A Law of Functional Expansion - Eliciting the Dynamics of Consumer Goods Innovation with Design Theory

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ABSTRACT

For more than two decades, mobile phone industry has shown that innovation is not only functional optimization and combination but can also be a "functional expansion". Sometimes called radical or disruptive innovation, this phenomenon leads to the development of new method for engineers and designers. However, the intensity remains undemonstrated: is functional expansion a rare phenomenon (few products during very short periods of time) – or is it an intense phenomenon, that even might have accelerated in the last decades? To answer these questions, the paper overcomes two main obstacles: how to measure functional expansion? And what would be a law of functional expansion, that would enable to test the importance and newness of the phenomena? Building on recent advances on the measurement of innovation and on new computational models of design derived from most advanced design theories, this paper presents unique data on functional expansion of 8 consumer products and tests that functional expansion significantly accelerated in the mid 1990s. The paper confirms quantitatively that our societies are now in a new design regime, a regime of innovative design.

Keywords: Design theory, Innovation, Functional expansion, Technology

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1 INTRODUCTION

For more than two decades, mobile phone industry has shown that innovation is not only functional optimization and combination but can also be a "*functional expansion*", ie it consists in regularly, repeatedly *inventing new functions for products*: over the last decades, the phone became a 'smart phone' with surprising new functions. This phenomenon of functional expansion is also analysed as 'disruptive innovation' (Christensen 1993, 1997) or 'radical innovation' (O'Connor 1998). For engineering design, this is a critical phenomenon, since the design of functional expansion requires new methods, coming and adding to the well-known methods of functional combination and optimization (Le Masson *et al*., 2017).

However: is this phenomenon so strong? Maybe it is just one type of products that is hit by this phenomenon, maybe functional expansion just happens once or twice on certain products and maybe functional combination and optimization still largely dominates the realm of product design? This would be the so-called "Lancasterian" hypothesis: Kelvin Lancaster is a very famous economists who, in the 60s, wondered how the general equilibrium model of economics, at that time based on the hypothesis of a finite (fixed) list of products, could be adapted to account for the phenomena of regular renewal of products that was already largely visible in the 60s, a time of mass-diversity and regular evolutions of mass consumption products. Lancaster saved the general equilibrium by proposing a theory (Lancaster 1991; Lancaster 1966) based on the hypothesis that product performances increase but each product has a stable set of function that defines it. Doing so he could rewrite the equations of general equilibrium on the set of (fixed) performances. This was a great success in economics. But this result is based on the hypothesis that there is no functional expansion. And to our knowledge, no studies were ever launched to check this hypothesis. By contrast, for some authors, this phenomena of "functional expansion" is a unique and specific feature to characterize contemporary innovation (Le Masson *et al*., 2010; Witt 2009; Becker *et al*., 2006); according to these authors, it is a phenomenon that is particularly visible on mobile phones but might also exist on other products; and it is a phenomenon that would have significantly increased in the last decades. Hence our research question: is the phenomena of functional expansion visible over long time period and on different products? And does this phenomenon increase significantly in the 1990s?

Testing these hypothesis raises critical issues: in case of functional optimization and combination engineering design can rely on several predictive models; when it comes to functional expansion, even basic elements are missing: 1) it is not self-evident to just roughly evaluate the phenomena of functional expansion. One can generally agree that the mobile phones changed to become "smarter" - but can one measure the level of functional expansion? Can one compare functional expansion on mobile phone with functional expansion on other products? 2) it is difficult to propose a reasonable predictive model because we don't know what might be relevant predictive variables. We need to relate the process of functional expansion to specific engineering resources and build a simple predictive model that would account for functional expansion, ie we need a so-called "law of expansion". If one would have a measure of functional expansion and this law of expansion, then it could become possible to test whether functional expansion significantly evolved in the last two decades.

Hence the program of this paper is as follows: building on existing literature, we will propose a way to measure functional expansion; building on recent advances in design theory, we will be able to propose a law of expansion; applying the law of expansion to our data of functional expansion, we will test whether there was a significant increase in functional expansion in the last decades.

2 LITERATURE REVIEW AND RESARCH QUESTION: FUNCTIONAL EXPANSION AND CHANGES IN DESIGN REGIMES

2.1 Measuring functional expansion

Over time, research on innovation analysed specific types of innovation. In early 20th century, innovation was associated to productivity, and political economists measured the productivity in steel industry or in coal mining. In mid-twentieth century, one rather measured the diffusion of innovation with equipment rates; one also measured functional performance increase (decrease in fuel consumption, increase in safety, comfort,…). Since contemporary innovation seems to consist also in functional expansion, we need to develop a new instrument. Note that this instrument was actually

suggested by a Kelvin Lancaster himself, who explained how his hypothesis should be tested (Lancaster 1991; Lancaster 1966). Building on Lancaster, the requirements for the measurement are as follows (and are quite demanding):
a) requirement 1: one measures "functions" in the sense of "reason to buy" - so many 'technical functions' should be ignored as long as they are not 'existence conditions' for a product on a market. Lancaster call them "product characteristics that have an economic effect". These are the "purchase" criteria that a buyer should you to maximise his/her utility function.
b) requirement 2: since it is difficult to access to all products of a certain family on a given market (all mobile phones on the French market at time t1), there is a sampling issue: how to sample all the products of a certain family on a certain market at time t1; and the sampling process must be stable over time.
c) requirement 3: the method has to be stable over time; there are two apparently conflicting requirements here: one has to avoid "anachronism" effects in which an observer of time t2 judges the emergence of function at time t1, t1<<t2; and this calls for "synchronous" observers (observation of functional changes at time t1 is made by an observer present at time t1); but one has to avoid too strong "subjective" differences so observers at time t1 and t2 have to share common criteria to evaluate the functional emergence.
One solution suggested by Lancaster is to rely on consumer reports. One can explain this suggestion:
a) consumer reports are "utilitarian" by construction: they claim to only focus on "pure" functions, avoiding fashions or so called "technical functions" that only technical experts could understand and value. Hence it meets requirements 1. Note that they will tend to "underestimate" functional expansion since they ignore some functions that might be a "function" for a few buyers. Note also that they are supposed to be independent from product designers.
b) consumer reports are companies or association that build on all the marketing knowledge for a given family of product on a given market for a given period of time. Hence they have developed a sampling capacity. Note that, as independent prescribers, they are supposed to control for possible biases (brand or company biases) in the sample. Hence they meet requirement 2.
c) consumer reports are companies and association that are stable over time: they make regular evaluation over time, hence there is a "synchronous" measurement; and they have well-established rules that are kept stable over time to evaluate what is a function - hence this is a synchronous and yet objective measurement instrument. Hence they meet requirement 3.
Recent works have helped to develop a new method for measuring functional expansion at an industry level based on consumer reports (El Qaoumi *et al*., 2017). These works have already largely validated the method. The measurements made on 4 types of products led to prove in particular that Lancaster was wrong. In this paper we built on the same method, relying on a larger set of products (we increase the data base to 8 families of products).

2.2 A model of functional expansion

What are the available models to account for functional expansion and functional combination? It is well-known that the existence of a new product will depend on customer acceptance (in a 'demand side' perspective) or technical discoveries (in a 'supply side' perspective). These approaches (detailed for instance in (Arthur 2009; Saviotti 2001; Saviotti and Metcalfe 1991; Nelson and Consoli 2010)) have taught us that a new product will require knowledge creation, either from the science point of view (knowledge creation for making discoveries and designing a new technique) or from the market point of view (knowledge creation to design new usages of the new product). *Hence a model of functional expansion should depend on the overall effort put on designing (the techniques and/or the usages)*. Hence the *design effort* is a first dimension that should characterize a design regime. Some authors went as far as considering that this single should be enough and propose, for instance, a Poisson law for the emergence of new products or new techniques where the Poisson parameter is proportional to R&D investment (see (Aghion and Howitt 1992), an endogenous growth model). But this model was considered as too simple and not empirically confirmed (Jones 1995).
A critical limit of a Poissonian model is that it considers that the events are independent - whereas many works have underlined that existing techniques might have more or less generic effect, ie enable more or fewer combinatorial applications, depending on the set of already existing technologies, the knowledge heritage. This logic of higher or lower generativity is illustrated by the works of Fink *et al*. (Fink *et al*., 2017) showing that in situations of "combinative" innovation, some new building blocks can have a much higher generative power than other (Fink *et al* paper relies on three combinative

situations where a new ‘component’ enable a certain number of new ‘products’: how a new letter added to a given list of letters enables to create new words; how a new ingredient added to a list of ingredients enables to create new recipes; how a new software development tools added to a list of software development tools enables to create new software). This model corresponds to so-called “generic”techniques (Kokshagina 2014; Bresnahan and Trajtenberg 1995) that can have an impact on several markets and applications, hence having much higher “generativity” power than a non-generic one. Hence the model of functional expansion should integrate the issue of genericity of the newly created function. It means that there is an “heritage” that determines the potential of future functional expansion. This is not only a “path dependency” (David 198, in the sense that it does not only describe the limits and restrictions to expansion but describes also the potential of future expansions.

How can one model this “heritage” of techniques that would determine expansions? It is today well-known that the logic of lower and higher genericity depends on *the structures of techniques and the interdependencies between techniques*: in the so-called C-K/Ma model, (Le Masson *et al*., 2016) model a system of techniques by the interdependences and is able to account for the expansion of systems of techniques. The paper also proposes a computable model that predicts the dynamics of a system of interdependent techniques. Hence C-K/Ma can lead to *propose a law of functional expansion parameterized by the design effort and taking into account the “heritage” of techniques that determine the potential of functional expansion*.

2.3 Research questions: characterizing design regimes and their evolutions

Based on the literature we have a measurement technique to measure functional expansion and we have building blocks to propose a law of functional expansion. In this paper we fit this law with the empirical data. *Our first research question is to check whether the law fits with the empirical data.*

Moreover, if there is a fit, this fit will reveal the design regime associated to the functional expansion. Hence it will be possible to test whether there is a significant change in the design regime over time. *Our second research question is hence to check that there is a change in the design regime - and check whether this change occurred in the mid 90s.*

We now build a law of function expansion in design regimes. We then present the empirical material and proceed to the tests.

3 A LAW OF EXPANSION IN DESIGN REGIMES

3.1 Principles of C-K/Ma

We build our law on the C-K/Ma model (exposed in (Le Masson *et al*., 2016)). In this model, a technique is an element of a matroid. The structure of techniques is the matroid of techniques. A product is called a “working system”, it is made of techniques that ‘work together’, techniques that can be said ‘compatible’, which correspond, in matroid terms, to a circuit. If we consider a graphic matroid G, the elements are edges; each technique is an edge ti, E = E(G) is the set of edges of the graph; a working system (a product) is a circuit and in a graph, a circuit is actually a path made of edges (techniques) that is connected and all vertices are of degree 2, ie the circuit foes only once through each vertex (see figure 1 below).

In this model, what is a function? It is both a property of a product and the effect of (at least) one function. In a graph, *one can assimilate a function to a vertex that is on a circuit*: a vertex on a circuit can be associated to two techniques and is an element of a product. The vertices of the graph are V(G).

In (Le Masson *et al*., 2016), the authors use the example figure 1 below: the graph G below can be interpreted as a synthesis of the technological know-how of a designer. The designer knows how to address {f1; f2; f3} (with the circuit t12-t23-t31); he doesn’t know any solution to address {f1; f4}. A matroid can be associated to this graph of designer’s knowledge, the matroid defined by the cycles of the graphs. In this matroid {t12; t13} is independent whereas {t12, t13, t23} is dependent. {t12, t45} is also independent.

The matroid representation has the first advantage to focus on the interdependencies inside a structure of techniques and to characterize all the known combinations that correspond to a product (all the cycles in the matroids). It also provides a critical quantifier: a matroid has a certain rank which actually corresponds to the size of the largest independent set. In a graph G, we have the rank function r(G) = |V(G)|-1. (r(G)=4 in the example below), where |V(G)| is the number of vertice.

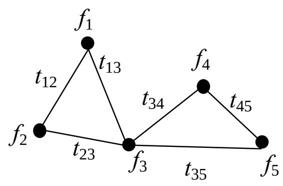
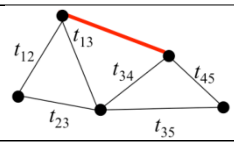
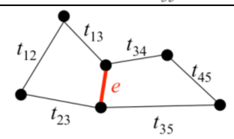


Figure 1: A graph G

C-K/Ma models the design of a new matroid from a given one. The paper shows that the design of a new system of techniques actually relies on two main operations (see table below):

- The extension, that consists in drawing a (dependent) edge between two existing functions to create a new circuit. This operation corresponds to a new product (working system) that is exactly the new combination of known functions. The impact of the extension on the structure of techniques is as follows: it doesn't change the rank r of the matroid; it decreases (by minus 1) the number of remaining possible combinations not done yet. Hence it decreases the potential of functional combination associated to the known techniques. Note that an extension is not possible if the matroid is said complete: this corresponds, in a graphic matroid, to the situation where there is an edge between any pair of vertices.
- The co-extension, that is less intuitive, and corresponds to a new independent edge common to several connected components. This operation corresponds to designing a generic technique, generic to several technical families. It adds one new function - this operation is the unique operation that enables functional expansion. In matroid terms, a co-extension corresponds to an extension made on the dual of the matroid. The impact of the co-extension on the structure of techniques is as follows: it increases the rank r of the matroid (by +1) ; it increases (by r) the number of remaining possible combinations not done yet. Note that, surprisingly enough, a co-extension is not possible if the dual of the matroid is complete.

Table 1. Main design operations in the dynamics of technique and in matroid (last colomn: illustration on the graph G of figure 1)

Cumulative design of working systems with new technique linking other techniques and minimizing propagations	*Extension* ie one dependent edge, depending on the techniques to be linked together	
Designing a generic technique, generic to several technical families	*Coextension* ie one independent edge common to several connected components	

3.2 Relying on C-K/Ma to build a law of expansion in design regimes

Let's now begin to model a design regime: given a certain product type T, we associate to T the set of techniques that enable to design the existing products. Techniques used in a known product are said dependent. The techniques are defined so as to meet the axioms of matroid (in (Le Masson *et al.*, 2016), the authors explain how to describe a structure of technique to meet the axioms of matroid theory). We suppose that the resulting matroid is graphic. To each edge of the matroid, we associate a function. This defines the initial rank, r0, of the matroid M of techniques of T.

We now design a new technique. Unless the matroid is complete, an extension is possible. Unless the dual is complete, a co-extension is possible. These operations can be repeated. In the repetition, a constraint emerges: extensions or coextensions, enabled alone, lead to deadlocked systems since extension leads to complete the matroid and co-extension leads to complete its dual. Hence a direct consequence demonstrated in (Le Masson *et al.*, 2016): "*the only way to get an unlocked dynamic consists in combining extension and coextension – ie the combination of the design of working systems and the design of generic techniques*".

This key property enables to identify several design regimes, and two of them deserve particular attention: the 'extension-driven' and the 'co-extension' one.

1- The "*extension-driven" regime* gives priority to extension (the design of working systems). In this regime, co-extensions (the design of generic techniques) are as rare as possible. Over time the matroid becomes complete and no extension is possible anymore. Hence one co-extension is required, it increases the rank by +1 (the rank becomes r0+1) and the generativity by +r0. Over time the rank increases slowly: one co-extension that increases the generativity by r0 and the rank with +1, then r0+1 extensions until generativity decreases to 0 and again co-extension, this time with the rank r0+1, then r0+2 extensions, etc. *In this regime, the creation of generic technique is "endogenous"*, in the sense that the internal logic of the extension of techniques pushes to 'invent' a new technique that changes the game. This contrasts with a logic where co-extension appears without the internal 'pressure' of extension (see below). Note that this can describe regimes with "low" functional generation or "high" functional generation" - this will mainly depend on the intensity of the design effort (see Next and Ncoext in equations 1 and 2 below).

In this regime, one can write the law of extension: at time t, the rank is r(t), at time 0 it is r0. At time 0, r0 extensions are possible. At time r0+1 a co-extension is required and the rank becomes r0+1. And so on. Hence at time (r0+1) + (r0+2)+…. + (r0+k) the rank is r0+k (see Figure 2 below).

Hence the equation:

$$r\left(k.r_0+\frac{k.(k+1)}{2}\right)=r_0+k$$

Hence $r(t)=r_0+k(t)$ with $t=\frac{k^2}{2}+\left(r_0+\frac{1}{2}\right).k$. There is one positive root for this equation:

$k=\sqrt{(r_0+1/2)^2+2t}-(r_0+1/2)$. Hence the general equation:

$$r(t)-r_0=\sqrt{(r_0+1/2)^2+2t}-(r_0+1/2).$$

If there is N_{ext} new techniques created per unit of time in this regime, then the equation becomes:

$$r(t)-r_0=\sqrt{(r_0+1/2)^2+2N_{ext}t}-(r_0+1/2).$$

If $N_{ext}t \ll \frac{r_0^{\;2}}{2}$, then $r(t)-r_0 \approx \frac{N_{ext}t}{\left(r_0+\frac{1}{2}\right)}$; If $N_{ext}t \gg \frac{r_0^{\;2}}{2}$, then $r(t)-r_0 \approx \sqrt{2N_{ext}t}$ (see figure 2).

Note that this law supposes that the matroid is fully completed. We could have a variant with a "saturation" at level rmin or at a fraction β of the full completion. In the first case: this consists in replacing r0 with r0-rmin. In the second case the fraction β shortens the time to reach completion, hence:

$$r(t)-r_0=\sqrt{(r_0-r_{min}+1/2)^2+2\mathrm{N}_{ext}\beta t}-(r_0-r_{min}+1/2). \qquad (1)$$

Or: $(r(t)-r_{min}-1/2)^2-(r_0-r_{min}-1/2)^2=2\mathrm{N}_{ext}\beta t$, linear in t. (1')

2- Conversely, the "co-extension-driven" regime favors co-extensions. We have then a symmetrical situation: a hand of dependent systems and many independent techniques. In that case the invention of a generic technique is not driven by the internal constraint of the system of techniques. Hence this is an *exogenous creation of independent techniques*. Note that over time, an extension becomes necessary to make an additional co-extension. This constraint implies a law on the "co-extension driven" regime: we have the following relation:

$$r\left(k.r_0^*+\frac{k.(k+1)}{2}\right)=r_0+k.r_0^*+\frac{k.(k+1)}{2}$$ where r* is the rank of the dual of the matroid.

Hence $r(t)-r_0=t-k(t)$ with $t=\frac{k^2}{2}+\left(r_0^*+\frac{1}{2}\right).k$.

Hence we have:

$$r(t)-r_0=t-\left[\sqrt{(r_0^*+1/2)^2+2t}-(r_0^*+1/2)\right].$$

If there is N_{coext} new techniques created per unit of time in this regime, then the equation becomes:

$$r(t)-r_0=t-\left[\sqrt{(r_0^*+1/2)^2+2N_{coext}t}-(r_0^*+1/2)\right]. \qquad (2)$$

If $N_{coext}t \ll \frac{r_0^{*2}}{2}$, then $r(t)-r_0 \approx N_{coext}t$; If $N_{coext}t \gg \frac{r_0^{*2}}{2}$, then $r(t)-r_0 \approx \mathrm{t}-\sqrt{2N_{coext}t}$ (see figure 2).

Note that, contrary to what appears on figure 2, r_0^{*2} is usually relatively big: in a matroid M we have $r^*+r=|M|$ where $|M|$ is the number of elements in the matroid (ie edges for a graphic matroid) -

when M is complete the magnitude of $|M|$ is in the order of r_0^2 so the order of magnitude of r_0^{*2} is r_0^4. Hence a very steep slope for the exogenous curve below.

3.3 Conclusion: a law to characterize functional expansion

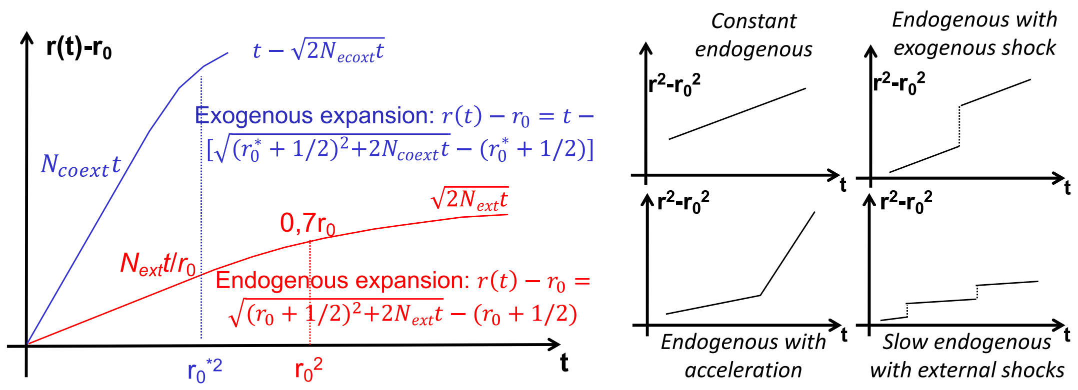


Figure 2: models of functional expansion (left graph: "pure" exogenous (blue) and "pure" endogenous cases (red); right: four mixt cases, represented on the anamorphosized data).

In the model above (eq. 1'), *a design regime can be characterized as a base of endogenous expansion with occasional exogenous expansion*. An endogenous expansion is characterized as a straight line in the graph $(r(t) - r_{min} - 1/2)^2 - (r_0 - r_{min} - 1/2)^2$ vs t, and its slope $2N_{ext}\beta$ relates to the design effort. A very low slope relates to an almost *pure functional combination (almost no expansion).* A positive break in the slope indicates an *intensification of the design effort* (change in the design regime). The endogenous regime can punctually be enriched by non-endogenous expansions. This creates a jump, *a break in the curve with a constant slope* (see figure 2).

4 TESTING THE LAW ON EMPIRICAL DATA

4.1 Material: empirical data on functional expansion

We used the archives of the French Consumer Report Que Choisir. We followed 8 types of products (see below) and we had access to integral archives of each product study of the period below.

Table 2. Sample: 8 consumer products, time period and number of studies during the period

Type of product	Period	Number of studies
Iron	1962-2014	24
Vacuum Cleaner	1969-2014	37
Freezer	1970-2014	17
Refrigerator	1973-2014	21
Toothbrush	1975-2014	7
Bicycle	1975-2014	13
Mobile phone	1996-2014	24
GPS	2007-2014	10

For each product, we compare the functions in the new test at time t+1 with all the functions that appeared in the test between time 0 and time t. If the function is semantically (significantly) different we consider it as new. We had a double (in certain cases triple) coding. We represent the result on the graph below (aggregated new functions until the date of the study vs date of the study, figure 3).
This graph calls for some comments:

- There is, for the 8 products, a visible functional expansion. Even the toothbrush shows regular creation of functions. The slowest functional expansion is the refrigerator.
- The fastest expansion is the smart phone - this is coherent with the intuition we mentioned in our introduction. It created 113 new functions in 18 years. Less intuitive is the fact that the vacuum cleaner created more functions (124) than the mobile phone, even if on a longer time period (46 years).

- This tends to invalidate Lancasterian hypothesis: there is a functional expansion on many products, not only on smart phones. We need to test it.
- Regarding our second hypothesis: it is less self evident that there is a regime change in the 90s even if it seems that there is a break in the design of vaccum cleaner around 1992, a break for Iron around 1995, a break for bike around 1995. This also needs to be tested.

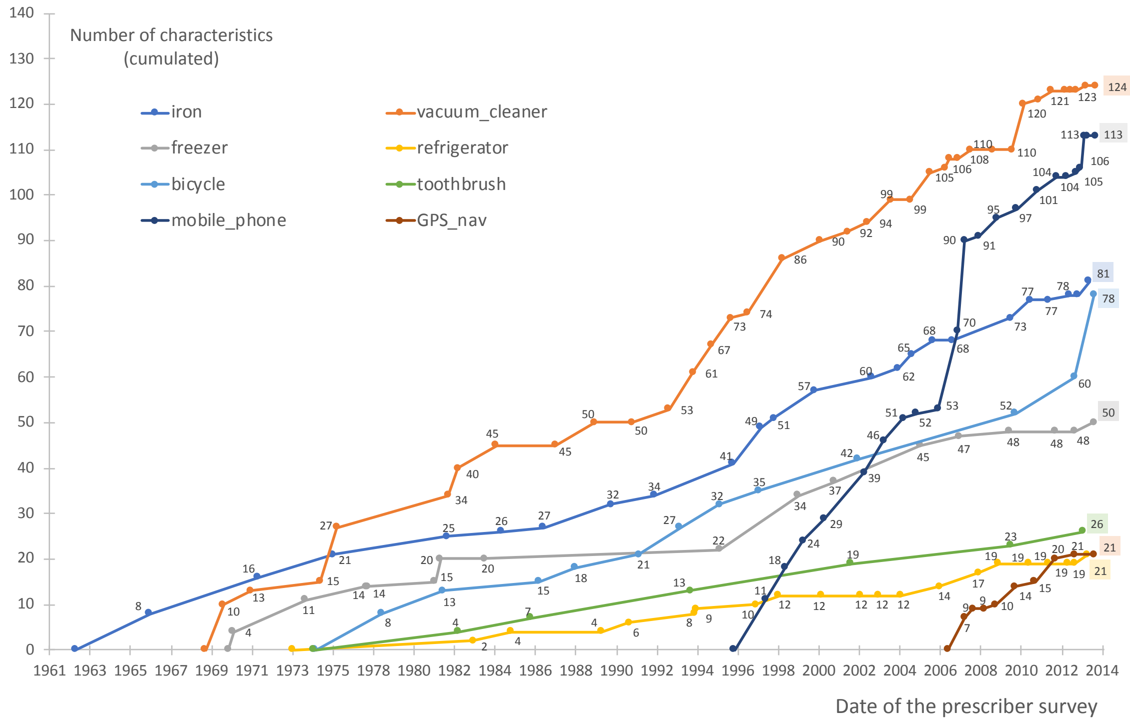


Figure 3: Empirical measurement of functional expansion on 8 consumer goods (w axis: time; y-axis: cumulated number of characteristics). Ex: in 1971, after the third study on vacuum-cleaner, the product vacuum-cleaner has gained 13 additional functions since the first study (done in 1968)

4.2 Result: fit of the law of functional expansion and change in functional expansion.

We fit the graphs of measurement vs time with the law of endogenous expansion. For the reader, we represent below the anamorphosized data (on y axis: $(r(t)-1/2)^2-(r_0-1/2)^2)$ (figure 4).

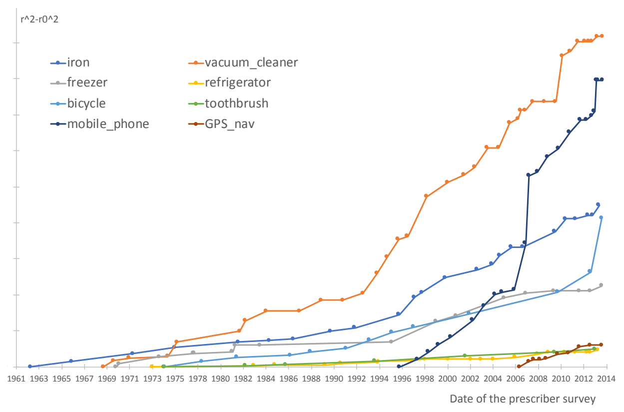


Figure 4: $(r^2-r_0^2)$ vs time: the breaks of slope and the jumps in the curves are more visible

For each product, we fit the endogenous expansion model (eq. 1') and estimate the slope as follows: for each product we conduct a regression on the all period, then we conduct a Chow test on all possible break dates to identify possible significant breaks in the regime. For each significant break we characterize the two regressions (before and after the break) and we check whether the slopes are significantly different (confidence interval at 95% level). In that second case, it means that the break in linear regression is a jump. The results are summarized in table 3 and below:

- Four products follow a model of endogenous expansion with a significant slope break: iron, vacuum cleaner, freezer and bicycle (the latter without outlier 2014). In a first phase there is slow endogenous expansion then a stronger one. The slopes ratios and dates are: 2,6 (freezer, in 1995-1999), 3,3 (bicycle; in 1991-1993), 3,66 (vacuum cleaner in 1993-1994) and 4,47 (iron in 1992-1996).
- One product follows a strong endogenous expansion with a jump: the mobile phone. The slope is very high (between 565 and 786). There is strong jump (in 2006-2008), without significant change in slope. It corresponds to the first "smart phones", that implied a strong change in the technologies (Glimstedt 2018).
- Two products follow a constant endogenous expansion: toothbrush and GPS. The toothbrush has one of the lowest slope (28,7); the GPS is relatively high (around 151).
- One product follows a very slow endogenous expansion: the refrigerator (slope around 25, with long periods of no changes in the functions, which explains why the regression is less significant). There is at least one testable jump (around 2006-2008; no significant change in slope) which can be considered as an exogenous expansion in a very slow endogenous expansion. This corresponds to the (well-known) fact that innovation on this product is largely driven (and constrained) by energy consumption, hence the very limited functional expansion.
- Additionally, one can notice other jumps on some curves: a jump in 2011 on vacuum cleaner (robot vacuum cleaner), a jump in 2014 on bicycle (electric bike). There is a (light) jump in 2014 in mobile phone related to a strong enrichment of camera functions.

Table 3. Results

	a	t_stat	Chow	p-value	a-before	p-value	conf int 95%	a-after	p-value	conf int 95%	Slope break
iron	197,99	***	1992-1996	2.10-14	68,2	***	[58; 78]	305	***	[284; 326]	yes
vacuum cleaner	461,41	***	1993-1994	2.10-16	176	***	[150; 201]	644	***	[610; 677]	yes
freezer	100,8	***	1995-1999	0,001	46,9	**	[22; 71]	121,9	***	[80; 164]	yes
bicycle (2014 outlier)	140	***	1991-1993	0,001	53	**	[33; 73]	175	***	[141; 209]	yes
mobile phone	1015,8	***	2006-2008	3.10-9	565	***	[439; 691]	786	***	[620; 951]	no
GPS	151,7	***	no								
toothbrush	28,7	***	no								
refrigerator	27,7	***	2006-2008	6.10-5	20	***	[17; 23]	26,9	*	[1; 52]	no

With these results, we can conclude on our research questions:

- Research question 1: a regime of functional expansion is present in all products. - at a very low pace for refrigerator or toothbrush; at a surprisingly high pace for vacuum cleaner or iron. And, as expected, at the highest pace for mobile phone. This means that even if irons or vacuum cleaners seem to remain "the same" over time, the reasons to buy them have significantly changed for the last decades.
- Research question 2: for the 6 products with long life time, 4 on 6 show a significant change in slope and this change in slope occurs in the 1990s (the earliest: bicycle 1991-1993, then vacuum cleaner 1993-1994, then iron 1992-1996, and finally freezer 1995-1999). The refrigerator and the toothbrush don't show a significant change in slope.

5 CONTRIBUTION AND DISCUSSION: 'DESIGN-METRICS' AND DESIGN HERITAGE

To conclude: this paper shows that *it is possible to predict a law of functional expansion of products and this law was successfully tested on a sample of 8 consumer products*. Contributions are as follows:

- We prove that functional expansion is not limited to mobile phone - it exists for all the tested consumer products.
- We prove that functional expansion significantly accelerated in 1990s.

Confirming the intuition of functional expansion, this work suggests that we are in a non-Lancasterian economy, an economy of functional expansion, hence it underlines the need to prepare the designers (engineering design as well as industrial design or architectural design) to functional expansion and not only to optimization. This is also important for managers of innovation management.

Moreover this work is a first step towards a "*design-metrics":* we have relatively few methods to measure innovation; and we have even less when it comes to measure expansion. It is already quite difficult to measure an "increase" (or decrease) of a functional performance; we can't underestimate the difficulties to measure the emergence of new dimensions. This work paves the way to further

research on measuring expansion of products. We have today many techniques of measurement in "econometrics" - but these techniques focus on optimization into a stable frame of references - they ignore generativity. If the expansion becomes critical for competition, we need today new methods and tools to measure and predict it. This calls for the development of a 'design-metrics', a discipline that would try to measure contemporary phenomena of design generativity, that are largely ignored by "econometrics" and could become critical for our societies.
Finally, this work also leads to a critical theoretical result: the empirical data confirm a model of "endogenous functional expansion" and this means that functional expansion, that is deeply related to "disruptive" innovation, actually relies on an "*heritage" of previously designed techniques* that actually determines the potential of future expansions. This heritage is more than a "path dependency" in the sense that it does not "reduce" the possibilities but it actually 'creates' them. And this heritage can be characterized by the interdependence structure of its elements. This result doesn't exclude exogenous shock but it reminds that endogenous logics can be very powerful and can explain contemporary logic of functional expansion.

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