mode (depending on which technology is the predator and which the prey).

Before launching into a discussion of each of the three modes, it is illuminating to refer to two interesting cases studies — one on the electronic components industry and the other on the early American telephone industry — that provide further evidence of the multi-mode interaction...
among technologies. Even though both of these studies focus primarily on the organizational ecology aspects, some inferences can in these two cases be made about the technological interaction as well because the firms that they considered are closely tied to specific technologies.

Brittain and Wholey examined the organizational ecology aspects of the electronics component industry, where they investigated the interactive dynamics of companies involved in the manufacturing of various active electronic components in the period 1949-81, specifically receiving tubes, transistors, diodes, integrated circuits, hybrid components and optoelectronics components [33]. They found evidence of symbiotic, competitive and predatory behaviour between the various companies. Because their study closely maps technologies to companies, it is appropriate in this case to apply their findings to the interaction among technologies as well, a fact that is underscored by their comment that, "... The resulting competitive structure is an amalgam of symbiotic, predatory and competitive relationships involving both strategic and technological competition" (italics added). Barnett and others did an extensive study of the early history of the American telephone industry where the effects of two technological innovations, viz. the change from magneto systems to the Hayes’s common-battery and the use of line loading, on the type of interaction among early telephone companies were investigated [19,37].

The aim of the study was to test hypotheses concerning factors that resulted in competition on the one hand and mutualism on the other hand. The predator-prey mode of interaction is specifically not mentioned in the article. As in the case of Brittain and Wholey’s study, Barnett’s
study also focused on the organizational ecology aspects, but because of the close links between the nature of the companies and the technologies involved, one can also make inferences about the nature of the technological interactions. Barnett concludes that "... if the density of organizations with a specific technology (italics added) increased failure rates, then there is evidence that those organizations generated competition. Conversely, if failure rates decreased as those organizations became more numerous, then there is evidence that they generated mutualism". Both the study by Brittain and Wholey and that by Barnett found evidence of multi-mode interaction. What is also of significance to the study described in this paper, is Barnett's comment that the competition changed form as time progressed, lending support to the notion of a temporal shifting between interactive modes. This notion leads us to the discussion on the temporal shift between modes, which follows the discussion of the three modes below.

**Pure competition**

Pure competition, i.e. where each technology exerts a negative influence on the other's growth, is a very prevalent case in an innovation context. It has been extensively covered in the literature (see for example [1-12, 38]), and hence it will not be addressed in great detail here. Farrell, for example, used a model based on Lotka-Volterra equations to examine pure competition between various technologies, including lead-free versus soldered food cans, woven versus tufted carpets, fountain pens versus ball-point pens, nylon versus rayon tire cords, and telephone versus telegraph usage [39,40].

The concepts of substitutes and complementary products are very useful in the context of the multi-mode framework. Competition is often embodied in substitutes, which have been recognized as a powerful force in competition. Porter, for example, considers substitutes as one of the five forces in his model of industrial competition [38]. Where substitutes address the same market niche as existing products, they will in general have an inhibiting effect on an existing product in the sense that they serve the same niche. One can argue that the emergence of hard disc drives, for example, had an inhibiting effect on the proliferation of floppy drives. Whereas many early PCs (notably the XT) originally had two floppy drives and no hard disk drives, the emergence of hard drives for the PC market resulted in PCs typically having only one floppy drive and one hard drive, rather than two floppy drives. Similarly, one can argue that the
emergence of 3.5" floppy drives has made a major dent in the diffusion of the older 5.25" drives. In the last two cases the inference would thus be that hard drives and 3.5" floppy drives have had a negative effect on the growth rate of 5.25" floppy drives.

_Symbiosis_

In the case where two technologies have positive reciprocal effects on one another’s growth rate, the interaction is considered to be symbiotic. Symbiosis is the “…association of two different organisms living attached to each other or one within the other to their mutual advantage” [41]. The concept of symbiosis is closely related to that of _mutualism_, which is “…the doctrine that mutual dependence is necessary for social well-being” and to _commensalism_ which is where “…an organism lives harmlessly with or in another and shares its food” [41]. With respect to the technological systems of interest here, symbiosis seems to be the more appropriate term since it is commensurate with species affecting one another’s growth rates. Mutualism implies a necessary interdependence, which may also be present in order for reciprocal enhancement or inhibition of growth rates, but not necessarily so. The subtle difference here is whether the interaction merely enhances or inhibits both technologies’ growth rates or whether growth and indeed survival of one of the technologies is dependent upon the other’s presence and well being. Commensalism is obviously too weak a term for our purposes. The term “symbiosis” is also used by some organizational ecologists, like Pianka, who states that symbiotic relationships include mutualism and commensalism [13], and Carroll who states that the relationship between certain forms of organizations can be either symbiotic or competitive [42]. We are thus in good company in using the term _symbiosis_, which will be used here in a sweeping sense in that the concepts of mutualism and commensalism are also included where appropriate to indicate technologies which have mutually positive effects on one another’s growth rate.

A case can be made, for example, that computer hardware and software for desktop computing interact in a symbiotic way. This relationship is underscored by statements such as “…
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Microsoft is Intel’s natural ally in its quest to market the latest chips. The software giant is selling increasingly complex and capable software that requires fast chips to work well” [44], “… Intel is simply trying to light a fire under Gates to make sure future versions of Windows keeps pace with Intel’s designs” [45] and “…Intel remains unique in its ability to build the fastest processors for Microsoft Windows” [46]. As another example consider the case of CD-ROM drives and computer games which seem to stimulate the demand for one another [47].

One can surmise that a product which is complementary to another will enhance the growth rate of the second, or at least not inhibit it. For example, the fact that hard disc drives are available for PCs certainly contributed to the popularity and widespread diffusion of PCs. If, for argument’s sake, hard disc drives had not been available for PCs, a PC’s usefulness would have been severely hampered and hence one can postulate that PCs would have experienced a much smaller growth rate. The fact that a large scale infrastructure for charging the batteries of electric cars is not available is probably a major factor contributing to the slow diffusion of electric vehicles. Cooper and Smith argue that in the case of microwave ovens, the lack of complementary products such as cookbooks and cookware could have retarded the market’s growth [9].

The phenomenon that innovations tend to cluster is a well recognized one, and it has been suggested that the various technologies in a given cluster often reinforce one another. This concept fits into that of new technologies that often follow from the merging of existing technologies. Girifalco, for example, mentions that “… railroads and steelmaking spurred each other’s development, as did electric lighting and the telephone, the jet engine and electronics and plastics and petroleum technology … cluster of new technologies that reinforce each other and more or less grow together; bottlenecks in one technology may call forth advances in another, advances in one may open up opportunities in another, or progress in one may have to await improvements in the another” [5]. This notion also ties in with that of technological systems. Hughes makes the point that, in the case of large technological systems, many interrelated subsystems are required to make the entire system work [48]. Sahal refers to “systems innovations” that “… arise from integration of two or more symbiotic technologies…” (italics added) [49]. He points to jet engines, the three point hitch and control systems for farm tractors,
as well as the electronic computer as major innovations that came about due to the symbiotic interactions of various other technologies.

**Predator-prey interaction**

Predator-prey interaction between technologies is an interesting case, both from research and managerial viewpoints. A survey of the literature shows that, except for some cursory references (see for example [50]), it has not been addressed seriously as a research topic. There is no obvious evidence of a research effort that has focused on investigating such a relationship between technologies, nor does it appear that work has been done to develop appropriate strategies for technologies that find themselves in a mode of predator-prey interaction.

Considering the examples given above one can envision, for example, that a predator-prey relationship may exist between an emerging technology and a mature technology where the emerging technology enters a niche market that is not served by the mature technology. In this case the emerging technology will benefit from the presence of the mature technology and the mature technology will thus exert a positive influence on the emerging technology’s growth rate. The mature technology may not recognize the threat posed by the emerging technology and hence the emerging technology does not trigger a significant resuscitation or growth spurt, i.e. the sailing ship effect, in the mature technology. At the same time the emerging technology may slowly be stealing market share from the mature technology. Under these circumstances, one can posit that the emerging technology has a negative influence on the growth rate of the mature technology. Hence there is a predator-prey interaction between them, with the emerging technology the predator and the mature technology the prey. On the other hand, one can also visualize a situation where the mature technology is the predator and the emerging technology the prey. Consider, for example, the case where the emergence of the new technology triggers a sailing ship effect in the mature technology, resulting in de-maturing and new growth (see for example [6]). This implies that the emerging technology has a positive influence on the mature technology.

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5 Moore makes an interesting comment in this regard when he says, "... Superficially, competition among business ecosystems is a fight for market share. But below the surface, these new competitive struggles are fights over who will direct the future" [51]
technology's growth rate. When this effect occurs simultaneously with one where the mature technology has a negative effect on the growth rate of an emerging technology, a predator-prey relationship results. Consider the example mentioned above which cited the emergence of ceramics that stimulated growth in high-alloy steels for engine components. The fact that ceramics is still a struggling technology in this regard whilst high-alloy steels prospered indicates a predator-prey interaction.

Another example of predator-prey interaction is the attack of radial-ply tires on bias-ply tires in the US [6]. As various technologies were battling for the bias-ply tire cord market in the US in the 1970s, notably polyester and nylon, the French company Michelin invented the radial-ply tire. At the time of their first introduction into the US market, radial tires were initially purchased by sportscar enthusiasts who bought the tires as replacements at Sears. One can argue that the interaction was initially in a predator-prey mode. Radial-ply tires benefitted by the existence of the existing technology (bias-ply tires in this case) in a very basic sense. Automobiles needed tires and hence there was a primary demand for tires. Had automobiles not used tires at all (moving about on the hovercraft principle for example, or used wooden or steel “tires” as did early tractors), then radial-ply tires would have had a much harder problem in breaking into the tire market in the first place. Hence, radial-ply tires benefitted by the existing market for tires in general. Furthermore, the fact that there were deficiencies in the bias-ply tires created a market niche for the radial-ply tires. On the other hand, the radial-ply tire was initially not a threat to the main market of bias-ply tires, inter alia because of the reluctance of automobile designers to redesign the suspension for radial-ply tires. However, Michelin eventually obtained the tire order for Lincoln Continentals, suddenly became a major competitor for bias-ply tires, and soon after drove bias-ply tires from the market. Bias-ply tires lost market share from 80% to 20% to radial-ply tires in four years [6].

6. Temporal shifts between modes

The notion of the dynamics of technological change, i.e. technology changes with time, is central to this article. Technological change is manifested and can be expressed in various mechanisms, including, for example, that of growth, substitution or diffusion as is often expressed in terms of an S-curve and life-cycle models [5,6,22,31], or the evolution and coupling of product and
process [1]. Very often one finds the temporal development is categorized in stages. Utterback and Abernathy, for example, identify three stages with regard to the interaction of product and process development, viz. the fluid stage, the transitional stage and the specific phase [1]. The progression of an S-curve is also often characterized in terms of an emerging phase, a growth phase and a mature phase. The notion that technologies and the industry in which they abide have different temporal stages has serious managerial implications, since it implies that different strategies need to be developed and applied for the different stages [1]. Loveridge and Pitt point out that the transitionary periods between the different stages need to be managed with particular care [18]. In this section we wish to address another dynamic, namely that of the temporal change of the interaction of two (or more) technologies between the various modes in the multi-mode framework. It should stressed again this discussion is a conceptual one, as in the rest of the paper.

The notion that the mode of interaction between two technologies can change with time differentiates the technological framework proposed here from an ecological one. In an ecological predator-prey system, for example, lion and antelope will have a relationship where the lion is the predator and the antelope is the prey *ad infinitum*. The nature of the interactions among technological systems and the related industries and companies, on the other hand, *do* change with time. These changes are manifested in the technology itself, product changes, process changes as well as changes in the structure of the industry and the various companies in the industry. Hence the fact that technologies and the environments in which they are applied change with time creates the possibility that the mode of interaction between two or more technologies can, in the general case, also change with time.

Consider the following hypothetical example to illustrate the transition from a predator-prey mode to a competition mode. An emerging technology enters the market, and benefits by the

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6 One of the anonymous reviewers suggested that the predator-prey mode may be no more than a transition between two steady-state cases. This may indeed be so, and if so, will strengthen the argument that temporal mode shifts can, in the general case, occur. Further research must be done into the nature of the various modes, and specifically the predator-prey mode to establish the transitionary nature of the predator-prey mode, and to establish what determines the time constants.
presence of the exiting technology in the manner described above in ways where the mature technology has a positive effect on the growth of the emerging technology. Assume that the entry of the new technology does not solicit any reaction from the mature technology. This may happen, for example, if the mature technology does not notice the emerging technology or it may be overconfident because it has seen previous attempts fail [6]. At the same time the emerging technology exerts a negative effect on the mature technology’s growth rate since it is in fact stealing market share and gaining more converts to the new technology as time passes. At this stage the interaction is in the predator-prey mode, with the emerging technology the predator and the mature technology the prey. Eventually, however, the mature technology realizes the threat and starts to fight back. A sailing-ship effect may be triggered for example or the defender may resort to the use of hybrids. Various types of marketing techniques may be deployed, including the use of negative publicity and attempts to have the new technology declared illegal or unsafe [1]. Foster mentions examples where Polaroid has retaliated against Kodak by linking price cuts to technological improvements, and similarly how Xerox retaliated against IBM and Kodak by the same methods [6]. The fact that these were retaliations, imply that they were defensive actions that were triggered by actions of the perpetrators. The point is that once the existing technology actively starts to defend, the picture changes. The sailing ship effect may well enhance the mature technology to such an effect that it has a negative effect on the emerging technology. The nature of this interaction will then have changed from predator-prey to competition.

One can also make a case to illustrate that the interaction can change from a symbiotic one to one of competition or predator-prey. Consider for example the nature of interaction between computer hardware and software, which are taken to be two different technologies for the purpose of this discussion. It was pointed out above that hardware and software can exist in a symbiotic mode where one will fuel growth of the other. One also finds, however, that there are times when the nature of the interaction between hardware and software can shift from a symbiotic one to either a competition of predator-prey mode. Functions that were previously performed by software can be taken over by hardware, in which case the hardware has a negative effect on the growth of software. Witness for example the introduction of math co-processors, which employ hardware circuits to perform calculations that were previously performed in
software. On the other hand there are also examples of functions that were performed in hardware, which have been taken over by software. The greater demand for storage memory stimulated the development for larger hard disc drives, i.e. software exerted a positive effect on the growth of a hardware. However, software packages are now available that will compress the data on hard discs and thereby effectively increase the disk space using software routines. The availability of such software will to some extent slow the growth in hard discs since many consumers will resort to the software compression routines instead of upgrading to larger hard discs (even though this may only be a transitional occurrence). This example illustrates the changing nature of the interaction between computer hardware, particularly storage memory, and software.

It is also possible to conceptualize a transition from predator-prey or competition to symbiosis. The interaction between radio and television is arguably such a case. When television entered the market, radio was the established technology in broadcast technology. Whereas there was no doubt a phase where the interaction between the two was of a general competitive nature the relationship seems to have stabilized to a symbiotic one. One hears advertisements for television on radio and vice versa. The technologies also seem to exhibit a trend towards merging, in that products are sold which embody both radio and television in same product.

The examples discussed above illustrate (albeit conceptually) that the mode of interaction between two technologies can change. A case can be made that interaction among technologies can, in general, shift from one mode to another with time.

7. Preview of strategies
It was stated above that the objective of this paper is to point out the usefulness of a multi-mode framework within which to assess the dynamics of technological change, and particularly the nature of interaction among technologies. The next logical step will be the development of managerial strategies to deploy in each of the modes as well as during the transition between modes. Although the development of such strategies will be left as a research challenge, it is appropriate to briefly touch on the issue here in a conceptual manner.
Before setting a strategy, the question should be asked as to what the strategy should accomplish. Recall that the effect that one technology has on the growth rate of another was used as the criterion to distinguish one mode from another, and we shall thus use growth as the objective of strategy in this case. The aim is to enhance the growth of one’s own technology, and the strategy should be deployed to this effect. Since the nature of the interaction in the various modes differ, one can surmise that strategies which are appropriate in one mode may be inapplicable in other modes, as the discussion below illustrates.

Consider the case where technologies A and B are interacting. In a pure competition mode, for example, A and B will have a negative effect on each other’s growth rate. In order to enhance its own growth, one would also want to eliminate any sources that have a negative effect on its growth. In the case of pure competition then, the strategies of both A and B would typically be aimed at inhibiting the growth of the other. In the case where the interaction is in a predator-prey mode on the other hand, the generic strategies will be different from those in a competition mode. Let A be the predator and B the prey, i.e. if A grows it has a detrimental effect on B’s growth, whereas B’s growth enhances A’s growth. In this case A would do better not to actively deter B, since B’s growth enhances A’s growth. The mere fact that A grows, however, will eventually kill B, but while it lasts A should reap all the benefits it can from B’s growth. A case can be made that A may even consider taking active steps to enhance B’s growth, since A will benefit thereby. However, had A perceived this situation as one of pure competition instead of a predator-prey interaction, its strategy would have been to actively deter B’s growth and A would subsequently have foregone the enhancing effect that B’s growth could have had on its own growth.

The simple example above illustrates the principle that generic strategies that are applicable in one mode will not necessarily work in another mode. In order to apply this principle, it is of course necessary to first recognize the existence of multi-mode interaction and the specific mode in which the interaction is in at any given time. The situation is complicated considerably by the possibility of a temporal shift in mode, since strategies must now be able to accommodate dynamic mode shifts in addition to dealing with a particular mode. If the interaction is a
symbiotic mode for example, the growth of A will also enhance the growth of B and vice versa. It would thus, in principle, be in each of the technologies interest to take steps to enhance the growth of the other, and certainly not to take steps to deter the other’s growth. Should the situation change, it will be necessary to change strategy as well. If B should become a predator and A a prey, B’s strategy will still be to enhance A’s growth as explained above, but A will strive to inhibit B’s growth. If A perceives that the mode of interaction may change from symbiotic to predator-prey, it may want to tone down its efforts to stimulate B’s growth in anticipation of change of mode. The mathematical model alluded to in the appendix can be used to simulate interaction in the various modes [52].

The substitution of electronic calculators for electromechanical calculators illustrates the devastating effects that the selection of the wrong strategy for the wrong mode can have. When electronic calculators first appeared in the 1960s, the manufacturers of electromechanical calculators considered electronic calculators to be complementary products, mainly because it seemed that electronic calculators addressed a market niche that electromechanical calculators did not serve [53]. In our parlance, they thus assumed a symbiotic-like interaction between electronic calculators and electromechanical calculators. This assumed symbiotic relationship was one of the primary reasons the manufacturers of electromechanical calculators did not take sufficient defensive action against the attack from electronic calculators. However, the relationship soon changed when electronic calculator technology developed to the point where it not only posed a serious threat to electromechanical calculators, but in fact took over electromechanical calculators’ main market and drove electromechanical calculators to near extinction. Had the manufacturers of electromechanical calculators realized that the nature of interaction was competitive or had changed to competition from symbiosis, they might have acted very differently.

8. Conclusions
In this paper it is proposed that the notion of multi-mode interaction which has been demonstrated for biological and organizational ecologies can also be useful to assess the interaction among technologies. This approach leads to a broader view of technological interaction than mere competition and provides a richer setting to analyze the interaction of
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technologies and to plot innovation strategies. Three distinct major modes of interaction among technologies are identified, viz. pure competition, symbiosis and predator-prey. The reciprocal effects that technologies have on one another’s growth is used as a classification criterion. Cases were cited to illustrate how these emerging and mature technologies can have positive and negative effects on one another’s growth rates. Examples were then cited to show that, in principle, each of the modes do exist, and that there can, in the general case, be a temporal shift from one mode to another. Although the cases were discussed here with regard to emerging and mature technologies, the framework can be applied to any two (or more) technologies.

It is suggested that further research be undertaken into the nature of the interaction in the various modes as well as the transitionary effects when the interaction shifts from one mode to another. The symbiosis and predator-prey modes, in particular, seem to have been neglected in the innovation related literature. Once the nature of the interaction in the modes and the transition between them are better understood, managerial strategies for dealing with the interaction in each of the modes as well as the transition between them, can be developed.
Appendix

Forces that influence a technology’s growth — the nature of the impact of another technology vis-à-vis those of other influences

The dynamics of technological change is concerned both with the forces that drive the change and the rates of change. One should keep in mind that the influence that technologies have on one another’s growth rate is just one of many influences, and in this appendix we consider the effect that one technology has on another’s growth rate vis-à-vis some other influences that can also affect the growth rate. For example, Mansfield suggests that “... the rate of adoption of an innovation is a direct function of the profitability of employing the innovation and a decreasing function of the size of investment required to use it” thereby implying an economic influence on the rate of diffusion [54]. Blackman et al. showed that the extent to which resources are allocated also has an influence [23]. Bundgaard-Nielsen suggests that a country’s industrial growth plays a role [55]. Davies discusses the influence that knowledge about the product, industry structure and growth and learning curves have on the rate of adoption [56]. In a recent review article Kumar and Kumar cite researchers who have investigated the role of price, advertising, promotion, product interrelationships, market size, repeat purchases and competition on the rate of diffusion [57]. Dosi comments that the rate of diffusion can also depend on the features of the technologies that are to be adopted and substituted, on economic incentives, characteristics of would-be adopters, the information available to them and their technological competence [58]. He also refers to several other researchers that have shown varying rates of diffusion depending on inter-firm, inter-industry and inter-technology relationships. The question now arises how factors of the nature mentioned above influence the growth rate of a technology, as opposed to the way in which one technology influences the growth rate of another technology.

It is illuminating to illustrate the effect of the different influences on a technology’s growth rate by considering a modified Lotka-Volterra model. Such models have been successfully applied to model organizational ecologies [14, 34, 42, 59], and also technological diffusion [50, 39, 60-62].

Let \( N(t) \) and \( M(t) \) denote two technology populations. The derivatives \( dN/dt \) and \( dM/dt \) are the growth rates of the two technologies, respectively, and can be expressed as

\[
\frac{dN}{dt} = a_n N - b_n N^2 \pm c_{nm} NM \\
\frac{dM}{dt} = a_m M - b_m M^2 \pm c_{mn} MN
\]

(1)

(2)

The formulation given above differs from the traditional Lotka-Volterra formulations in that the signs of both the \( a- \) coefficients are positive, but more important we allow the signs of the \( c- \)coefficients to vary (after [42]). The \( c- \)coefficients are the coupling coefficients that determine the amount that one technology will influence the growth of another, and it is in fact the signs of these coefficients that determine which of the three modes the interaction is in. Note that the signs in the equations correspond to the signs in Figure 1. For example, two positive signs indicate a symbiotic relationship, two negative signs a pure competition mode whereas one positive and one negative sign indicates a predator-prey mode.

Obviously all the terms on the right hand side of the equation influence the growth rate of the technology. The first two terms on the right hand side correspond to the Pearl-type growth model, which is a well known and accepted model for technological growth processes [5]. The third term on the right hand side accounts for the fact that the other technology can also have an influence on the growth of the technology under consideration. From the formulation above it should be clear that the various influences mentioned above impact in a very different way on the growth of a technology than does the presence of another technology. The influence of another technology is manifested in the terms \( NM \) and \( MN \), whereas the other factors influence the growth through the \( a- \) and \( b- \)coefficients and “leverages” the effect that another technology has through the \( c- \)coefficients. The influences described in the paragraph above, will typically determine the value the coefficients \((a,b,c)\). Note that these coefficients can, in general, be time dependent (see for example [60,63]). The time dependence of the \( c- \)coefficients will account for the temporal shifts between the modes.
References


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