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The technology life cycle: Conceptualization and managerial implications

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ABSTRACT

This paper argues that the technology life cycle literature is confused and incomplete. This literature is first reviewed with consideration of the related concepts of the life cycles for industries and products. By exploring the inter-relationships between these, an integrated view of the technology life cycle is produced. A new conceptualization of the technology life cycle is then proposed. This is represented as a model that incorporates three different levels for technology application, paradigm and generation. The model shows how separate paradigms emerge over time to achieve a given application. It traces the eras of ferment and incremental change and shows how technology generations evolve within these. It also depicts how the eras are separated by the emergence of a dominant design, and how paradigms are replaced at a technological discontinuity. By adopting this structure, the model can demarcate the evolution of technologies at varying levels of granularity from the specific products in which they may be manifest to the industries in which they are exploited.

By taking technology as the unit of analysis the model departs from previous work, which has adopted a product-based perspective predominantly. The paper discusses the managerial and research implications associated with the technology life cycle, and indicates how these inform future research directions. As well as contributing to academic knowledge, the results of this research are of value to those who make decisions about the development, exploitation and use of technology including technology developers, engineers, technologists, R & D managers, and designers.

1. Introduction

In the literature, it is common to see the terms industry life cycle, product life cycle and technology life cycle used interchangeably, ambiguously and often inappropriately. Moreover the discourse is dominated by the product life cycle (PLC) while the technology life cycle (TLC) has largely been neglected. This is only the tip of the iceberg since there are also disconnects and inconsistencies pertaining to the various perspectives on the TLC such that there is no "*single, strong, unified theory of technological evolution*" (Sood and Tellis, 2005: 152). The focus of this paper is to highlight the imprecision and confusion which exists in relation to the TLC and to address the need for clearer conceptualization.

We draw together and extend previous work on the TLC, which represents a wide ranging debate from multiple disciplines and perspectives. We develop an integrated view of this beguiling concept using three distinct entities—the technology application, paradigm and generation. We also depart from previous work by taking technology as the unit of analysis, rather than any product or artefact in which it is used. This facilitates examination of how the 'macro' view of technology evolution (e.g. Anderson and Tushman, 1990) is related to the S-curve perspective (e.g. Foster, 1986); how technology progression occurs within and between the three entities of the TLC; and to what extent progression may be influenced by management action.

Our aim is to increase recognition and understanding of the phases that make up the TLC, arguing that, as firms seek to manage technology, they need to be able to position specific technologies within the life cycle and to understand the implications of this for managerial decisions. Few studies have discussed the links between the TLC concept and the reality of managerial decisions. The paper addresses this gap by pointing towards the challenges associated with the profitable exploitation of technology from the perspective of both developers and users. This dyadic perspective is unusual and important, especially as an individual organisation may act in both capacities.

Finally, we consider how technology progression links with the product focus associated with the PLC and the industry life cycle (ILC), and in the cases of simple and complex products (Tushman and Rosenkopf, 1992). The synthesis of these various perspectives is intended to strengthen the theoretical base on which technology management decisions are made and to create

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a foundation upon which future research can build. To summarise our analysis we propose a new conceptualization of the TLC.

The next section introduces the life cycle literatures and demonstrates the conceptual imprecision which exists. In Section 3 the TLC is considered in detail from the distinct perspectives that emerge from the literature, followed, in Section 4, by a discussion which explores how the principal perspectives associated with the TLC are linked. A new conceptual model is presented in Section 5. The implications of our work for future research and for managerial decision making are considered in Section 6, before we draw conclusions in Section 7.

2. The life cycle literatures

The streams of literature that are relevant to this work pertain to the industry life cycle, the technology life cycle and the product life cycle. While these concepts are inter-related, it is crucial to understand the distinctions between them so that each is used appropriately in the right context and with accurate terminology. A lack of normalised and consistent terminology (Nieto et al., 1998), separation between the views of different stakeholder disciplines (Nieto et al., 1998), ill-definition and transposition between terms (Routley et al., in press) and ambiguous or unspecified units of analysis (Murmann and Frenken, 2006; Routley et al., in press) have all contributed to confusion and misunderstanding in the field.

It is not uncommon to see synonymous and interchangeable use of the life cycle terms in the literature: industry and product, for example, in Peltoniemi (2011) and Rice and Galvin (2006); product and technology in Cetindamar et al. (2010). Perhaps as a consequence, it is not surprising to read in a Business encyclopaedia that "*to simplify the discussion, both the product life cycle and industry life cycle will be combined and simply called the product life cycle*" (Reference for Business, 2011). This glosses over important distinctions that are critical to the achievement of understanding. One of the underlying causes of this may relate to the dominance of the PLC in the extant literature.

As Table 1 shows, unlike their counterpart "*product life cycle*", both the terms "*industry life cycle*" and "*technology life cycle*" are not widely used. Table 1 represents a search of the ABI Inform academic and trade databases for articles and resources published during the last 20 years which include any of these terms in the citation or abstract. Of all the hits for all terms, around 96% concerned the PLC with approximately 2% relating to each of the TLC and ILC. The papers emanate from a variety of journals across a range of disciplines. While these figures are by no means conclusive, they suggest that the concept of the TLC is underdeveloped from both academic and practitioner perspectives.

One aspect of the confusion surrounding the TLC derives from the nature of technology itself, for which there are differing definitions. Schon (1967) asserts that technology is used to extend human capability and can take the form of a tool, technique, product, process, physical equipment or method. Bohn (1994) sees it as technical knowledge that organisations apply in order to enhance their ability to provide products and services. Emphasising both hard and soft aspects, Drejer (2000) refers to hardware, human resources and organisational aspects within a firm, thereby acknowledging the role of human skills and experiences. Using similar notions Heffner and Sharif (2008) categorise technology into "technoware" or tools, "humanware" or talents, "infoware" or facts, and "orgaware" or methods. The variety of forms which technology may take is articulated as "*a machine, an electrical or mechanical component or assembly, a chemical process, software code, a manual, blueprints, documentation, operating procedures, a patent, a technique or even a person*" (Stock and Tatikonda, 2000: 721). Others link the definition of technology to its physical manifestation in products: "*We use the word 'technology' in the tradition of the technology life cycle literature to mean technology as applied in a particular product context and as embodied in a physical artifact. So technology is not just the knowledge from which products are elaborated, but also includes the physical manifestation of that knowledge within a product.*" (Kaplan and Tripsas, 2008: 791).

These definitions serve to reinforce the inextricability of a technology and the product(s) in which it may be manifest; a situation which arguably forms part of the barrier to a clearer conceptualization of the life cycle of a technology.

A further cause of misunderstanding may be the superficial similarity in structure, shape and terminology between the different life cycles. Fig. 1 shows the most generally recognised form of the PLC which depicts sales volume or revenue plotted against time as a bell-shaped curve with distinguishable stages representing the introduction, growth, maturity and decline of a product (e.g. Urban and Hauser, 1993; Nieto et al., 1998). Introduction represents the phase when the product has first been launched onto the market, during which sales volumes are low. During the growth phase, consumer acceptance of the product builds, and sales volumes increase rapidly. At maturity, sales volumes stabilise before decreasing in the decline phase.

Whilst the PLC has traditionally been used to assist with marketing decisions, it has more recently been used as a framework for other management decisions associated with supply chain strategies (Aitken et al., 2003), supply chain partner selection (Chang et al., 2006), inventory control policies (Hsueh, 2011) and demand forecasting (Chien et al., 2010).

The axes, terminology and shape of the PLC are generally accepted and widely adopted, although there are concerns about its empirical validity. In particular, there is little standardisation over the length and timing of the phases between products or over the sales levels that will be reached (Grantham, 1997). The shape of the PLC varies between products, with some existing in maturity for extended periods, dying at the introduction stage or moving back from maturity to growth (Dhalla and Yuspeh, 1976). Finally, use of the PLC often does not distinguish between product

Table 1
Hits for technology life cycle (and lifecycle), product life cycle (and lifecycle) and industry life cycle (and lifecycle) (01/01/1991 to 18/03/2011) (ProQuest search engine).

	Technology life cycle (TLC)[a]	Product life cycle (PLC)	Industry life cycle (ILC)	Total: TLC or PLC or ILC	% TLC	% PLC	% ILC
ABI Inform Global (journals)	67 (78)	2679 (3440)	88 (94)	2834 (3612)	2.36 (2.16)	94.53 (95.24)	3.11 (2.60)
ABI Inform Trade and Industry	25 (37)	1771 (2763)	15 (16)	1811 (2816)	1.38 (1.31)	97.79 (98.12)	0.83 (0.57)
Total hits	92 (115)	4450 (6203)	103 (110)	4645 (6428)	1.98 (1.79)	95.8 (96.50)	2.22 (1.71)

[a] In searching Proquest, alternative spellings of "life cycle" were considered. Where articles used "life-cycle" (hyphenated) the searches yielded similar total numbers of articles, most of which also appeared in the non-hyphenated results. Where articles used "lifecycle" (one word) these have been added to the hit count to form separate totals for each concept (in parentheses). It should also be noted that some articles appear in both databases used—i.e. Global (journals) and Trade and Industry, so the total number of hits for each term is inevitably inflated.

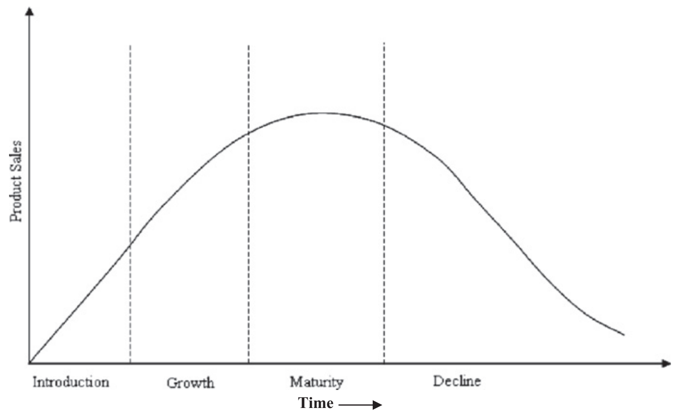

Fig. 1. Typical product life cycle.

class (e.g. automobiles), form (e.g. diesel cars) and brand (e.g. Volkswagen) (Grantham, 1997).Thus the value of the PLC as a predictive managerial tool is questionable. Moreover, while each of its phases requires different marketing strategies, it can lead to inappropriate decisions if incorrect inferences are made about the position of a product within the cycle, "*needlessly consigning products to following the curve into maturity and decline*" (Moon, 2005: 85) as a kind of self-fulfilling prophecy.

By contrast, the "*life cycle of the market*" introduced by Gort and Klepper (1982: 630) measures the diffusion of product innovations, by plotting the number of producers of a new product against time. Purposely omitting the technical development of a new product, it considers only the phase of product innovation that relates to its introduction to the market. In this way it mirrors the PLC. However, whilst it is based on the market for a new product, by focussing on diffusion it measures the net entry rate of firms. This is reflective of the progress of an industry (defined by the product class that it provides) over time. Thus, whilst Gort and Klepper consider empirical evidence from the life cycles of 46 products, they draw conclusions that relate to the associated markets and industries, i.e. to the industry life cycle which describes how an industry emerges and develops. That said, whilst the discourse of the ILC concerns the phases of evolution which follow the birth of an industry, it seems to be inextricably linked with the underlying products. Indeed, the depiction of the ILC is often described by reference to an associated PLC (e.g. Werker, 2003) and has been termed the "*product life cycle* (*PLC*) *view of evolution*" by Klepper (1997: 148). Klepper also notes the interchangeability of the terms 'industry' and 'product' by scholars from different stakeholder disciplines, and opts to follow a similar practice in his own work.

Klepper's model of the ILC begins with an embryonic or exploratory phase when market volume is low and there are high levels of uncertainty. As a result of primitive product design and the need for unspecialised production machinery, many firms enter the industry during this phase. Competition based on product innovation is intense. During the growth phase which follows, product design tends to stabilise and the production equipment becomes more specialised. The number of entrants reduces and there is a shakeout of producers. Finally, during the mature phase, as growth slows, the number of entrants declines further. This cycle, also described by Werker (2003), can be represented as an inverted U-shape (Murmann and Frenken, 2006) which is not dissimilar to the bell-shape of the PLC. However, whilst the PLC normally has four phases, the ILC is typically depicted with three.

Like the PLC, the ILC has been used in support of management decisions. In particular, studies have been concerned with the entry rates (Geroski, 1995; Audretsch, 1995) and exit rates of firms (Fotopoulos and Spence, 1998; Sarkar et al., 2006) during its various stages. Others have considered the survival characteristics of those firms which are most capable of continuing to compete (e.g. Agarwal et al., 2002; Bayus and Agarwal, 2007; Thompson, 2005).

Re-examination of the concerns listed for the PLC suggests that some of them also apply to the ILC. In particular, the same uncertainties exist about the length and characteristics of each phase such that it is difficult to predict the pertaining stage of the cycle at any time. This is problematic for managers seeking to position a firm in relation to an emerging or maturing industry; for example in deciding when and how to enter the industry and when to prepare for an exit from it. Therefore the ILC seems to possess no more predictive utility than the PLC and as such its value for practising managers is questionable.

Regardless of its complexity, any product is underpinned by technology. Furthermore, since the ILC represents the progress of industries based on particular product classes, both the PLC and the ILC are, at best, partial proxies for technology progression. Between the two extremes of product and industry however, lie a number of life cycles for product brands and forms, depending on the unit of analysis. What they have in common is that they are all a function of an enabling technology which is itself subject to progression through a complex life cycle. It is this concept of the technology life cycle which forms the focus of our work. Later on in the paper, we return to the PLC and ILC in considering how they fit with the TLC, but meantime there follows an examination of the TLC literature itself.

3. The technology life cycle

The ensuing discussion is based primarily on two key perspectives which emerge from the literature, namely the macro view and the S-curve. For completeness, it subsequently considers a number of alternative views that adopt a more managerial stance.

3.1. The macro view

Anderson and Tushman's (1990) technology evolution model is central to what some describe as the "technology life cycle literature" (e.g. Kaplan and Tripsas, 2008; Murmann and Frenken, 2006; Suarez, 2004). This is concerned with technological evolution, technology progression within industries and industry evolution (e.g. McGahan et al., 2004; Murmann and Frenken, 2006), and with the macro level of technological trajectories (Dosi, 1982). The cyclical model incorporates individual technology cycles, each of which begins with a technological discontinuity, i.e. a breakthrough innovation affecting either processes or products. The classes of technology that represent a discontinuity are known elsewhere as revolutionary, discontinuous, breakthrough, radical, emergent or step-function (Yu and Hang, 2009). Such discontinuities are followed by a period of ferment during which rivalry and competition among variations of the original breakthrough eventually lead to the selection of a single dominant configuration (Abernathy and Utterback, 1978).The dominant design becomes the industry standard. It is widely adopted and is associated with changes in the nature of competition within the corresponding industry (Murmann and Frenken, 2006). Following the emergence of the dominant design, an era of incremental evolution of the selected technology makes up the remaining stage of the cycle. During this period, emergent changes are also known as evolutionary, continuous, incremental or 'nuts and bolts' technologies (Yu and Hang, 2009). Once this is over, the cycle of variation, selection and retention (Murmann and Frenken, 2006) begins again with a further technological discontinuity. Fig. 2 summarises the key elements of the macro TLC.

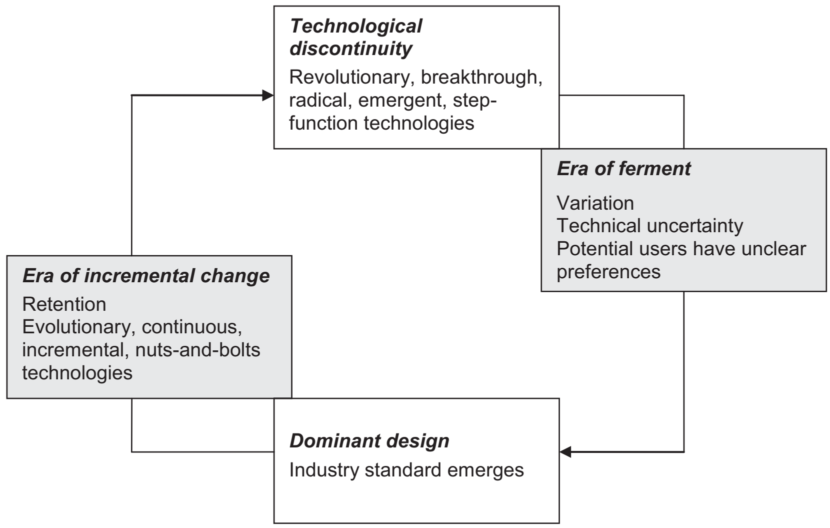

Fig. 2. Macro TLC.
(Adapted from Kaplan and Tripsas, 2008).

In Fig. 2 the era of ferment is intentionally touching the preceding block to emphasise that it follows immediately from the technological discontinuity. Similarly the era of incremental change begins without delay following the emergence of the dominant design.

Although it is generally accepted that Anderson and Tushman's model of technological change concerns innovations of both product and process, subsequent development has highlighted the changing emphasis between these during the cycle. Pyka (2000) describes how in the early phase which is "*mostly congruent to the emergence of a new technological paradigm*" (Ibid: 29), there is much technological uncertainty and a strong emphasis on product innovation. Later, as volume expands, research focuses more on incremental innovations for the associated production processes. Thus, during the era of ferment, the developmental focus is on product technology with the emergence of a dominant design reflecting scientific maturity and standard-acceptance. At this point, customer demand increases in both volume and sophistication. During the era of incremental change, product technology changes incrementally and greater emphasis is placed on the development of processes which will meet customer demands at lower costs (Herrmann, 2005). Also, at this stage, once the basic technological and market uncertainties have disappeared, there is increasing activity to develop market applications by which the technology may be exploited (Haupt et al., 2007). The emphasis changes from technology development *per se* to its commercialisation through extension of its range of applications.

An alternative perspective on the same phenomenon involves plotting the rate of major innovation for a technology against time; this results in the inverted product curve shown in Fig. 3. Adding the rate of process innovation to this completes the 'Dynamics of Innovation model' (Utterback, 1994; Utterback and Abernathy, 1975).The notions embedded in this model further show how during the early stage of technology development (in this case, termed the fluid phase), innovation effort focuses on the development of products. Thereafter, the transitional phase, characterised by market acceptance and the emergence of a dominant design, involves greater cohesion between product and process innovation effort. The emphasis moves to designing operations for large scale efficient production and involves development of process technology. The resulting rigidity of the process restricts the extent to which further product innovation is possible (Utterback, 1994). Finally, during the specific phase – so-called because a very specific product is produced at a high level of efficiency – the inherent system rigidity means that changes to product or process can be costly, difficult and inter-linked. Thus, innovation or technological development is minimal. Utterback suggests that prior to the relatively recent introduction of more flexible production systems and mass customization, the specific phase would be ended by a significant event such as another technological breakthrough, or as Adner observes, "*as the technology matures, opportunities for innovations of both types dwindle, and the opportunity space becomes ripe for competition and replacement by a new emerging technology*" (Adner et al., 2004: 36).

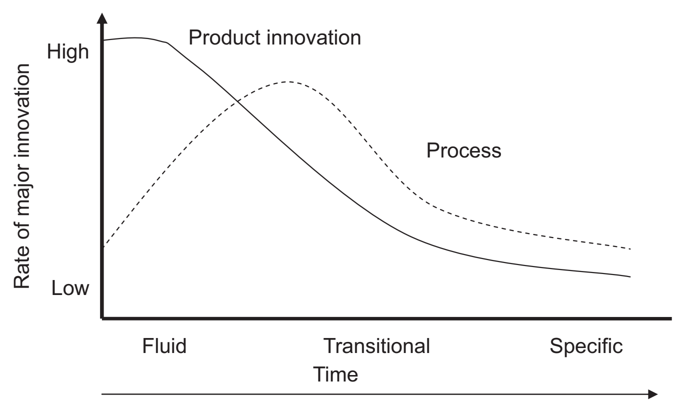

Fig. 3. Utterback 'Dynamics of Innovation model' reflecting the technology life cycle.

These ideas have been re-interpreted by Adner and Levinthal (2001) who argue that the nature of customer demand in the early phase of the cycle is for the technology to meet minimum thresholds of performance (hence the emphasis on product innovation), subsequently replaced by a focus on price (thereby requiring process innovation) later on.

Having explored the literature on the macro-view of technology progression, we now turn our attention to the S-curve which represents the other major perspective on technological progress.

3.2. *The S-curve*

Technology progression "*advances slowly at first, then accelerates, and then inevitably declines*" (Foster, 1986: 20), thereby conforming to the general form of an S-curve (Cetindamar et al., 2010). The use of the S-curve within the technology literature is far from consistent however, most notably in relation to the dimensions which it portrays. A common interpretation plots the cumulative adoption of a technology over time, resulting in what is sometimes called the diffusion model (e.g. Nieto et al., 1998). This is delineated into a number of phases such as 'embryonic', 'growth', 'maturity' and 'ageing' (Cetindamar et al., 2010).

Alternatively, it can be used to plot the change in performance or rate of technology improvement over time (Dosi, 1982; Sahal, 1985; Foster, 1986). Here it depicts progress as being slow in the early stages as the industry wrestles with fundamental uncertainties about the technology; being faster as the preceding technical obstacles are overcome; before finally slowing down again as the natural limits of the technology are approached. Despite its widespread use, empirical evidence has cast doubts over the validity of the performance vs. time S-curve suggesting instead that technological evolution is closer to a step-function in which distinct performance improvements occur after long periods of no improvement, rather than to a smooth S-curve (Sood and Tellis, 2005).

Other authors such as Lu and Marjot (2008) label the *y*-axis in the S-curve model with both diffusion and performance, and still others replace the passage of time on the *x*-axis with the amount of effort (funds) put into development (e.g. Foster, 1986), or with the expenditure of engineering effort more generally (Christensen, 1992, Chang and Baek, 2010; Nieto et al., 1998). Investment in the development of a technology (e.g. hours worked, budget allocated, researchers employed and so on) is argued to be the most appropriate *x*-ordinate as this has an influence on the time needed for technical performance to improve (Nieto et al., 1998). Whilst using time is claimed to be erroneous (e.g. Foster, 1986), in empirical investigations it has often been used as a substitute since the data necessary to establish total levels of investment is difficult to obtain (Nieto et al., 1998). Fig. 4 summarises the foregoing discussion and depicts typical forms of the S-curve.

Another S-curve approach monitors the attractiveness of a technology for investment, by plotting the evolution of patent applications as the *y*-ordinate (Andersen, 1999). Indeed the measurement of patent activity is well established within technology forecasting models (e.g. Chang et al., 2009, Tseng et al., 2011). Debackere et al. (2002) argue that this is preferable to the use of cumulative sales generated by all products enabled by the technology since it is an earlier indicator and is also easy to measure using objective data from patents databases.

Embracing the notion that the market appetite for technology improvement may not be insatiable, a further variation on the

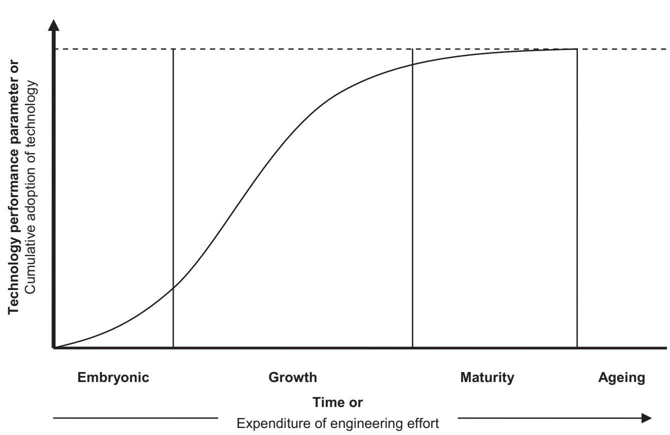

Fig. 4. Typical technology S-curve.
(Adapted from Cetindamar et al., 2010).

S-curve plots the willingness of customers to pay for the increased performance provided by the technology over time (Adner et al., 2004). Adner argues that this "*demand S-curve*" (Ibid: 26) and its position relative to the performance S-curve holds important implications for a firm, depending on whether the market demand or the technology performance flattens first. Thus, once technology performance has reached a minimum acceptable level, consumers base their choice on the relative price/performance of competing offers. However, as performance continues to improve, consumers may or may not place the same premium on further technology development as their demand curve matures. Adner works through these various scenarios at different points in the life cycle to show how they influence the way that a firm should interpret the "*different stages of a technology's maturity, the nature of competitive threats, and the incentives and scope for further innovation activities*" (Ibid: 29). Interestingly he does not attempt to delineate the stages or to label them. Moreover he argues that the notion of willingness-to-pay offers a new logic for understanding innovation incentives over the whole technology life cycle.

However plotted, S-curves reach saturation at maturity. At this point, a new disruptive technology may emerge to replace the old one and the cycle begins again (Cetindamar et al., 2010). In effect the technology has been substituted by emerging technology whose own S-curve has either overtaken the incumbent's performance levels (Adner et al., 2004) or has the potential to do so (Foster, 1986). There can, as a result, be an unsettling, even chaotic, period of discontinuity characterised by "*competing technologies, each with its own S-curve*" (Foster, 1986: 103). If the replacement technology has a higher performance than the old one, then the relationship between the S-curves is said to be disconnected but if it is lower, then it is connected (Chang and Baek, 2010). The resulting situation leads to technology progression characterised by multiple S-curves or technology cycles occurring over time.

Multiple life cycles feature elsewhere in the literature but do so with a different meaning and in a different context (e.g. Murmann and Frenken, 2006; Tushman and Rosenkopf, 1992; Tushman and Murmann, 1998). Interestingly, they herald a return to the product perspective with which we began this review. Whereas Chang and Baek's curves occur in chronological sequence within a single technology paradigm, Murmann and Frenken (2006) conceptualise nested hierarchies of technology cycles at a single point in time, as a snapshot, to model the various technologies involved in a specific (usually complex) product. In similar style to an engineering bill of materials, the complex artefact is organised in a series of levels of decreasing complexity, each one consisting of subsystems and components. Each item at each level in the hierarchy is subject to its own individual technology life cycle. On this basis, for all but the most simple products, it is impossible to envisage one single TLC that represents all technology progression which is relevant to a particular artefact, and we argue that, for this reason, the conceptualization of the technology life cycle should focus on the application of the technology rather than on any artefact or product in which it is used. Despite its different perspective on the TLC, the importance of the work on nested hierarchies of technology cycles for complex products is such that we return to it in our discussion after we consider the final body of literature relating to the TLC.

3.3. Alternative views of the TLC

For completeness of the review, we now turn to a number of other studies which do not fall neatly into the mainstream views discussed above. They all present versions of the TLC that reflect their primary focus, which is on the links between the TLC and management decision making. They include some that consider the managerial decisions encountered at different stages of the

TLC, and others that reflect the activities associated with managing technology throughout its life cycle.

Based on Utterback's model, Roberts and Liu (2001) present a 4-stage "*externally focused technology life cycle*" (Ibid: 34) which incorporates fluid, transitional, mature and discontinuities phases. They assert the need for managers to "*recognize which phase each of their products is in*" (Ibid: 26),[2] in order to determine the most suitable type of external partnership to facilitate speedy development, whether it be an alliance, a joint venture, arrangements involving licensing or equity investment, or a merger or acquisition. They argue that this choice is influenced by the pertaining phase of the TLC. As the technology evolves over its life cycle and competitive pressures vary, industry structure and critical success factors change, thereby requiring alternative acquisition choices to be made. The questions underpinning their work are how a company can decide which form of relationship to use, and when. Cetindamar et al. (2010) also note the changing role of collaboration during the TLC, arguing that as technology is developed to improve technical performance and/or product differentiation during the 'incubation' (introduction) and 'take-off' (growth) phases, alliances with external entities are more common than later on during maturity.

Unlike many practitioner-oriented studies in the technology management field where the emphasis is on the user-organisation, Ford and Ryan (1981) propose a technology life cycle as viewed from the perspective of the technology developer. Their model traces the evolution of a technology from the idea through development to exploitation by direct sale, in six stages comprising technology development, technology application, application launch, application growth, technology maturity and technology degradation. Arguing that different corporate (marketing) strategies apply at different stages, they seek to determine how an organisation which develops technology may best profit from it through appropriate marketing activity. The argument is made that understanding the stages of the TLC allows organisations to make more informed management decisions.

By contrast, rather than reflecting on the decisions facing an individual organisation during the TLC, Kim (2003) considers how an entire economy or society should manage the transition between technologies. To do this, he proposes a TLC that is similar to the PLC but with "*a more macro perspective*" (Ibid: 371). This includes introduction, rapid growth, maturing and decline stages.

A further approach to the definition of the TLC derives from work which considers the activities that are undertaken during technology development and use. In this context, the TLC stages have been defined as conception, design and manufacture, service and disposal (Bevilacqua et al., 2007). Others focus only on the life cycle associated with the use of technology. Foden and Berends (2010) present a framework which they argue aligns with the entire TLC ("*from concept to abandonment*" (Ibid: 33)), and includes identification and monitoring, selection and approval, development research, acquisition and adaptation, exploitation and review and protection. Elsewhere, the activities that form the TLC are articulated as "*feasibility*, *justification*, *requirements definition*, *engineering*, *system design*, *details design*, *test and pre-operation*, *implementation*, *operation*, *maintenance and post-implementation audit/evaluation*" (Irani and Love, 2000: 163). In both cases, since the life cycle stages are activities to be undertaken by the firm during the process of acquiring and using technology, the implicit unit of analysis is the firm that is implementing technology rather than the technology itself. In these conceptualizations which already exclude the process of technology development, neither the stage(s) after audit such as degradation and obsolescence are considered, nor are the activities that may be required at this stage such as disposal and replacement. While we have included a brief overview of these 'activities-based' studies for completeness, we argue that the use of this approach is not particularly helpful in reaching a discipline-independent conceptualization of the TLC, as it relates to how technology is managed through time rather than understanding the stages in its evolution. However, once the TLC is better understood, research that seeks to determine the activities associated with managing technology at the different stages in its life cycle would be of significant benefit to both developers and users of technology.

Table 2 summarises the review of the TLC literature by articulating the various stages that have been identified. It serves also to demonstrate the multiplicity of terminology used in the field.

The foregoing review brings together the concepts and vocabulary used by the various stakeholder disciplines. It illustrates the confusion that exists around the concept of the TLC and shows how the contributions of authors from multiple disciplines and with different perspectives create complexity. There is little doubt that the ideas underlying technological progression are complex. However, we have already seen how management action can, and should be, influenced by greater understanding of the issues and this can only be achieved by improved conceptual development. Our analysis of the literature, which follows, begins to address this need.

Table 2
Summary of stages in the TLC from different perspectives.

Stages in the TLC	Source
Macro view:	
Discontinuity, ferment, dominant design, incremental evolution	Anderson and Tushman (1990)
Fluid, transient, specific	Abernathy and Utterback (1978)
Fluid, transitional, specific	Utterback (1994)
S-curve:	
Introduction, growth, maturity, decline	Haupt et al. (2007: 388)
Incubation, take-off, maturity	Cetindamar et al. (2010: 201)
Invention, innovation, diffusion, growth and maturity	Cetindamar et al. (2010: 195)
Embryonic, growth, maturity and ageing	Cetindamar et al. (2010: 195)
Fluid, transitional, mature and discontinuities	Roberts and Liu (2001)
Bleeding edge, leading edge, maturity, decay	Lu and Marjot (2008)[a]
Alternative views:	
Fluid, transitional, mature and discontinuities	Roberts and Liu (2001)[b]
Introduction, rapid growth, maturing and decline	Kim (2003)
Technology development, technology application, application launch, application growth, technology maturity and technology degradation	Ford and Ryan (1981)
Feasibility, justification requirements definition, engineering, system design, details design, test and pre-operation, implementation, operation, maintenance and post-implementation audit/evaluation	Irani and Love (2000)
Conception, design and manufacture, service and disposal	Bevilacqua et al. (2007)
Identification and monitoring, selection and approval, development research, acquisition and adaptation, exploitation and review, protection	Foden and Berends (2010)

[a] Although Lu and Marjot (2008) comment that the TLC is different from the PLC, their TLC model is bell-shaped (and reminiscent of the PLC) rather than S-shaped.

[b] Roberts and Liu (2001) base their TLC on the S-curve but it is additionally included in the practitioner section of the table because – as indicated in the text – the primary focus of their work is on the management decisions faced during the TLC.

[2] Here again we see an example of imprecise terminology in relation to the TLC and products.

4. Discussion

It is possible to examine technology at several levels of analysis (Anderson and Tushman, 1990), and a key disconnect in the discourse relates to the granularity of analysis which different scholars have adopted (Murmann and Frenken, 2006). Central to the work of Abernathy and Utterback (1978), which underpins the macro view, is the notion that dominant designs emerge only once in the evolution of a product class and that these persist for as long as there are customers in the marketplace. By contrast, and reflecting greater granularity, Anderson and Tushman (1990) argue that the evolution of product classes is marked by recurring technological discontinuities, each followed by the emergence of a new dominant design. This represents what Murmann and Frenken (2006) term a second level of abstraction below the general operational principle, in which more specific criteria are used to distinguish between different designs within a particular approach. The level of granularity distinguishes between these influential schools of thought, as does the varying use of the term 'product class' (e.g. in Tushman and Rosenkopf, 1992).

Highlighting further the inconsistencies in the field, Foster (1986) notes how S-curves have been described for products (p. 96), processes (p. 96), technologies (p. 102) and technology generations (p. 124). He cites examples of S-curves being constructed for different types of phenomenon e.g. products (organic insecticides), performance (e.g. efficiency of electric light bulbs) and applications (e.g. travel). So, in addition to the existence of different levels of analysis, multiplicitous use of the S-curve contributes to the confusion.

In order to rationalise the differing views and approaches, we distinguish our work from previous contributions by taking technology as the unit of analysis rather than any product or artefact in which it may be used. This point of departure reflects how the value or worth of an artefact to society is based primarily on the functions that it performs, rather than on its structure (Baldwin and Clark, 2000). We conceptualise the TLC using three distinct entities—the technology application, paradigm and generation. With a core objective being to examine how the macro and S-curve perspectives are linked, we base our discussion around progression within and between these entities, considering also how progression may be plotted and to what extent it may be influenced by management action. In so-doing we suggest some ways to reconcile disconnects and inconsistencies in the literature. Finally, we consider how progression, when viewed from the perspective of a technology, links with the product focus associated with the PLC and ILC, and in the cases of simple and complex products. Whilst the discussion aims to extend understanding of the TLC and to begin to develop a consensus, given the wide-ranging debate from multiple disciplines and perspectives, we do not claim that our analysis is conclusive. Rather, we attempt to draw together the various views and to organise these in a way that creates a foundation on which future research may build. To summarise our analysis we propose a new conceptualization of the TLC which we present thereafter.

4.1. The TLC—applications, paradigms and generations

In this section we define the three core concepts that underpin the TLC and examine how they are linked. We illustrate the discussion by reference to technological developments for recording and storing music[3] , and we also refer, as appropriate, to other examples including the well-documented cases of cement and glass manufacture.

With technology as the unit of analysis, and reflecting the purpose or goal of using it, the highest level of conceptual abstraction is the application to which it is put. A similar concept describes the 'job' of a technology as being "*a fundamental problem a customer needs to resolve in a particular situation*" (Lichtenthaler, 2010: 431). With examples including 'for recording and storing music', and 'for producing glass', it is clear that the application of a technology is expressed using a verb. This is distinct from describing it using a noun that refers to a product or process in which it is instantiated, such as a compact disc or the float glass process.

- The application of a technology is described by the purpose for which it is used.

The nature of technological substitution for an application is such that, over time, alternative approaches emerge and decline. Beginning around the end of the 19th century analogue methods were used for recording and storing music, firstly onto a phonographic cylinder and subsequently onto a phonographic record (Daniel et al., 1999). In the 1930s the use of magnetic tape to store the analogue signal emerged as an alternative. Finally, in the 1970s, the compact disc was launched as an optical disc for the storage of digital data (Morton, 1999), and began the era of digital music storage which pertains today. It is similarly possible to break down technological progression for other applications to a number of key approaches. For glass making, four distinct eras have been identified beginning with the Lubbers cylinder blowing process, through the Colburn and continuous drawing processes to the float-glass process that is used today (Anderson and Tushman, 1990). Each of these approaches signified a discontinuous advance that revolutionized the manufacturing process in turn. Separate approaches have similarly been articulated for the manufacture of cement (Tushman and Rosenkopf, 1992). The distinct technological approaches that emerge for a particular application represent different technology paradigms, and reflect an increased level of granularity in the conceptualisation of the technology life cycle.

In general, whilst the beginning of one paradigm approximates to the end of a preceding one, there is rarely an instant in time when one replaces another. Similarly, although an emerging technology may take over as the dominant paradigm for a particular application, an earlier approach may continue into perpetuity in niche form (Foster, 1986). Thus, the motor car has not completely replaced the horse as a means of human transport although it has taken over as the dominant paradigm, and despite engine-powered ships replacing wind-powered vessels for the majority of maritime transport, some companies still continue successfully to make sailing craft for the leisure market. Paradigms have alternatively been described as "*individual technologies*" (Chang and Baek, 2010); "*operational principles*" (Murmann and Frenken, 2006); "*revolutionary technological advances*", "*modes*" or "*regimes*" (Tushman and Rosenkopf, 1992); and "*technologies*" or "*platforms*" (Sood and Tellis, 2005).

- A paradigm represents a particular technological approach that is used to achieve a target application. It is characterised by being based on "*scientific principles that are distinctly different to those of existing technologies*" (Sood and Tellis, 2005: 153).

At the final level of abstraction in modelling the TLC, we draw on the distinction made by Ford and Ryan (1981) between "*major*" and "*minor*" technologies. Having parallels to the comparison of a generic PLC with that of an individual brand, a major technology, "*developed by one company, may differ in a number of ways from the minor technologies or "brand" variations introduced later by others*" (Ibid: 121). A major technology reflects the paradigm, whilst minor technologies reflect the individual generations that evolve therein (Kim, 2003), and are indicative of the

[3] So as not to detract from our central focus we limit our technical discussion to the more significant and accessible elements of this application, and we do not in any way claim to provide a comprehensive historical account. Such accounts are available elsewhere—see Daniel et al. (1999) and Funk (2009).

developments that occur following a technological discontinuity. During the paradigm which used magnetic media for recording and storing music, alternative variations or "*second level designs*" (Murmann and Frenken, 2006) emerged. Initially these took the form of reel-to-reel systems, before progressing through stereo 8-track cartridge systems (1960s) to the compact cassette that was widely used from the 1970s to the 1990s (Funk, 2009).

The generations that emerge during the lifetime of a paradigm reflect the changing emphasis between product and process innovation as time passes, and exhibit gradually decreasing levels of product-related innovation. During the era of ferment, competition between rivals means that there are often several different versions of a new technology (Anderson and Tushman, 1990) and product innovation prevails. Once the dominant design is established, there is less emphasis on product development with the result that successive generations reflect only minor changes. For example, analysis of the history of cement manufacture shows that, for each of the three main paradigms (Edison long kiln, computerised kiln and suspension pre-heating), the number of new product-related designs was lower during the era of incremental change than it was during the era of ferment (Anderson and Tushman, 1990).

- A generation represents a particular form or variation of technological solution, but shares the underlying scientific principles of all other generations within the same paradigm.

Fig. 5 presents a summary of technological developments for the recording and storing of music, using the notions of application, paradigm and generation. Whilst highly simplified, it serves to demonstrate how these three entities are linked in a hierarchy of increasing granularity.

4.2. The TLC—modelling and reconciliation

This section discusses how technological progression may be described between and within the three core elements of the TLC described above. We examine how the macro and S-curve perspectives on technology progression are linked. We also consider how progression may be plotted, and to what extent it may be influenced by management action.

The technology used to achieve an application progresses over time, with transfer between paradigms or the process of "*technological substitution*" (Tushman and Murmann, 1998) occurring as a result of technological discontinuity. The evolution of technologies for the manufacture of cement and glass has been traced against time (Anderson and Tushman, 1990), and adopting a similarly temporal focus, Foster (1986: 160) indicates that "*it usually takes between five and fifteen years for a new technology to supplant an old one*". The speed of technological substitution is influenced by factors such as the relative economics of the rival technologies, pricing strategy, timing and customer characteristics, but not specifically by effort (Foster, 1986). Technological progression relating to a particular application (in which economic, technical, social, political and organisational factors all play a part) can therefore only be plotted with any degree of accuracy retrospectively against time, and is modelled chronologically. Other than by historical analogy, it is not predictable to any great degree; nor is it directly under the control of any individual organisation.

As regards the modelling of paradigms and generations, the classic macro perspective (e.g. Utterback, 1994) describes how a paradigm emerges at a discontinuity, takes in eras of ferment and incremental change, and ends when a new technology emerges. Although most agree on this description of progression, there are only some who model it using an S-curve (e.g. Sood and Tellis, 2005; Foster, 1986; Chang and Baek, 2010). These scholars argue that once a discontinuity is reached, a new S-curve begins for the emerging technology and exists until it is replaced by a new paradigm. Thus, in this view, each paradigm is modelled using a single S-curve. Whether or not the paradigm is modelled as a single S-curve or as a macro cycle incorporating eras of ferment and incremental change, the S-curve is frequently associated with progression within it. Where progression through the paradigm is itself represented as an S-curve (a high level construct), multiple S-curves exist at the next level down (Chang and Baek, 2010). In the "*large-scale S-curve, there are several overlapping regions representing the transition from one S-curve to the next one*" (Chang and Baek, 2010: 714). The paradigm is characterised by the occurrence of multiple S-curves, each reflecting a different generation.

Significantly, where the paradigm is itself modelled as an S-curve, time is generally used as the independent variable rather than effort. This S-curve paints a picture of history, depicting change during the lifetime of a paradigm in the same way that Tushman and Rosenkopf (1992) traced the time taken for the emergence of dominant designs for glass and cement manufacture. S-curves of this form are "*graphic histories of human efforts to solve problems*" (Foster, 1986: 96). By contrast, when the S-curve is plotted against effort, the implication is that by altering the effort put into a technology, an organisation, both individually and as part of a technology community, can influence progress. Additionally, with knowledge of the performance limits of a technology, and using effort as the independent variable, organisations can predict the onset of maturity and thereby recognise the need to switch to an alternative. "*Limits, if known, and known correctly, confer a degree of predictability on the S-curve that it would otherwise not have. And predictability is what makes the S-curve a useful concept*" (Foster, 1986: 66). The plot against effort has predictive utility that can be used to inform management action whereas that plotted against time is minimal (Foster, 1986). With this in mind, we can begin to examine the applicability of each in describing progress of technology generations within the two eras that comprise the paradigm.

During the era of ferment it is both the "*dimensions of merit*" (Tushman and Rosenkopf, 1992: 320) and the technical

Granularity ↓								
	Application	Technology for recording and storing music						
	Paradigm	Analog - phonographic		Analog – magnetic			Digital	
	Generation	Cylinder	Record	Reel-to-reel	8-track cartridge	Compact cassette	Compact disc	MP3
		Time →						

Fig. 5. Technological developments for the recording and storing of music.

performance of rival technologies that are unclear (ibid), i.e. the parameter of performance on which rivals will compete has not yet been decided. In the same way that the dominant design emerges from this era, so too does the key performance metric. Given this additional uncertainty, it seems most probable that during the era of ferment, the S-curve can be plotted against time and used retrospectively to trace the history of technological progress. The fact that dominant designs only emerge retrospectively (Tushman and Rosenkopf, 1992; Tushman and Murmann, 1998) serves to reinforce this view. That said, it is not the case that organisations cannot influence progress at all during the era: even though dominant designs emerge in retrospect, they are "*amenable to managerial action*" (Tushman and Murmann, 1998: 260). However, it is not technical logic in isolation that affects the emergence of a dominant design, but also the actions of individuals, organisations, and networks of organisations (Anderson and Tushman, 1990). To some extent the influence comes from firm level factors that can be manipulated by managers but also from environmental factors that moderate these (Suarez, 2004). Thus, whilst social, political and organisational dynamics all influence the selection of an industry standard and hence determine the end of the era of ferment (Cusumano et al., 1992; Rosenkopf and Tushman, 1998; Herrmann, 2005) there is still scope for some management action which will affect the outcome. This implies that an individual organisation may, to a limited extent, shape progression through the era of ferment.

During the era of incremental change, the situation is different. Tushman and Murmann (1998) note the increased emphasis on technical endeavour in this era such that "*deterministic, technology-driven processes… characterize eras of incremental change after dominant designs emerge*" whereas broader "*socio-political/institutional processes characterize eras of ferment*" (Ibid: 252). In the same vein Tushman and Rosenkopf argue that "*only during periods of incremental technical change does technical logic dominate non-technical logic in shaping technological progress*" (Ibid: 342). Thus, until the emergence of the dominant design, progress is determined more by socio-political factors and chance than by the direct effort of individual organisations. Once into the era of incremental change, organisations can influence progress either individually, or as part of a technology community, primarily by the input of engineering effort. By plotting against effort, the S-curve can be used in semi-predictive mode for the technology generations that develop after the dominant design has emerged.

The foregoing discussion has demonstrated that the S-curve may be plotted in different ways, at different levels and for different purposes. Firstly, it can be plotted retrospectively, in the form of the single large-scale S-curve against time, to represent progression through the paradigm. It can also be used to model technological progress within the paradigm but here, there are clear differences between the two eras. In the era of ferment the S-curve, plotted against time, can be used retrospectively to trace the history of technological progress. By contrast, in the era of incremental change, it may additionally be plotted against effort, where it can be used by organisations to predict the effects of altering investment in the development of a particular technology generation.

4.3. The TLC—links to product-based perspectives on technology progression

Having examined technological progress from the perspective of the technology, it is apposite to consider how this links with the product focus associated firstly with the PLC and ILC and thereafter, in the case of simple and complex products.

Despite inconsistent use of the term 'product class' by the TLC community, in the PLC literature it refers to a generic product, such as the motor car (Grantham, 1997). The product class PLC which retrospectively plots sales volume against time, reflects market demand for a class of product that has been enabled by a particular technology paradigm (e.g. motor cars enabled by automobile technology). Similarly, the ILC is a retrospective view of the number of firms entering an industry, where 'industry' is defined by the product class which it produces (motor cars) or the technology paradigm on which it is built (automobile technology). With this in mind, progression through a technology paradigm can be linked to the product class PLC and to the ILC, as follows. At the point of discontinuity, both sales volumes and the number of entrant firms are low. During the era of ferment when there are high levels of uncertainty, sales volumes are low and the number of entrant firms is high. As the emphasis changes, during the era of incremental change, to process innovation rather than product development, sales volumes are high but the number of entrant firms decreases. Finally, as growth slows, sales volumes decrease and the number of entrants declines further. At product decline, the industry which has established itself around the paradigm also declines. The technology is replaced by a new paradigm for which a new product class PLC and a new ILC ensue. In a similar way, but at a lower level, the life cycles of individual product forms or brands reflect the developments associated with individual technology generations. These forms of the PLC therefore occur within the technology paradigm in parallel with, but separate from, the progress of the technology itself.

Turning now to technological progression for the cases of simple and complex products, we draw on the typology of product types articulated by Tushman and Rosenkopf (1992), from which we summarise salient features in Table 3. Just as a technology is used for a particular application, and regardless of complexity, all products are designed to accomplish a particular purpose. The technological basis that underpins the product class to which they belong is a reflection of the pertaining technology paradigm. For non-assembled and simple assembled products, whilst the paradigm to which they belong remains active, technological progress is characterised by developments in materials and production processes (Tushman and Rosenkopf, 1992). As we saw earlier, for the application of making glass, technological progression is marked by the emergence of different paradigms (cylinder blowing, continuous drawing and float glass) each of which reflects a breakthrough process innovation. Whilst these developments inevitably impact on the specification of the product they produce, it is the application of making glass (i.e. the technology) that experiences these changes as it goes through its life cycle, and not the glass (i.e. the product) itself. The dimensions of merit on which developments are judged similarly refer to the achievements of the process, albeit that this is sometimes reflected in the associated product. For simple products, the dimensions of merit relate to aspects of both the product that is produced (quality, price) and to the process itself (efficiency) (Tushman and Rosenkopf, 1992).

The situation for complex products is more involved. Whether in the form of open or closed assembled systems they can be conceptualised using a nested hierarchical structure that results from the use of modularity in building up the design from constituent elements (Baldwin and Clark, 2000). The multi-level structure of complex artefacts typically incorporates subsystems that are designed to accomplish different goals within the parent product. Thus the passenger airplane is a complex artefact which has subsystems to accomplish goals such as propulsion, lifting, landing, and accommodating passengers (Tushman and Murmann, 1998). Complex products are further distinguished from simple ones by the need for linking and interface mechanisms to join the subsystems. Each subsystem and mechanism has its own unidimensional time path, technological history, and dimensions of

Table 3
Simple and complex product typology.
(Adapted from Tushman and Rosenkopf, 1992).

Product classification	Product type	Characteristics	Examples	Dimensions of merit
Simple	Non-assembled products	Having no separable components	Cement, glass	Simple, clearly defined and measured. e.g. quality, efficiency, price related
	Simple assembled products	Made up of distinct subsystems that are combined or fit together	Skis, containers, guns	
Complex: made up of separable subsystems and artefacts that each achieve different goals; distinguishable from simple products by the need for linking and interface mechanisms to join the component subsystems	Closed assembled systems	Having a distinct boundary, made up of separable subsystems and artefacts that interact with each other. Produced by a single organisation	Watch, automobile, CT scanner	Diverse and multiplicitous, reflective of the various different subsystems
	Open assembled systems	Having no boundaries, made up of distinct subsystems and artefacts that are linked through interface technologies. Delivered through a network of multiple organisations	Power, television system	Diverse and multiplicitous, reflective of the various different subsystems and interfaces

merit (Tushman and Rosenkopf, 1992) and is subject to its own individual technology life cycle incorporating the processes of variation, selection and retention (Murmann and Frenken, 2006). Considering the parent product as a whole therefore, technological progression is highly complex, not least because it involves diverse and multiplicitous dimensions of merit which reflect the performance of each of the various subsystems and interlinking mechanisms. By de-constructing a complex product to its constituent elements, and taking technology as the unit of analysis, it is possible to reflect the less complex circumstances of technological progression described above that pertains to simple products. By so-doing, the technological developments associated with subsystems within a complex product can be modelled using the entities of application, paradigm and generation.

Taking technology as the unit of analysis in considering technological progression gives a different perspective to that seen when the product forms the focal entity. The two approaches are not mutually exclusive, however. Rather, they are complementary as, by tracing the technology life cycle for individual applications that form part of the design of a product, a further analytic dimension is added.

5. Conceptualization of the technology life cycle

Our conceptualization of the technology life cycle summarises the key elements of the preceding discussion of the literature (see Fig. 6). Taking technology as the unit of analysis, and based on the twin dimensions of granularity and time, the model incorporates the three key entities of application, paradigm and generation. The application for a technology forms the highest level of abstraction, and is delivered over time by a number of different paradigms.

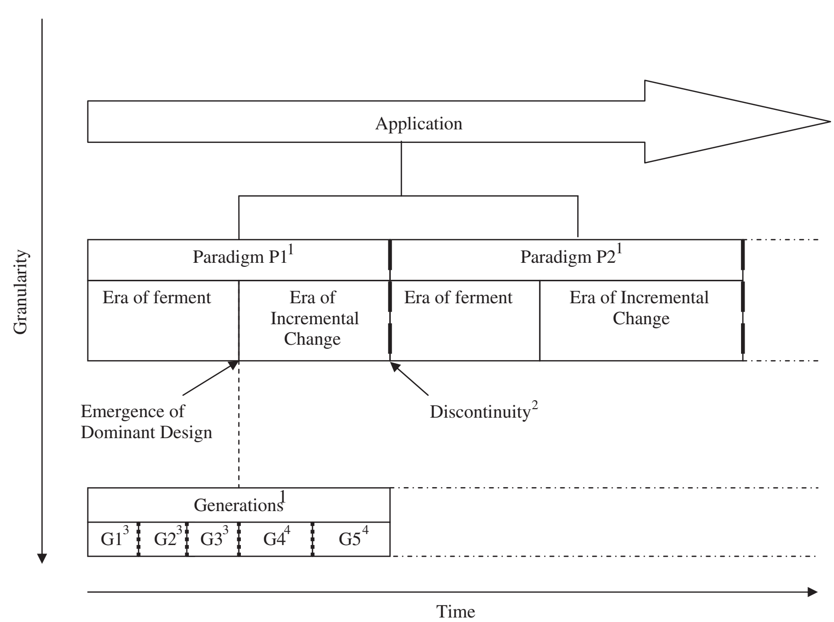

Fig. 6. A conceptualization of the technology life cycle incorporating application, paradigms and generations. *Key to footnotes*: 1. The figure presents the general case and does not apply to any particular situation: the number and durations of paradigms and generations, and the duration of the constituent eras that it portrays are illustrative only. 2. The paradigms are depicted separately; in reality they may be separate in time or they may overlap. 3. During the era of ferment the focus of development is predominantly on product innovation. 4. During the era of incremental change the focus of development is predominantly on process innovation and the search for spin off applications.

Within each paradigm, the model differentiates between the eras of ferment and incremental change which are separated by the emergence of a dominant design. Following one school of thought the S-curve, plotted against time, may be used to model the paradigm itself. Progression within the paradigm is characterised by a number of generations, typically with a greater focus on product development prior to the emergence of the dominant design and on process development and the search for spinoff applications thereafter. The S-curve is widely used to represent progress within the generations; during the era of ferment, it is most typically plotted against time but post dominant design, it may additionally be plotted against engineering effort. The generic conceptualization facilitates capture of situations in which paradigms and generations can be separate in time, or can overlap, and allows for the modelling of the complete technological development associated with a particular application.

This achieves the primary objective of the paper which was to extend current thinking and to establish conceptual consolidation of the technology life cycle. Mindful that "*technology management is a challenging topic*, *in terms of both theory and practice*," (Phaal et al., 2006: 336), we now turn to consider the implications of our work for the future. In doing so, we aim to address the needs of both academics (to extend knowledge) and organisations (to successfully exploit and manage technology for profit).

6. Implications for research and practice

The discussion has shown how scholars have wrestled over many years with the conceptualization of technology progression. In many cases, this has been undertaken in light of managerial action that may be relevant at different stages in the life cycle, but the field still lacks a solid framework on which to map and review these associated decisions. Our new conceptualization draws together the various perspectives on technology progression and offers the prospect of such a foundation.

Like any new theoretical approach, there is a need for further conceptual development. Our analysis of the literature indicates that unanswered questions remain which require investigation, for example, of the process by which dominant designs emerge, of the validity of the S-curve both through the paradigm and within its constituent eras, the differences in form and utility between S-curves plotted against time and effort, and the influence of more flexible process technology on the cycle. Furthermore, empirical investigation is necessary to validate the structure and content of the proposed model and to explore how it may be used to represent progression in applications involving the technologies associated with both simple and complex products. Determination of the factors that influence both the duration of elements (paradigms, constituent eras and generations) and the number of paradigms and generations that make up the cycle for different applications would be of value. It would additionally be of interest to investigate differences in these regards between situations where technology underpins products of varying complexity.

From a practitioner perspective, there are also some outstanding research questions. Individual firms may be involved at different stages in the life cycle of a technology depending on whether they are involved with its development (Ford and Ryan, 1981) or its acquisition and use (Chiesa et al., 2004; Lichtenthaler, 2006) or both (Popper and Buskirk, 1992). Each of these role-alternatives brings a different set of managerial challenges that future research should investigate. For all cases, a significant challenge is to develop a means of identifying the stage of the TLC and of predicting future progression. To achieve this, the most appropriate means of plotting technology progression in different situations needs to be established. Key questions remain over whether, and when, progression should be plotted against time or effort. Similarly, there is, as yet, no resolution of the most appropriate measure of progress in different situations, whether it be in terms of performance (Dosi, 1982; Sahal, 1985; Foster, 1986), adoption (Nieto et al., 1998; Cetindamar et al., 2010), attractiveness for investment represented by patent activity (Haupt et al., 2007; Nelson, 2009; Kleinknecht et al., 2002; Järvenpää et al., 2011), complex Technology Life Cycle indicators using a mix of bibliometric factors, patent indices and citations in the popular press (Watts and Porter, 1997) or something else.

Similarly, where the literature on technology decisions and on the links between these and organisational performance are inconclusive (e.g. Swink and Nair, 2007; Baines, 2004; Ranft and Lord, 2002), there is scope for future research. Finally, there is also a role for future research to help with the development of systematic managed processes that are based on discipline, deliberate action and calculated choices, and that are underpinned by sound theory (Chapman, 2006). There are frequent calls for the development of structured approaches to technology management whether it be in the context of specific activities such as external technology exploitation (Lichtenthaler, 2006), external technology integration (Stock and Tatikonda, 2008), or for technology management more generally (Dougherty, 2001; Gregory et al., 1996; Chiesa et al., 1996; Baines, 2004).

It is clear that the challenges associated with managing technology are multifarious. Strategic decisions associated with research and development, technology adoption choices, involvement in emerging standards, and straightforward business survival (Anderson and Tushman, 1990) all impact on more tactical areas such as investment (Haupt et al., 2007), resource allocation (Suarez, 2004), marketing (Ford and Ryan, 1981) and alliance/partnership formation (Roberts and Liu, 2001; Cetindamar et al., 2010; Rice and Galvin, 2006). The conceptual and managerial implications of the technology life cycle represent a fertile area for future research with the promise of benefit to both the academic and the practitioner communities.

7. Conclusions

Our paper has shown how the confusion over technology cycles that was highlighted by Tushman and Murmann in 1998 pertains today and continues to hinder understanding. With multiple stakeholder disciplines (such as history of technology, economics, and technology management), it is as important as ever to try and pin down the phenomenon of the technology life cycle. It is a beguiling concept that has, to date, defied universal clarification. In this paper we attempt to re-energise the debate by synthesising the views from relevant disciplines and by presenting a new conceptualization. Differing from previous work, our framework takes the application of technology as its primary unit of analysis rather than any product or artefact in which technology is used, and we model the TLC using the three related entities of application, paradigm and generation. We believe that this representation is useful in its synthesis of previously fragmented perspectives, and that it provides a common foundation on which future research may build.

Ultimately, the value of such work is to contribute to managerial decision making, and whilst the primary purpose of the paper has been to advance conceptual understanding of the technology life cycle, our aim was to do this in light of the research and managerial implications that arise. We have argued that neither the ILC nor the PLC possesses adequate predictive utility to be used by managers to determine the decisions which are necessary at any point in time. Whether the TLC is any more valuable to practitioners in this regard is yet to be determined but we assert that our model is a necessary pre-condition before such investigation can take place.

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