Paper to be presented at the

35th DRUID Celebration Conference 2013, Barcelona, Spain, June 17-19

"Future is Evolution" - Locus, Tempo and Mode of evolution in a technological system

Anke Piepenbrink
Azerbaijan Diplomatic Academy
Business School
apiepenbrink@ada.edu.az

Fariborz Damanpour
Rutgers
Management and Global Business
damanpour@business.rutgers.edu

Abstract

Models of technological change follow the biological model of evolution of variation, selection and retention, where technological discontinuities in the dominant design lead to punctuated equilibria (PE). We argue that the designed and coordinated technological evolution in a standard developing organization leads to fundamental differences between biological and technological evolution with three key implications: Change of the system occurs in the core of the system rather than in the periphery, the major mode of change is gradual change with shift of gears rather than punctuation and simultaneous innovation types. We test our model with data of Third Generation Partnership Project (3GPP), a standard developing organization for cellular telecommunications.

Jelcodes:M11,-

”FUTURE IS EVOLUTION” — LOCUS, TEMPO AND MODE OF EVOLUTION IN A TECHNOLOGICAL SYSTEM

Models of technological change follow the biological model of evolution of variation, selection and retention, where technological discontinuities in the dominant design lead to punctuated equilibria (PE). We argue that the designed and coordinated technological evolution in a standard developing organization leads to fundamental differences between biological and technological evolution with three key implications: Change of the system occurs in the core of the system rather than in the periphery, the major mode of change is gradual change with shift of gears rather than punctuation and simultaneous innovation types. We test our model with data of Third Generation Partnership Project (3GPP), a standard developing organization for cellular telecommunications.

Keywords: technological change, punctuated equilibrium, gradualism, innovation types

”Future is evolution not revolution”

Third Generation Partnership Project

INTRODUCTION

At the center of technological change models is the debate of punctuated equilibria (PE), long periods of stasis punctuated by sudden, discontinuous change, versus gradualism with continuous incremental change (Anderson & Tushman, 1990; Gersick, 1991; Tushman & Anderson, 1986). This study questions some of the fundamental assumptions in the transfer from evolutionary theory in biology with the key elements of variation, selection and retention to technological evolution. At the heart of the PE model is the core (Murmann & Frenken, 2006) or the deep structure (Gersick, 1991) of the system. It remains mainly untouched during the periods of stasis and its sudden change leads to punctuation, a jump in trait characteristics, followed by long periods of stagnation again based on the new deep structure.

A key distinction between technological and biological evolution is the engineered design of the former — change is not by chance, but by intent. This difference is well acknowledged by biologists — ”natural selection is not an engineer” (Hansen, 2003, 85) — as well as by evolutionary economists (Dosi, 1982). The notion that change mainly occurs in the periphery rather than the core of the system (Murmann & Frenken, 2006) is based on the assumption of uncoordinated and therefore detrimental change of service characteristics in case of core elements of the technological characteristics. The engineering process however has the reverse direction: it begins with the desire to improve the service characteristics and then changes the required components and interfaces based on the architectural knowledge of the system. Furthermore, modularity of the system contains impact largely within modules (Simon, 1962).

As a first consequence change in the core is possible and will happen in contrast to the assumption of change dominantly in the periphery. A second consequence, without its basic assumption of stable deep structure, the PE model of change is questioned and we posit a major mode of gradual change with varying pace, including stagnation and rapid change. Stagnation and PE are in this perspective more extreme points on a continuum rather than two distinct types of change as pointed out by Hunt (2008, page 361) with "How rapid is punctuation, and how sluggish is stasis?" However, it matters were the change occurs, and gradualism will be the major mode based on a changing core or dominant design driven by augmentation and substitution in the modular system (Baldwin & Clark, 2000). Substitution of a core element can lead to rapid change and the resulting mode of change will be punctuated gradualism rather than PE. The third consequence is the simultaneity of different types of innovation due to the continuously growing system In a typology of innovations based on the novelty of service and technological characteristics (Murmann & Frenken, 2006) all four types of innovations, including radical ones, will occur.

The major theoretical contribution to the literature of technological change is that in the engineered process of the evolution of a modular system the distinction between gradualism and PE is more a matter of degree and perspective, rather than a fundamental difference. The empirical contribution is the transfer of recently developed methods of determination of mode and tempo of change in paleontology to technological change. We use data of the Third Generation Partnership Project (3GPP), a standard developing organization (SDO) for the development of a cellular telecommunications system. The data cover the period of third generation (3G) and begin of the fourth generation (4G).

This study proceeds in the following: In the next section we provide the literature and development of hypothesis, then we describe the data and methods, present the result and end with a discussion.

LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

This study builds on the literature of evolutionary change that was largely borrowed from biology and Darwin's theory of evolution. We focus in particular on two important, interrelated aspects: the role of a designer in evolution and the contrast of gradualism versus PE. We first provide an overview of evolutionary models as the point of departure of this study. We posit that the key distinction between the evolution of biological and technological system is the purposeful design that leads to a different locus of change in the core, rather than the periphery of the system. This results in gradual rather than punctuated change and simultaneity of innovation types.

Evolutionary models

In this section we first turn to the literature of biological, then to technological evolution and finally the key distinctions between these two evolutionary models.

Biological evolution. Darwin's fundamental discovery was that of a ”creative, though unconscious” process resting on three elements: variation, selection and retention (Ayala, 2007). With the discovery of DNA, the genome, the full set of genes of an organism, is now established as retention mechanism. The random change in the genome or *genotype* leads to changes in the traits or *phenotype* of the species, on which natural selection acts and variations with better fit to the environment are retained. A species is defined as ”a population of interacting individuals, reproductively isolated from all other groups” (Eldredge & Gould, 1972, page 92). The key process is selection, rather than the variation. Darwin predicted gradual change of species and their characteristics or traits via a chain of incremental steps that accumulate over time, leading to the development of new species (Ayala, 2007; Eldredge & Gould, 1972; Hunt, 2010).

This perspective was challenged by Eldredge & Gould (1972), who suggested a model of species evolution characterized by stasis over long periods of time, interrupted by a rather rapid speciation event resulting in a new equilibrium. Eldredge & Gould coined the term *punctuated equilibria* for these change patterns. In contrast to Darwin, who suggested that new species arise via transition from the ancestor to the descendant, they posited a speciation event in such a way that a small part of the population becomes isolated in a distinct different geographic area and hence experience different selection criteria.

Technological evolution. The description of product or technology development in the evolutionary models follows also the pattern of variation, selection, and retention. The life cycle is triggered by a technological discontinuity, which can be either competence-destroying, leading to obsolescence in the competencies of the former technology or competence-enhancing, building on these competencies (Tushman & Anderson, 1986). The discontinuity leads to high innovation activities and competition among variations in product designs (the era of ferment). This period is characterized by high levels of technological and market uncertainties. There is strong competition between old and new technologies, and among designs along ”functional dimensions of merit that is, which technological characteristics are important and which design is superior in delivering performance (Clark, 1985). With the emergence of the dominant design the technological uncertainty is greatly reduced and the era of incremental change begins. In this era, the dominant design is refined by incremental innovations and common procedures and norms are developed within the industry. With a new technological discontinuity, the next cycle begins.

Tushman & Rosenkopf (1992) argued that the emergence of the dominant design is not only based on technological performance, but is primarily a sociopolitical process that spans a variety of non-technological factors within and between organizations. The sociopolitical influence ”is shaped by a process of compromise and accommodation between suppliers, vendors, customers and governments” (Tushman & Rosenkopf, 1992, page 322).

Levinthal (1998) used the PE framework to reconcile the two contrasting models of technological change — gradual and incremental on one hand (Dosi, 1988) and disruptive on the other hand (Tushman & Anderson, 1986). His main tenet was that the application of a technology in a new domain is a speciation event, which does not require necessarily large changes of technology itself. The new domain constitutes different selection criteria to those in the original domain and it may result in different resource abundance due to the size of the domain. The novelty of the environment will lead to a distinct evolution — a very similar argument as in the biological PE.

In summary we conclude that the study of an evolutionary model requires several definitions. First the ”species” and speciation events. This specifies the unit of analysis, the lineage, which is the concatenation of ancestors and descendants. Second, the deep structure, the choice of elements and governing rules that define the function of the system. This also implies the definition of the genotype-phenotype map (GPM), i.e. which change of rule or genes leads to which functional or characteristics change. This allows to map a variation into a phenotype that underlies the natural selection. Third, the definition of the environment and its selection criteria on the new phenotype.

Differences between biological and technological evolution. There is a fundamental distinction between the evolution of biological and (socio-)technical systems, with two important consequences. As Ayala (2007) put, Darwin’s theory is a theory of ”design without designer”, while socio-technological systems have. The first consequence is the socio-technological regime as defining boundary of technological species. In a socio-technical regime the full complexity of the interaction of social rules and technical feasibility is confounded in the PGM, the map of the change in rules and the resulting technical characteristics. We choose a simpler approach by focusing on the technological system, whose evolution is embedded in the innovation ecology of the SDO. We use the stable rules of the SDO to operationalize the evolution of the technological system. The second consequence is in the order of evolutionary steps because of the engineered process. In the technological system is first the decision on a desired functionality and then the change of the system based on detailed architectural knowledge. In the following sections we elaborate the locus, the mode and pace of change and finally the typology of innovations.

Locus of change: Core or periphery

Murmann & Frenken (2006) used the distinction between core and periphery to identify the dominant design by the choice of core components of a system. This requires the identification of the core-periphery structure. They followed the analogy in biology of the phenotype-genotype distinction, where the genotype contains all the hereditary information and the phenotype the traits or characteristics of the organism. The genotype is the part where variations occur that lead to changes in the phenotype, which underlies selection based on fit. The number of phenotypes affected by a given genotype is called *pleiotropy*. The variation of a high-pleiotropic genotype will affect many traits and it is very unlikely that the combined change of these many traits will overall improve the fitness of the new phenotype. This argument leads to the conclusion that retained variations mainly occur in low-pleiotropic genotypes. With the identification of the high-pleiotropy elements as core and low-pleiotropy as periphery, the locus of change in this line of argument takes mainly place in the periphery. The mapping of the genotype to phenotypes, the genotype-phenotype map (GPM) defines the architecture of the system (Murmann & Frenken, 2006; Wagner & Altenberg, 1996; Wagner & Zhang, 2011).

Similar concepts are known for technological systems. Saviotti & Metcalfe (1984) defined the mapping between the service (phenotype) and technical (genotype) characteristics of a technical system as the key element of a framework of technological change. They used this mapping to define different types of services and innovations. Services can be either main services, complementary services or externalities, where the complementary services support the main services and externalities are unwanted services. In systems engineering the *design matrix structure* or *dependency structure matrix* (DSM) define the system architecture between the elements of the system (Baldwin & Clark, 2000; MacCormack, Rusnak & Baldwin, 2006; Sharman & Yassine, 2004).

Though Murmann & Frenken (2006) acknowledged that a designer is manipulating the technical characteristics, they maintain the biological constraint that changes of high pleiotropic technical elements will most likely lead to unsuccessful phenotypes. We posit that the purposeful design based on an engineered design process has two important consequence: First, it reverses the dependence between genotype and phenotype and second, it allows the change of high-pleiotropic genotypes. In an engineered process the change of the technical characteristics or genotype do not occur randomly as in nature, but are guided by the desire or need to implement a new service.

At the beginning of 3GPP's development process is the approval of each innovation. After the approval of an innovation the development process proceeds in three sequenced stages: in stage 1 the services are identified and described – either existing or new services. In stage 2 the architectural description is provided, a step between service and technical description. It defines the parts of the systems that are affected by the new or extended services and how the functions and interfaces need to be changed. Stage 2 provides the roadmap for the implementation of the detailed changes in the technical characteristics in stage 3. In analogy to the phenotype and genotype we call this the *archotype* of the system. Each of these steps undergoes an approval process, which may lead to several revisions before approval or final rejection. In case a change is finally approved it will be integrated into an implementation specification, which is part of the genotype of the technological system. This staged process is applied to several innovations simultaneously. The transparency of all ongoing changes allows to detect inconsistencies and resolve them. For instance, each specification has a rapporteur, who among other tasks, has the responsibility to ”identify and resolve clashes” (3GPP specification 21.900). This process is very different to the unconscious, random variations in biology and it directs from the services (phenotypes) to the implementation (genotype) rather than the other direction. With the reverse direction of dependence in the change process, the argument that a random variation affecting many phenotypes is unlikely to result in better fit, is not any longer valid. The change can be designed in such a way that detrimental effects to traits not affected by the innovation, do not occur, while simultaneously the intended change is implemented. The engineered process enables changes in high-pleiotropy genotypes. Rather than a genotype-phenotype-map the flow of change and impact is defined by a phenotype-genotype-map (PGM). It requires a lot of coordination, which is the major rational for creation of a SDO and distinguishes the process to marketdriven evolution. It allows the change of the deep structure of the technological system.

On the other hand the high pleiotropy of a genotype makes it much more likely that this genotype will be needed to be changed in case of a service change. While this argument applies to a random choice of an existing service, the distinction of main and complementary services (3GPP actually calls them supplementary services) makes it even more likely. The first system release focuses on basic or main services and functions, which are implemented by the core elements of the system. The core elements are defined by the underlying technical principle that have not yet reached their full technical potential. In order to improve their performance from a basic level they need to be extended and this will occur in the core elements that develop along their technological trajectory to their full potential (Saviotti & Metcalfe, 1984). The argument that change occurs in high pleiotropy elements does not exclude other changes as augmentation, i.e. adding of new components and interfaces or change in the periphery, but it states that change in high pleiotropy elements happens and is dominant.

Hypothesis 1 *There is a positive association between the degree of pleiotropy of genotypes and their degree of change.*

Gradualism versus Punctuated Stasis

The stability of the deep structure and its sudden change is the key proposition of the PE paradigm. With the possible change in core elements based on the PGM the rigidity of the core structure is not any longer given and gradualism is a viable option. The technological characteristics of the core elements define the technological regime or dominant design (Murmann & Frenken, 2006; Saviotti & Metcalfe, 1984) and the technological trajectory is the improvement of the system to its full technological potential (Dosi, 1982; Saviotti & Metcalfe, 1984). The technological trajectory is an accumulation of many changes and follows a gradual development rather than stasis. A new set of technological characteristics define a new technological regime with its own gradually changing trajectory. The PE paradigm is replaced by a punctuated gradualism.

While the development of the new technical regime can be rather fast, it still takes some time. Gould suggested one to two percent of the whole life time as the span for the species creation based on a similar percentage of the gestation of human beings (Prindle, 2012). The fuzzyness of the definition of punctuation and the unclear distinction between the modes of stasis and punctuation was pointed out by Hunt (2008, page 361) "How rapid is punctuation, and how sluggish is stasis?". Hunt (2006) solved the issue by introducing mathematical models for stasis and gradual change and allowing for shifts in modes of models. Hunt (2008) introduced the so-called *sampled punctuation*, which is a rapid, though gradual change from one level of stasis to a new level, and contrasts it to the standard notion of PE with a sudden shift (*unsampled punctuation*). Figure 1 contrasts the unsampled punctuation (left side) with a sampled punctuation (right side), which is a gradual change from one level to another.

The distinction between the both types of punctuation depends on the trajectory itself as well as the granularity of measurement. A measurement on a coarser scale will not allow to detect the gradual transition. It is therefore important to have the appropriate time resolution in the empirical data based on the theoretically expected dynamical range. The sampled punctuation implies that on a sufficiently fine-grained resolution of time the distinction between punctuation and gradualism may become more a matter of different pace rather than different modes. Together with the previous argument, that PE in a coordinated SDO environment is replaced by a punctuated gradualism, the evolution will be dominated by gradual change with different pace or tempo over time. In the development process of the SDO the change is triggered by the phenotype change that leads to a phenotype change. The evolution of the system includes the evolution of the phenotypes, archotypes and the genotypes.

Hypothesis 2 *The evolution of the phenotype (a), archotype (b) and genotype (c) of the technological system is dominated by gradual change, allowing for different tempo over time.*

Typology of innovations

Murmann & Frenken (2006) introduced a classification of radical innovations based on the novelty of required knowledge and the improvement of system performance. Innovations can be either incremental with little new knowledge and minor performance improvements, radical, type 1, with little new knowledge, but large performance improvement, radical, type 2, with a large new knowledge base, but small performance improvements and finally radical square with large performance increase based on a new knowledge base.

The dimension of knowledge novelty is closely related to the distinction between exploitation and exploration in organizational learning (March, 1991). Exploitation is based on the current knowledge base and its refinement and is associated with rather low uncertainty. In contrast exploration targets the unknown, which inherently includes a high level of uncertainty. While March (1991) saw them as two opposite sides of a continuum and incompatible, Gupta, Smith & Shalley (2006) argued, that exploitation and exploration are orthogonal and differ in the type and amount of learning. Based on an extensive review of the literature on the different definitions of the concept, Li, Vanhaverbeke & Schoenmakers (2008) developed an unifying framework of exploitation and exploration, extending the distinction between type and amount of learning. They distinguished between two domains, where exploitation and exploration can occur: the *function domain* and the *knowledge distance domain*. In the ”function domain” learning crosses various functions along the value chain. In the ”knowledge distance domain” the distinction is between local and distant search or depth versus breadth. Following the exploitation-exploration framework in the alliance literature Lavie & Rosenkopf (2006) identified partnering downstream the value chain as exploitation of existing technological capabilities, while partnering upstream the value chain as exploration of new technologies. Similarly Danneels (2002) argued from an intra-firm perspective, that in product innovation technological competence and customer competence, the knowledge about customers need to be linked together. Depending on the novelty of these too competences to the firm, the innovation can be either exploitation, exploration or two intermediate cases: in the first case, existing technological knowledge is leveraged to extend the customer knowledge and in the second case knowledge about customers is used to develop new technological knowledge. The common theme of Murmann & Frenken’s and the organizational learning literature are two dimensions of knowledge, technological and customer-oriented, and the level of novelty. The differences in the level of these two knowledge dimensions lead to distinct types of products or innovation. The system performance can generally be described by the phenotype of the system and the technological knowledge by the genotype.

Though the major motivation for most firms to participate in the SDO is the influence of the standard, access to and sharing of knowledge is one of the benefits (Rosenkopf, Metiu & George, 2001). SDOs have the potential of simultaneous exploitation and exploration due to their diversity of different member organizations. Due to the complexity of the system new services are introduced as basic functionalities that are extended in future releases. These extensions will have low novelty of the phenotype and often exploit the existing genotype, but can also require new technological knowledge. In addition 3GPP allows an easy implementation of small technical enhancements via the CR process without the administrative overhead of the work item process for larger innovations.

The balance between exploitation and exploration are important for organizations' sustainable innovation performance: exploration allows for novelty, exploitation for stability and efficiency. Tushman & O'Reilly III (1996) coined the term ambidextry for the simultaneous balance between exploitation and exploration. An alternative way to achieve the balance is a sequenced approach as punctuated equilibria (Gupta et al., 2006). The system modularity and the hypothesized gradual change allow for simultaneity of exploitation and exploration. The separation does not occur via distinct organizations, but on the innovation project level with the four innovation types of figure 9 occuring simultaneously.

Hypothesis 3 *Four types of innovation, based on the novelty of phenotype and genotype, exist simultaneously.*

DATA AND METHODS

The data

3GPP is a SDO that consists of member organizations, either firms, research institutes, universities of government bodies that jointly develop a cellular telecommunications standard. The standard development occurs in so-called releases every year or second year. Each release consists of a full set of specifications that describe the technological system completely. For this study we use three data sets from 3GPP: the specifications, the change requests and the work item plan.

Specifications. The major data source are 3GPP's specifications. First we define the master list of all specifications. Then we use the references that specifications make to other specifications for the definition of the PGM and changes of specifications for the definition of mode and tempo. The specifications are the ultimate result of the standardization work, where the full set of specifications completely defines the technological system. Specifications are uniquely defined by their number and their evolution is tracked via the version. They can be grouped in service specifications (phenotype), technical realization (archotype) and detailed implementation specifications (genotype) based on their numbers and 3GPP's numbering scheme. This list of all instances of specifications defines the population of specifications for the analysis. This results in 27.595 entries of specification-version combinations for 1941 unique specifications. We downloaded the specifications to extract their references to other specifications.

Change requests. After a newly created specification reaches a completion level of about 80 percent it leaves the draft status and can only be changed via change requests (CR). The list of all CRs includes the specification, innovation (work item) and release it belongs to as well as a category and status. We keep only CRs that are finally approved, leading to change in specifications. In total 91.366 CRs are kept. The number of change requests per specification is the measure change of a specification.

Work items. The work item plan is used to define the innovations and the mapping of innovations to specifications. Related to the work items 3GPP provides a mapping table of work item identifiers and affected specifications, which allows the mapping to phenotype and genotype. Innovations can map either to one or more phenotypes.

Methods

In this section we describe the three major tasks to construct the variables to test the hypothesis: the identification of the core-periphery structure of the system, the measurement of change and the statistical description of the mode and tempo of change.

Core-periphery identification. There are several ways to define the core-periphery structure of the technological system. We choose the approach based on the PGM following

Murmann & Frenken (2006) with adaptations from the literature on DSM (MacCormack et al., 2006; Sharman & Yassine, 2004). The PGM is a two-mode network with phenotypes or services as one type of node and genotypes or implementation specification as the other type and a relationship that defines the ties. All service specifications define the phenotypes and the implementation specifications the genotypes.

The relationship between the service and technical implementation is the references in specifications, which we will call citations. Each specification contains a list of other specifications it relies on. The citing relationship is a directed relationship, where information flow is established from the cited specification to the citing one, similar to citations of academic papers. Citing specifications depend on cited ones. This is in particular important as it allows to prove the basic assumption of hypothesis 1, that the service is first defined and then the technical implementation follows. The normal citation flow is that phenotype specifications are cited by archotype specifications, which are then cited by genotype specifications. With the list of directed ties extracted from all specifications for each release we construct release specific directed PGM.

The first approach, which defines the default PGM, follows 3GPP's development from phenotype over archotype to genotype. We include all genotype specifications that either cite directly the phenotype or archotype that cites the phenotype specification. We call this *staged process* PGM. In the second approach we remove the restriction for the indirect citation via the archotype specification and allow for any indirect citation to the service specification. In all cases the resulting PGM satisfies the basic idea of coupling the service and technical characteristics of the system (Murmann & Frenken, 2006; Saviotti & Metcalfe, 1984). The distinction between core and periphery is based on the pleiotropy of implementation specifications. The pleiotropy of a genotype is identical to the degree centrality in the two-mode network, defined as the number of services it is citing.

Change of specifications. The change of specifications is measured as the number of CRs in a given release.

Construction of the lineage and trajectory. The lineage is”a continuous line of descent”, in the case of specifications the descent along different versions, either within a release or across releases. We construct the lineage in the following way: All versions of a specification are ordered along the month of creation. Within a release this orders specifications according their technical identifier. The transition from release n to release n+1 is handled in the following way: The last created specification in the previous release at the time of creation of the new release version is the ancestor. The lineage of a specification created in an early release and with many changes is presented by a by a lineage with several branches, where specifications still change in several releases. In order to define the trajectory, the part of the lineage where progress happens, we switch to the specifications of a new release as soon as they are created as this will include all changes in the new release as well as in previous ones. Furthermore we treat the number of accumulated CRs as trait of the specification. In order to cover the full standard, we aggregate the trajectories of single specifications to functional trajectories by adding up the CRs for each specification of this function. In a similar way the trajectory of the whole system is obtained by adding the trajectories of all functions. This allows to study the system at different levels.

Tempo and Mode. We follow the recently developed methods in paleontology (Hunt, 2006) to distinguish between different modes based on maximum likelihood models. Based on the best model we derive the parameters of change (Hunt, 2006, 2008). First we give an overview of three basic modes, random walk (unbiased and general) and stasis, and their statistical representation. Second we describe the procedure to select the best model based on the log likelihood and third we discuss the split of the lineage in sets of possible segments with differing mode and tempo along the trajectory.

The modelling is based on the lineage of species or entities whose traits or properties change over time. In the general random walk (GRW) model the ancestor species at the begin of the sequence has a given mean of the trait X_A of interest. After t discrete time steps the descendant at the end of the observed lineage has a trait mean of X_D with

$$X_D - X_A = \sum_{i=1}^{t} s_i \quad (1)$$

where s_i is the change at step i. The s_i are random variables drawn from a probability distribution with a mean μ_{step} and standard deviation σ_{step}. With the assumption of independent steps s_i and a sufficiently large number of discrete steps the central limit theorem applies and the expected difference between descendant and ancestor is normally distributed with a mean of μ and a standard deviation of σ. This allows to maximize the log likelihood of the observed trait differences which will result in the estimates of μ_{step} and σ_{step}. In the general random walk model the mean μ is different from zero, while in the unbiased random walk (URW) model the mean μ equals zero. This implies, that the GRW model has two parameters (mean and standard deviation of the steps), while the URW requires only one parameter, the standard deviation of the steps.

While stasis appears intuitively clear as a model of stagnation and no change, it is not uniquely defined. Hunt (2006) adopted an approach with the underlying assumption of an optimal trait level θ with some allowed variation about this level, however without any net change in the trait level. The trait means are normally distributed with the mean of the optimal trait level θ and variance ω. It is a model of the trait values rather than the steps of change. As a consequence the difference to the random walk model is that the expected mean of the steps is not constant, but varies with the traits of the ancestors. As the trait level is assumed to be constant, a level larger than θ will lead to negative steps and vice versa. The maximization of the log likelihood model of the stasis model defines the optimal trait level θ and the variance ω.

For each of the three models the log likelihood is maximized. The best model is selected based on a modified Akaike information criterion AIC with

$$AIC = -2l + 2K, \qquad AIC_c = AIC + (2K[K+1])/(N-K-1)\,(2)$$

where l is the log likelihood, K the number of free parameters. The AIC penalizes for additional parameters and favors the more parsimonious model, which gives preference to the URW in case of equal log likelihood. The modified AIC_c is a better criterion than the AIC in case the number of observations N is less than approximately 40 times the number of parameters

$$AIC_c = AIC + (2K[K+1])/(N-K-1)\,(3)$$

The model with the lowest AIC_c is chosen as the best model of change.

The procedure introduced so far allows to choose the best model for the whole lineage or trajectory. However, a key element of hypothesis 2 is, that the mode and tempo of change varies in the development process. In order to account for this, the time period of the trajectory is cut in up to $n_{segment}$ segments with a minimum number of observations $n_{minimum}$ in each segment. For each possible combination of segments the three models are calculated and the best model combination determined. For instance in case of a combination of five segments we calculate for each segment the three models and choose as best the one with the lowest AIC_c. The overall best model for the segment combination is the combination of the best models for each segment. The AIC_c is the sum of the single AIC_cs. The model over all possible segment combination with the lowest AIC_c is the overall best model. This procedure allows for different modes and tempo in each of the segment. The split into segment can occur in two ways: either allowing for overlap of segments or clearly separating them. The non-overlapping segments allow for punctuated change with jumps between levels. The model of punctuated equilibrium with stasis over a period, sudden change and stasis on a different level is in this approach modelled by two non-overlapping segments with two different stasis models, varying in the trait level θ and ω. In contrast, gradual change will result in GRW models. Two parameter choices enter into the modelling: the minimum number of observations per segment $n_{minimum}$ and the number of segments. Hunt (2006) reported that models with five or more observations work rather well. In order to keep the computational effort tractable and yet have different segments, we choose $n_{minimum}$ to be six and a maximum of five segments.

There is an important difference to the approach in paleontology, that leads to an conceptual and an empirical difference. Paleontologists model the traits of species as e.g. the beak length or beak shape, while we model the accumulated change measured in CRs, which is a measure of individual changes in the specification, not a direct property of the technological system. The underlying assumption is, that the change of system characteristics are proportional to the number of CRs. The advantage is that it applies to all specifications and series (in the aggregation) and number of CRs are comparable across specifications. The species we are modeling is either on the system or function level.

Innovation typology. Each innovation consists of one or more work items that can be mapped to phenotype and genotype specifications. From the master specification data set we infer whether the specification is new or already existing. Based on the number of total pheno- and genotype specifications and new ones the number of innovations in each quadrant can be conferred. The analysis is performed on release level.

RESULTS

We used the statistical package R, version 14.1, to perform the analysis. The package *igraph* (Csardi & Nepusz, 2006) was used to construct the directed networks and the PGMs based on neighborhoods in the network, the package *bipartite* (Dormann, Gruber & Fruend, 2008) for the degree calculation and plots of the incidence matrices. The package *paleoTS* (Hunt, 2006) was used for the evolutionary models for the specifications.

The PGM and hypothesis 1

Hypothesis 1 states that there is a positive association between the degree of pleiotropy of a design specification and its change.

———————————— add table 1 about here ————————————

Table 1 shows the correlation between the degree of pleiotropy and change in the specifications for Release 97 to Release 10 for three different PGMs as described above. The change is measured by the count of all approved CRs. The correlations for each PGM and for each release are positive. With the exception of Release 97 the correlations are significant. There is a growing trend from Release 97 to Release 10 across all three PGMs with a dip in Release 8. While the values differ, the level of 0.15 to 0.3 or even higher applies to most releases (earlier releases are not included due to small number of genotypes). Overall we conclude that hypothesis is confirmed with some caveats for early releases, which may be due to data issues rather than lack of correlation. While the correlation is positive and in many cases significant, the median value in the range of 0.2 to 0.3 also suggests that there may be high pleiotropy specifications with little change and/or low pleiotropy specifications with high change.

Hypothesis 2: Mode and Tempo

Hypothesis 2 postulates that gradualism is the dominant mode of change with changing pace over time for phenotypes, archotypes and genotypes. GRW models are associated with gradualism, while URW and stasis are associated with stagnation. We look first at change at the system level from the beginning of 2G to the evolution of 4G with Release 8, then on functional areas that define pheno, archo- and genotypes from the period of 3G and 4G development. 2G is excluded as many of its specifications have a rather short period, which makes the modeling unstable. In the following figures the trajectories for the full system as well as different functional areas are shown with the number of accumulated change requests (CRs) on the y axis. Blue dots indicate unbiased random walk with step length of zero, red points general random walk and black points stasis. For each segment the type of model and parameters are given. The parameters for random walk models are length and standard deviation of steps, for stasis model the optimal levels and standard deviation of steps.

—————————————— add figure 2, 3, 4, 5 about here ——————————————

Figure 2 shows the trajectory of the whole system. The system trajectory shows four distinct periods of change. With the exception of the first two years that are characterized by unbiased random walk, the evolution is characterized by general random walk with varying step length and standard variation. The transition from 2G to 3G is not a punctuated change, but a shift in gears with an increase of the step length in the random walk model by an order of magnitude. While this indicates a shift in the evolution dynamics, it is not a short-term sudden change, but prevails during the 3G evolution. With the advent of 4G the dynamics is increased again, with an increase in step length by nearly a factor of two. While the system trajectory is very smooth with increasing tempo of evolution from 2G to 4G, different parts of the system can show different patterns of change. In March 2012 the system trajectory had accumulated 67.343 CRs. The 2G evolution accumulated 4033, the 3G and 4G evolution, excluding the GSM part, accumulated 55.023 CRs and the GSM part within the 3G period 8297 CRs. Figure 3 shows the trajectory of all phenotype specifications with five different GRW models. Overall the change is very low with values between six and fourteen CRs per month. The phenotypes show greatest change after the introduction of 3G and then slows down. The shift to 4G is characterized by an increasing variance in step length, rather than increase of step length. With less than 1500 CRs the phenotype change contributes 2.5 percent of the 3G changes. Figure 4 shows the trajectory of archotype specifications. Again gradualism is the dominant mode with a slowing down in tempo for later 3G release and an increase of approximately a factor of four prior to the first 4G release (Release 8). After two years the evolution slows down to less than half the previous level. The accumulated number of CRs of 6811 is 12.4 percent of the system trajectory, emphasizing the importance of the archotype. Figure 5 shows the trajectory of the radio subsystem. The largest change rate was during the early period of 3G with a slow down during later releases and slight increase previous and during the introduction of 4G. The highest pace at the beginning reflects the introduction of a new radio network with 3G. This trajectory lacks the strong increase of pace with 4G, because a new specification series for 4G radio network was created. Its development shows the ongoing change within 3G even after the introduction of 4G. With 11.504 accumulated CRs, 21 percent of the 3G trajectory, the radio network is the largest single functionality within the system and it still surpasses the new radio network by 40 percent in number of accumulated CRs on the trajectory. Figure 6 shows the trajectory of the core subsystem. Similarly than the trajectory of the radio subsystem it shows a steady increase of pace during the 3G period and increase of tempo by a factor of approximately 2.5 prior to the first 4G release and slowing down again to the previous level after three years. With 6377 accumulated CRs this trajectory contributes 11.6 percent to the 3G trajectory.

————————————— add figure 7, 8 about here —————————————

Furthermore the tempo varies along the trajectories with the largest increase in the period prior to the first 4G release, though rate change by a factor of approximately two occurs also during the 3G period. Figure 7 shows the ratio of mean path lengths of the new over the last period. The size of the dot indicates that size of the trajectory. The largest change of a major series is the archotype change with an increase by a factor of four.

The dominance of the GRW model does not yet allow the conclusion whether there are punctuations, i.e. jumps between the models. The rational is to compare the jump, the difference between the level of the last data point of the previous model and the first data point of the new model, with steps of the model with higher dynamics. First we substract from the mean jump (the total jump divided by the number of months between the models) the mean path length of the model and then divide by the standard deviation of the model path length. While there is no clear definition of what constitutes a punctuation, often an order of magnitude is used (Anderson & Tushman, 1990). Figure 8 shows the distribution of jumps expressed in terms of the standard deviation of the more dynamic model. All are below ten and even a more conservative approach of two standard deviations will lead to smooth transitions between models in most cases. Table 8 shows the jumps with more than two standard deviations. Jumps occur through the whole period with the largest values either at the early 3G or 4G periods. We conclude that hypothesis 2 is supported with gradual change the dominant mode of change for all three types of specifications.

Innovation typology

Figure 10 presents the empirical innovation types. The distinction between low and high in the typology is drawn by the mean value for new phenotype and genotype specifications respectively. The size of each data point indicates the total number of specifications it impacts. On the left side all new specifcations are considered, independent on the existence of an ancestor specification in 2G, while on the right side only truly new specifciations without ancestors are considered.

————————————— add figure 10 about here —————————————

All four types are populated. A couple of innovations impact a rather high number of new services, however when the ancestry is taken into account the number is reduced. This implies that these innovations impact several 2G services. For the typology we use the truly new specifications.

The quadrant of new phenotype/new phenotype contains several innovations. The innovation with three new services is the introduction of the new radio network with 3G. It impacts three new, general service specifications: *Service aspects* (22.101), *Services and service capabilities*, and *Service aspects, charging and billing* (22.115). This is an innovation that is regarded in the literature as radical (Ansari & Garud, 2009). The two major innovations for 4G are in the radio and core network. The core network innovation has one new service

(*Service requirements for Evolved Packet Service*) and 32 new implementation specifications (*3GPP Architecture Evolution Specification - Evolved Packet System*). The radio innovation in 4G has no new service, but 69 new implementation specifications (*Long Term Evolution - Evolved Packet System RAN part (LTE)*). It is an example of a radical 2 innovation that enhances existing services with new technology.

————————————— add table 4 about here —————————————

While figure 10 shows that all four types occured during 3G and 4G, it does not yet prove simultaneity. In table 4 the number of innovation types for each release is presented. While Release 99, 5,6,7, and 8 have all innovation types, Release 4 has only incremental innovations,

Release 9 lacks radical 2 innovations and Release 10 radical 2 and radical square. With this hypothesis 3 is partially confirmed. However, table 4 also reveals a data issue: the included innovations are much less than those developed during this period. For many innovations no phenotype specification information is provided. While this suggests a conservative test of hypothesis it also raises questions regarding the distinction of quadrants based on the mean. While the above discussed innovations and their classification makes sense, results need to be interpreted with care. In particular no conclusions can be drawn regarding the number of innovations for each type.

DISCUSSION

The literature of technological change, either as life cycle models or technological trajectories, follows a paradigm of revolutionary change based on punctuated equilibria with a stable core or deep structure (dominant design) underlying the stagnation and its change the sudden shifts or punctuation. The key thrust of this study is that the engineered process in a SDO with a modular system is largely different to biological processes, on which the PE paradigm is built upon. The designed evolution in the system's core structure leads to gradual change with varying tempo. The distinction between revolution and evolution in such a regime is more a matter of degree rather than fundamental shift. The fine-grained data of the development process of the standard together with recently developed methods of modelling the evolutionary allow the determination of mode and tempo of the trajectory.

Change process

The development process in the SDO differs from the biological-oriented process by the direction of causality between genotype and phenotype. In the SDO the definition of new service characteristics start the change, and the genotype specifications and their relationship are identified in an archotype and finally the genotype specifications are changed. This also occurs at product development in firms and for systems with low complexity via the coordination by a hub firm or platform leaders (Gawer & Cusumano, 2008). However with increasing complexity one firm may not be able to perform this task as it requires sufficient knowledge to define the detailed archotype of the whole system. Mondragon, Mondragon, Miller & Mondragon (2009) described this shift in the automotive industry, where the high complexity of electric and electronic architecture lead to the formation of AUTomotive Open System ARchitecture (AUTOSAR), a development partnership of car manufacturers, suppliers and firms from the semiconductor and software industry. The fundamental distinction between an ecology lead by a platform leader and a SDO or innovation partnership is the broader base of involved firms in the architectural definition. It leads to reduction of uncertainty with the combination of technological and market knowledge that shapes a common understanding of the development direction. It also allows to integrate a broader range of knowledge from the whole innovation ecology. Consensus-driven decision making, the approval process for service, architecture and technical changes, and transparency about all ongoing changes provide the routines to let a SDO act as a single designer.

The species — the unit of analysis. In biology a species is defined as a group of interacting individuals that are isolated regarding their retention mechanism. We choose as species the trajectory of the technical system, which is a concatenation of several releases of the system along the functional change and study the dynamics of phenotype, archotype and genotype. Each release segment can be seen as a distinct species as the functional change acts only on this release. However, there are three important caveats: First, some innovations and their functional change refers to 2G and 3G, both covered in the same specification. Hence, there is a retention connection between 2G and 3G and they are not independent in their development. Second, while functionally an old release migrates into a new one and results in the studied trajectory, it still coexists for a long period with the new release. This behavior is different to the gradual speciation in biology where a large part of the ancestor population transforms. Also in a broader scope independence between different species or trajectories will be given only approximately at best.

Innovation typology and ambidexterity

The innovation typology is based on new phenotype and genotype specifications, where new genotype specifications are largely due to augmentation of the system by new system components. Despite a reduced innovation set there is some evidence that for most releases all four type of innovations exist, underscoring the ambidexterity of 3GPP.

The simultaneity of innovation types identifies 3GPP as an ambidextrous organization with exploitation and exploration at the same time, in both dimensions, technical and service-oriented. The exploration on the technical level can be the extension, substitution or augmentation on the level of a subsystem. The SDO as open system with influx of resources from outside by the participating member organization alleviates the resource constraint in the balance of exploitation and exploration. Furthermore the openness leads to a large heterogeneity of knowledge resulting in a broadening of the knowledge base within the SDO, even when member organizations perform rather local search The separation between exploration and exploitation occurs on project level of single innovations, where however in most cases exploitation, the building on existing services and knowledge occurs in parallel with the creation of new services and knowledge. This implies that contributing firms to an exploratory innovation do not necessarily perform an exploratory task — they can contribute on the exploitative part. The creation of new specifications is a joint effort of member organizations, where proposals are presented, discussed and refined based on other proposals. However, the detailed process goes beyond the scope of this study, which is empirical built on the CR process.

Limitations and future research

This study has several limitations. First, the study of change is based on the CR process, which only covers change after specifications reach a certain maturity. It does not cover the creation of new specifications. Second, while the system trajectory is studied from 2G to 4G, the analysis of phenotype, archotype and genotype is restricted to the period of 3G and 4G development. Third, the functional areas of genotype are rather broadly defined and do not allow the resolution on component and interface level of the system below the distinction of first level subsystems as core and radio network and terminal equipment. Fourth, while the measurement of change based on CRs is close to the monitoring of the change process within 3GPP, it is only an indirect measure of system characteristics. Fifth, the lack of identification of phenotypes for all innovations weakens the test of the simultaneity of innovation types and is more an indication rather than a rigorous test.

The findings of this study and above mentioned limitations points to several promising avenues for future research. Though 3GPP is identified as ambidextrous organization, the antecedents and process remain largely descriptive. While ambidexterity is normally applied to a single firm, the SDO is a community of diverse organizations. This raises questions whether the concept, antecedents, process and outcome are still the same as within firms. The study of the process of creation of new specification and the interplay of the diverse input by various organizations can help to understand the exploration within SDOs. While it is acknowledged that the balance of exploitation and exploration is crucial for the performance of firms, the question arises whether this is also true for SDOs and if so, what defines the performance of SDOs? This questions becomes increasingly important with the pervasiveness of cellular telecommunications and ICT in general and emerging SDOs in industries traditionally void of them. 3GPP and its rival SDO, 3GPP2, can serve as a natural experiment with a comparison in the same industry.

References

Anderson, P. & Tushman, M. L. (1990). Technological discontinuities and dominant designs: A cyclical model of technological change. *Administrative Science Quarterly*, *35*(4), 604– 633.

Ansari, S. & Garud, R. (2009). Inter-generational transitions in socio-technical systems: The case of mobile communications. *Research Policy*, *38*(2), 382–392.

Ayala, F. J. (2007). Darwin's greatest discovery: Design without designer. *Proceedings of the National Academy of Sciences of the United States of America*, *104*, 8567–8573.

Baldwin, C. Y. & Clark, K. B. (2000). *Design rules*. Cambridge, Ma: MIT Press.

Clark, K. B. (1985). The interaction of design hierarchies and market concepts in technological evolution. *Research Policy*, *14*(5), 235–251.

Csardi, G. & Nepusz, T. (2006). The igraph software package for complex network research. *InterJournal*, *Complex Systems*, 1695–1704.

Danneels, E. (2002). The dynamics of product innovation and firm competences. *Strategic Management Journal*, *23*(12), 1095 – 1121.

Dormann, C. F., Gruber, B., & Fruend, J. (2008). Introducing the bipartite package: Analysing ecological networks. *R News*, *8*(2), 8–11.

Dosi, G. (1982). Technological paradigms and technological trajectories : A suggested interpretation of the determinants and directions of technical change. *Research Policy*, *11*(3), 147 – 162.

Dosi, G. (1988). Sources, procedures, and microeconomic effects of innovation. *Journal of Economic Literature*, *26*(3), 1120–1171.

Eldredge, N. & Gould, S. (1972). *Models in paleobiology*, chapter Punctuated equilibria: an alternative to phyletic gradualism, (pp. 82–115). Freeman, Cooper & Co, San Francisco.

Gawer, A. & Cusumano, M. (2008). How companies become platform leaders. *MIT Sloan management Review*, *49*(Winter 2), 28 – 35.

Gersick, C. J. G. (1991). Revolutionary change theories: A multilevel exploration of the punctuated equilibrium paradigm. *Academy of Management Review*, *16*(1), 10 – 36.

Gupta, A. K., Smith, K. G., & Shalley, C. E. (2006). The interplay between exploration and exploitation. *Academy of Management Journal*, *49*(4), 693 – 706.

Hansen, T. F. (2003). Is modularity necessary for evolvability?: Remarks on the relationship between pleiotropy and evolvability. *Biosystems*, *69*(2/3), 83–94.

Hunt, G. (2006). Fitting and comparing models of phyletic evolution: random walks and beyond. *Paleobiology*, *32*(4), 578–601.

Hunt, G. (2008). Gradual or pulsed evolution:when should punctuational explanations be preferred? *Paleobiology*, *34*(3), 360–377.

Hunt, G. (2010). Evolution in fossil lineages: Paleontology and the origin of species. *American Naturalist*, S61 – S76.

Lavie, D. & Rosenkopf, L. (2006). Balancing exploration and exploitation in alliance formation. *Academy of Management Journal*, *49*(4), 797 – 818.

Levinthal, D. A. (1998). The slow pace of rapid technological change: Gradualism and punctuation in technological change. *Industrial & Corporate Change*, *7*(2), 217 – 247.

Li, Y., Vanhaverbeke, W., & Schoenmakers, W. (2008). Exploration and exploitation in innovation: Reframing the interpretation. *Creativity & Innovation Management*, *17*(2), 107–126.

MacCormack, A., Rusnak, J., & Baldwin, C. Y. (2006). Exploring the structure of complex software designs: An empirical study of open source and proprietary code. *Management Science*, *52*(7), 1015–1030.

March, J. G. (1991). Exploration and exploitation in organizational learning. *Organization Science*, *2*(1), 71 – 87.

Mondragon, C. C., Mondragon, A. C., Miller, R., & Mondragon, E. C. (2009). Managing technology for highly complex critical modular systems: The case of automotive by-wire systems. *International Journal of Production Economics*, *118*(2), 473 – 485.

Murmann, J. P. & Frenken, K. (2006). Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. *Research Policy*, *35*(7), 925–952.

Prindle, D. F. (2012). Importing concepts from biology into political science: The case of punctuated equilibrium. *Policy Studies Journal*, *40*(1), 21 – 44.

Rosenkopf, L., Metiu, A., & George, V. P. (2001). From the bottom up? technical committee activity and alliance formation. *Administrative Science Quarterly*, *46*(4), 748–772.

Saviotti, P. & Metcalfe, J. (1984). A theoretical approach to the construction of technological output indicators. *Research Policy*, *13*(3), 141 – 151.

Sharman, D. M. & Yassine, A. A. (2004). Characterizing complex product architectures. *Systems Engineering*, *7*(1), 35–60.

Simon, H. (1962). The architecture of complexity: Hierarchic systems. *Proceedings of the American Philosophical Society*, *106*, 467–482.

Tushman, M. L. & Anderson, P. (1986). Technological discontinuities and organizational environments. *Administrative Science Quarterly*, *31*(3), 439–465.

Tushman, M. L. & O'Reilly III, C. A. (1996). Ambidextrous organizations: Managing evolutionary and revolutionary change. *Calif.Manage.Rev.*, *38*(4), 8–30.

Tushman, M. L. & Rosenkopf, L. (1992). Organizational determinants of technological change: toward a sociology of technological evolution. *Research in Organizational Behavior*, *14*, 311–347.

Wagner, G. P. & Altenberg, L. (1996). Perspective: Complex adaptations and the evolution of evolvability. *Evolution*, *50*(3), 967–976.

Wagner, G. P. & Zhang, J. (2011). The pleiotropic structure of the genotype-phenotype map: the evolvability of complex organisms. *Nature Reviews Genetics*, *12*(3), 204 – 213.

	Staged PGM	DSM: all stages	DSM: only stage 3
Release 97	0.071	0.107	0.068
Release 98	0.255*	0.192**	0.185*
Release 99	0.287**	0.152**	0.198**
Release 4	0.274**	0.141**	0.164*
Release 5	0.244**	0.154**	0.183**
Release 6	0.399***	0.207***	0.275***
Release 7	0.402***	0.206***	0.285***
Release 8	0.284***	0.138***	0.166***
Release 9	0.413***	0.33***	0.411***
Release 10	0.453***	0.261***	0.32***

Table 1: Correlation between pleiotropy and counts of all change requests with three different PGMs.

	incremental	radical 1	radical 2	radical square
R99	7	2	4	8
Rel-4	8	0	0	0
Rel-5	5	0	4	1
Rel-6	3	3	7	5
Rel-7	11	3	1	1
Rel-8	5	2	9	2
Rel-9	7	1	0	2
Rel-10	6	1	1	0

Table 2: Typology of innovations based on the percentage of new services and new implementations for all 3G releases

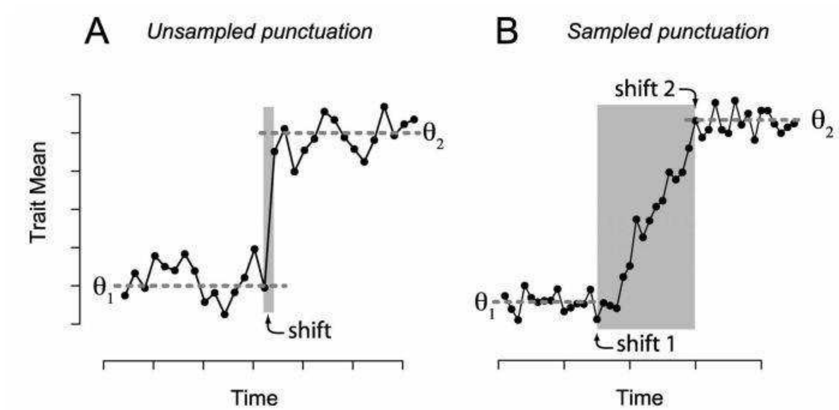

Figure 1: Unsampled versus sampled or gradual punctuation (adopted from Hunt (2008), figure 1).

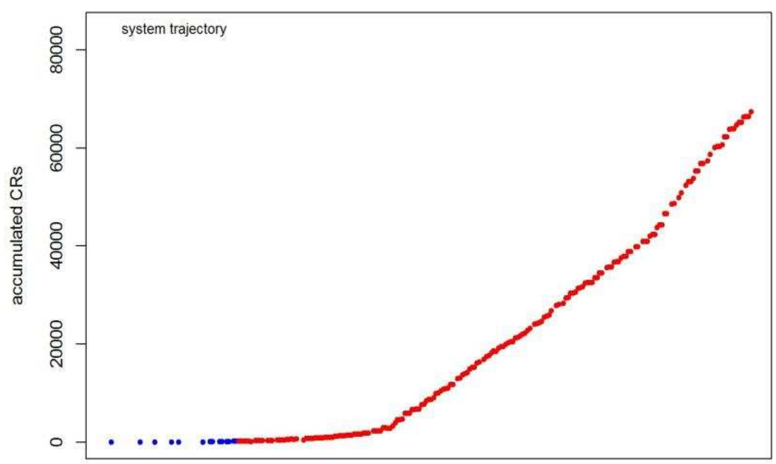

Figure 2: System trajectory from 2G to 4G

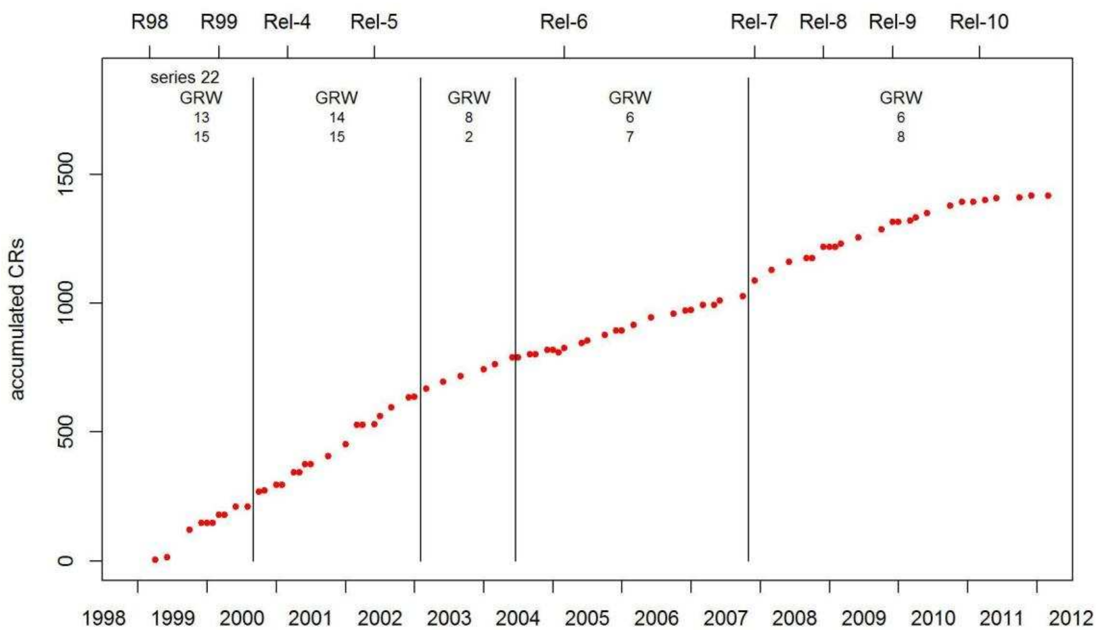

Figure 3: Phenotype trajectory for 3G and beyond

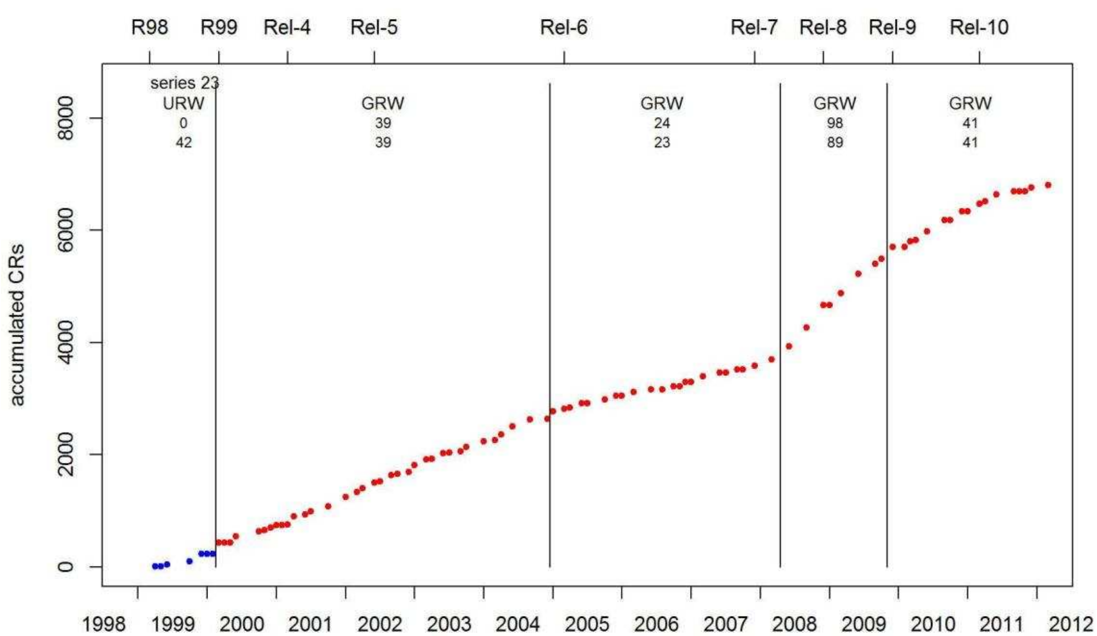

Figure 4: Archotype trajectory for 3G and beyond

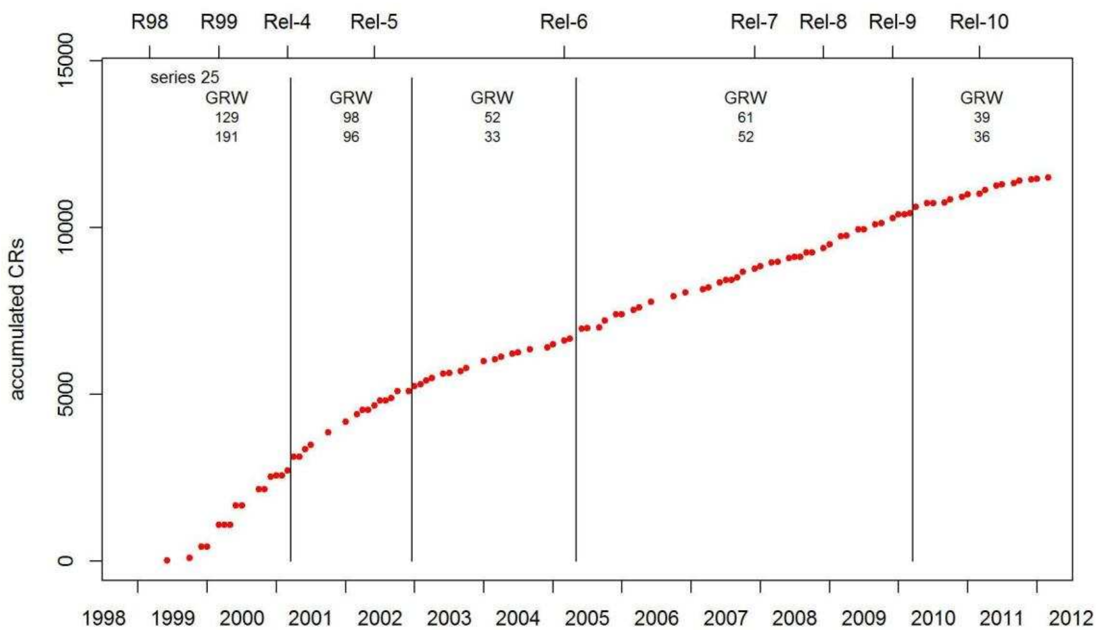

Figure 5: Radio subsystem trajectory for 3G and beyond

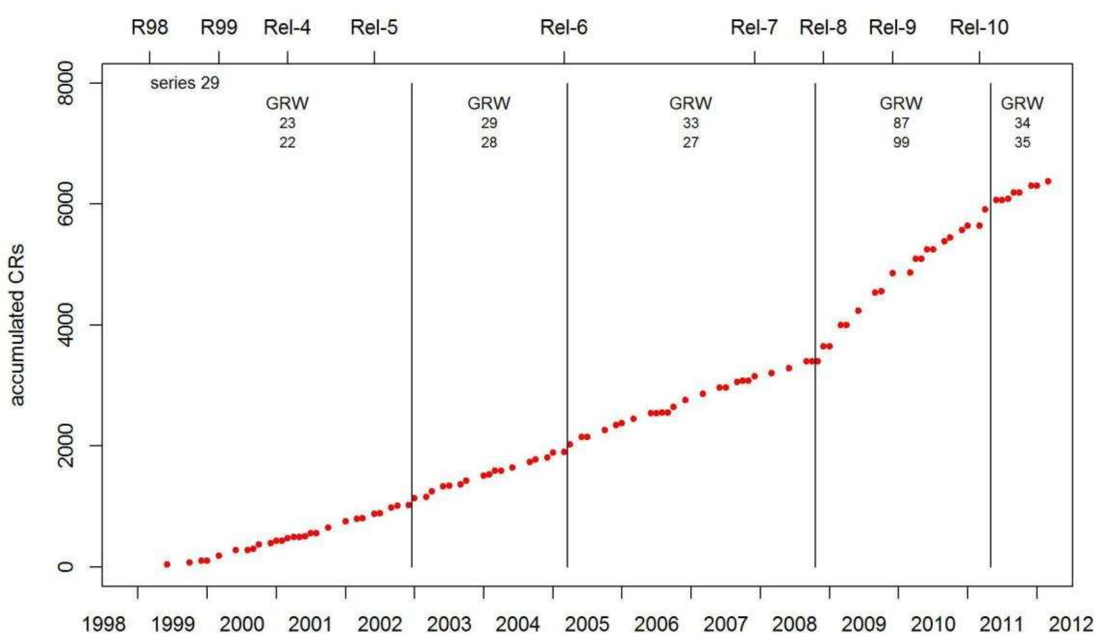

Figure 6: Core subsystem trajectory for 3G and beyond

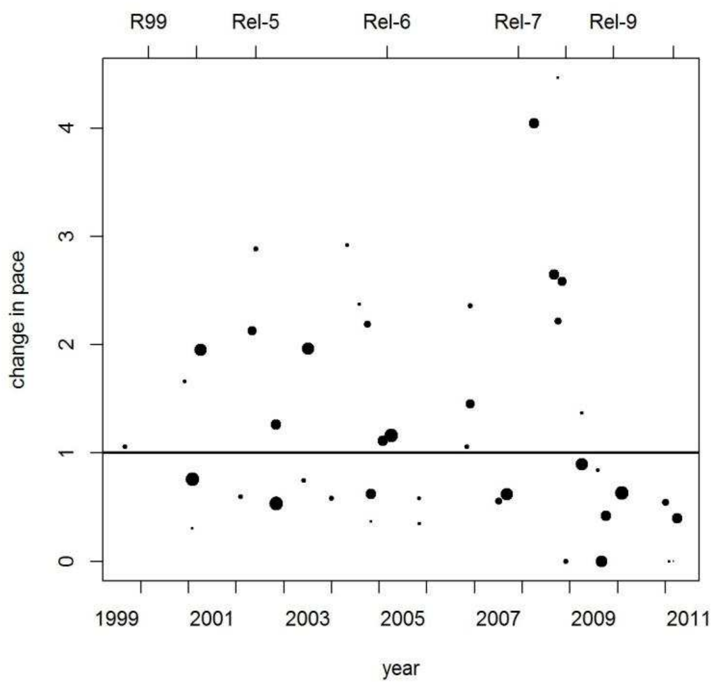

Figure 7: Ratio of mean step length over time.

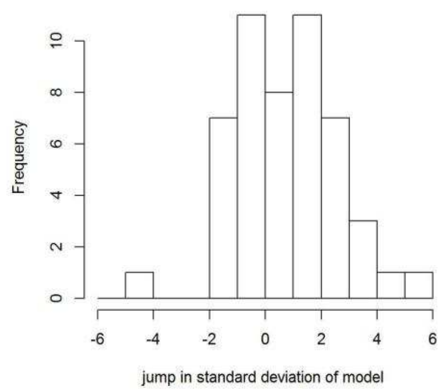

Figure 8: Distribution of jumps in standard deviations of the change model.

Novelty of phenotype

Low high

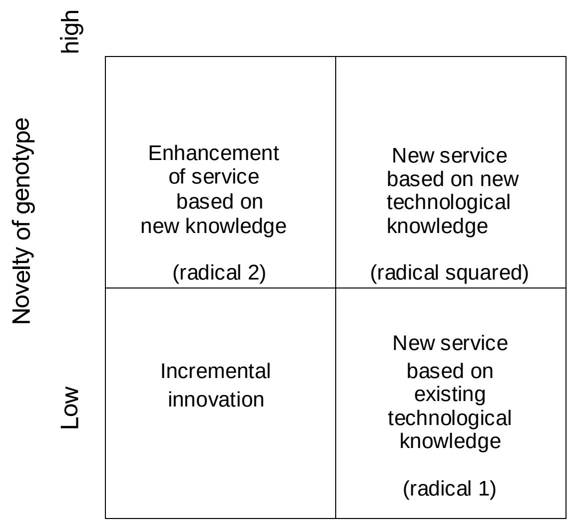

Figure 9: Innovation typology based on novelty of phenotype and genotype.

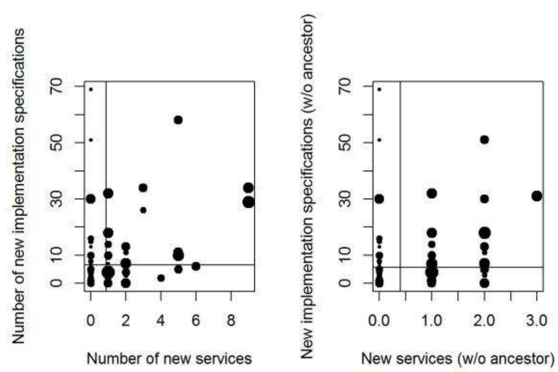

Figure 10: Empirical innovation types for all new specifications (left side) and new specifications without ancestor (right side).

Series	Month of shift	Jump
22.0	216.0	3.0
23.0	123.0	4.2
23.0	181.0	2.5
24.0	243.0	2.8
25.0	244.0	2.6
26.0	136.0	4.0
29.0	157.0	2.9

29.0	184.0	3.4
31.0	178.0	2.2
32.0	256.0	5.2
34.0	244.0	2.0
36.0	256.0	2.1

Table 3: Model transitions with deviations larger than two standard deviations.

	incremental	radical 1	radical 2	radical square
R99	9	4	1	7
Rel-4	8	0	0	0
Rel-5	7	1	1	1
Rel-6	5	5	5	3
Rel-7	10	3	2	1
Rel-8	11	2	3	2
Rel-9	7	2	0	1
Rel-10	7	1	0	0

Table 4: Innovation types for all 3G releases.

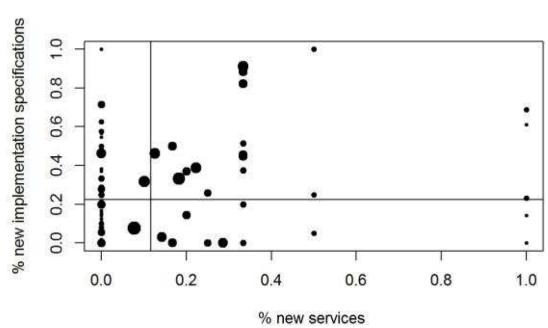

Figure 11: Empirical innovation types based on percentage of novelty for all new specifications.