GROWTH OF THE FIRM BY REPEATED INNOVATION:
TOWARDS A NEW MICRO-ECONOMICS BASED ON DESIGN FUNCTIONS

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Introduction

Innovation is at the heart of economic development, but nevertheless raises considerable theoretical challenges in the fields of both Economics and Management. In this article, we will be examining recent work on innovation in these two disciplines, which leads us to introduce a crucial function for innovation that we have called the "design function" inherent to firms. This function cannot be formally assimilated with a traditional production function. It requires specific management methods that determine its "efficiency". Its study helps us relate innovation strategies to firms' core learnings. This change in representation has three advantages: (i) offering an interpretation of the regimes of growth by repeated innovation observed in certain firms; (ii) unifying and simplifying ad hoc micro-economic models of innovation; (iii) providing a representation of the firm that is better suited to capitalism, particularly when based on competition by innovation.

In the field of Economics, innovation was subject very early on to critical movements (such as Schumpeter's) contesting the approach whereby firms were treated as a production function¹. However, such works did not lead to changes to the micro-economic representation of the firm. Hence, studies on the relationship between innovation and growth, on the impact of R&D or on innovation-related aid policies are often still analysed within the traditional framework of production functions. Models of endogenous growth attempted to circumvent this representation without giving a new theoretical framework, with the paradoxical results that we will be examining below.

In the field of Management, initial work sought to identify the "structures" of firms that were most favourable to innovation (Burns and Stalker 1961). A large number of studies were then devoted to comparing the paths followed by different innovations. In more recent years, research has focused on product development, project organization and long-term analyses of innovative firms. These studies shed new light on the notion of innovation from the firm's point of view: rather than one successful, isolated innovation, it is more important for a firm to maintain a well thought-out, sustained rate of innovations and thereby be able to organize repeated innovations. From this angle, although for a long time little attention was paid to the organization of design activities (engineering, research, industrial design, marketing, methods communications, etc.), hidden as they were by the traditional notion of R&D, it now appears as the main vector of innovation, a vector whose static and dynamic "returns" must be clarified.

In this article, we will introduce a model of design functions aimed at furthering the understanding of innovation in terms of Economics and Management. We start with a series

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¹ We can even note that Walras' notion of "manufacturing function" was introduced during a discussion on technical progress and economic progress (Chapter 36, 5th edition, 1926): it was aimed at showing that technical progress in fact corresponds to a change in the "manufacturing coefficients" of the "manufacturing equation", whereas economic progress is in fact a substitution between the different factors, with the manufacturing equation remaining unchanged (Walras 1988).
of stylised facts taken from empirical and historical research on innovative firms. We then propose a model for firms' design activities that takes into account these stylised facts. The model sheds a new light on certain economic studies on innovation, and enables us to put forward new ideas for research into firms and also for drawing up sounder innovation-related aid policies.

I. Growth of the firm by innovation: a few stylised facts

A. Firms that grow by "repeated innovation"

Although there is abundant literature on innovations (both successes and failures), there is very little longitudinal data on companies that have been able to sustain a high rate of new product design over several decades. Nonetheless, several recent and historical works have shown how useful this approach can be.

1. Recently, Chapel (Chapel 1997) studied new product development in a French household electrical goods company, over a period of twenty years. Tefal, a subsidiary of the SEB group, managed to maintain double-figure growth over the long term. This was obtained without any major acquisitions and was a result of its policy on innovations, which allowed for constant product renewals. The original products (non-stick frying pans) underwent continual changes, and diversifications were made that would be surprising to anyone who was not aware of the dynamics of the underlying techniques: weighing, telephony, home automation, infant care, and food preservation. The study also shows that the company focused on the design activities. As for its production activities, it maintained final assembly, where flexibility to new products is strategic, and certain manufacturing processes that required specific savoir-faire or skills that led to innovations. The company was actually founded on the strength of an innovation (the non-stick frying pan) resulting from an original adaptation of several techniques. It then went on to combine the development of "lineages of competency" (special plastics, silkscreen printing, properties of Teflon) with the exploration of new user values giving birth to "product lineages" (household electrical goods, food preservation, weighing, etc.).

Despite fierce international competition both in Europe and in countries with low labour costs, this growth by repeated innovation was accompanied by exceptional financial results over the long term (the company constantly led the household electrical goods market in terms of profitability). At the beginning of the 1980s, a simplistic view of competition in the sector would not have rated the company's chances very high, or would have predicted that it would relocate to countries with lower labour costs. The study shows that Tefal's surprising path stems from the way it organized and managed a permanent programme of innovations. It is not a "representative" firm, but a truly original management model. The research highlights what a "pure" approach to growth by innovation can be like. Such behaviour is not necessarily dominant and cannot always be achieved. Nevertheless, the fact that France's leading incumbent in this sector, Moulinex, had serious difficulties during the same period gives a plausible indication that the model of growth by innovation provides a higher probability of survival over the long term.

2. A similar model can be found in firms that have long been famous for their ability to innovate. Recent studies on the Edison company-laboratory underline an original organization of design activities for new products, close to the Tefal model (Israel 1998; Millard 1990). Edison is portrayed not so much as the inventor of the incandescent light bulb, but more as the organizer of an "invention factory", whose declared aim was to develop the
business of innovation. Far from a series of lucky intuitions, Edison managed a programme that was already based on "product lineages" and "lineages of competency". Let us take the example of the "phonograph lineage" (one of his 1,368 patents). The first prototype was born in 1877, but several additional innovations were required (cylinders, electric engine, wax, diaphragm, regulation, stylus, etc.) before the first product could be made. In 1888, Edison launched the first "talking doll" on the same technical basis, then, a year later, having discovered the potential impact of recorded sound in the leisure sector, he developed the "coin slot amusement machine", requiring an amplifier, recording and duplication of the recorded cylinders, etc. The same year, he proposed a wind-up phonograph and then designed the first dictaphones for the administrative offices that were booming at that time. The lineage continued in 1903 with an improved phonograph, then in 1910 with a disc phonograph: no more cylinders! Work on the phonograph then had an impact on other areas of research that led to the development of the low power electric engine. It should be noted in passing that each additional stage within the same product lineage can be interpreted as the combination of incremental and radical innovations, both from the firm's and the clients' standpoint.

This well thought-out succession of innovations was backed by a very special organizational structure at the premises in West Orange. The entire building was designed to ensure that knowledge concerning current innovation programmes was produced rapidly. The centre contained a library with subscriptions to the main scientific reviews; chemical and electrical laboratories studied the different phenomena, set up experiment protocols, applied experiment plans; workshops constructed mock-ups and prototypes; and vast stocks of original objects served to feed the explorations. Albeit on a smaller scale, a similar organization was to be found three quarters of a century later in Tefal's research and design departments (with the exception of the library).

3. What is the relationship between these repeated innovation processes and what we usually call R&D? A study carried out in a research laboratory belonging to the Saint-Gobain group (Le Masson 2001) observed a recent move towards a "repeated innovation" approach. The new organization had been obtained once the laboratory had carried out wide-reaching transformations taking it away from its former "R&D" based operations. Historically, Research was required to explore knowledge without immediately looking at future applications. In contrast, Development activities (engineering and design department) responded to needs observed in the market with the available techniques. The path from R to D was therefore occasional, difficult, uncertain and long. Changing to an organization based on repeated innovation meant that it was essential to consolidate an innovative design activity, guiding and stimulating Research and Development (Hatchuel, Le Masson and Weil 2001). This new function cannot be assimilated with either research or development. It seeks to generate and test concepts for new products which serve as a base for questions to the research department, or for new skills to be experimented on the old products (Le Masson, 2001 #763). It is on this level that structuring choices are made that help build lineages of products and competencies.

What can we learn from these observations? How can they be interpreted in micro-economic terms? What is managed by the firm in such cases? Summarising the above observations with a few stylised facts will help us introduce a model of what we call "design functions".
B. Stylised facts: the design activity as a reasoned co-evolution of products and competencies

In the three cases mentioned above, we are dealing with a specific form of innovation management. The fact that it is "organized" may seem surprising but it is quite obviously not a totally random process. In fact, this paradox becomes clearer when we look at the nature of design activities and how, in certain circumstances, they can generate innovation regimes leading to the firm's growth.

1- Fact n°1: The firm "designs" and manufactures (all or part) of its products and processes.

According to Walras, "the entrepreneur is the person who buys raw materials from other entrepreneurs, ..., and having applied productive services to the raw materials, sells the products obtained for his own account" (§189). But what happens when this activity has a dynamic dimension? The list of goods manufactured is no longer stable and the production factors vary, including the qualifications required. In this case, the firm must organize the activities designed to "generate" the variations. The result is that the firm not only has the function of choosing between "productive services" but it also acts continuously to expand its own competencies and the value created (Hatchuel 2002). The variations are mainly generated by the design activities, whose continuous development over the past century is widely acknowledged.

2- Fact n°2: The design activity simultaneously creates knowledge (or competencies) for the firm.

It has long been recognised that firms create knowledge. Arrow's work on "learning by doing" (Arrow 1962) relates it directly to the activity; technological economists (Freeman, Rosenberg,...) attribute this knowledge creation to industrial research; the intensification of such creation (Foray 2000) is even at the heart of certain approaches to contemporary economies. However, recent work in the field of management underlines the close interdependency between the way in which design activities are organised and the dynamics of the renewal of professions and knowledge (Hatchuel and Weil 1995, Charue-Duboc and Midler 1998; Weil 1999). We should point out that this does not only cover scientific or technical knowledge: design knowledge can concern marketing, strategy, methods or industrial design. The design activity modifies products but also processes or corporate rules, so that it automatically influences the overall renewal of knowledge within the firm. It can also cause its obsolescence: for example, if a given material is abandoned (e.g. steel), the knowledge accumulated for acquiring and shaping the said material will lose all its value in the short term.

3-Fact n°3: there is no determining relationship between the production of knowledge and growth. The innovative firm re-establishes this correlation by its organization.

By nature, design activities (like research) create or mobilise more knowledge than is necessary to develop a single product, if only through the exploration of variations, new scenarios, or the preparation of prototypes or mock-ups, and the lessons learnt will not always be retained for the project in hand. Managing these activities therefore raises new questions as the firm must either i) minimise the "over-production" as much as possible (by using validated technologies, limiting explorations, etc (Wheelwright and Clark 1992); or ii ) make it profitable by reusing as much of it as possible in new products or new product lineages. It
is precisely in this second form of management that the innovative firms mentioned above were the most successful. This serves, in particular, to underline a well-known micro-economic observation: Boyer (Boyer 1988), Mairesse and Sassenou (Mairesse and Sassenou 1991), Klette and Kortum (Klette and Kortum 2000) all underlined the paradox of R&D whereby it is difficult to find a statistically significant correlation between investment in R&D and growth in firms. We can therefore assume that one distinctive feature of innovative firms is that they maintain a positive relationship between innovative design activities and the firm's growth. This clearly results in a rationalisation that is specific to design activities.

The studies on Tefal, Edison and St. Gobain confirmed that any excess knowledge produced was used by the firm for later products. The situation of repetitive innovation transforms the "over-production" of knowledge into "learning rent" (Hatchuel et al. 1998) which the firm can use to its benefit. This phenomenon is present to a greater or lesser degree in all design organizations: all research departments are to a certain extent libraries, as can be seen from the descriptions of such departments at the beginning of the 20th century in French, American, English or German engineering reviews (König 1999). However, the scope of the learning depends on the company concerned, as it must be thought out and organized. It can be interpreted as coding of acquired knowledge, but also as selection, coding and mobilisation, oriented by the product lineages, of the generation of knowledge. The building-up of a simple library in itself involves choices and tools that depend on the product design strategies. Similarly, the stabilisation of a "dominant design", of common platforms or standard modules for a product lineage represents a selective strategy for the routinisation of the design activities. Repeated innovation is therefore a particularly efficient way of building up and renewing such strategies.

Fact n°4: Growth is not related to a product but to the repetition of the innovation. Notion of return on a trajectory of innovations.

This helps us understand the stakes involved in a process of repeated innovation. It keeps up a firm's competitiveness whilst also building up "learning rent" which would be impossible without it. Neither Edison's lamp, nor the non-stick frying pan, nor a new, highly successful windscreen are sufficient to explain the firm's continued growth over several years in highly competitive environments. The notion of repetition also stems from the fact that learning rent does not last forever: each new product may have a temporary monopoly but it is rapidly attacked by competitors. In this case, the firm's competitiveness is set in a model with successive products which, whilst not generating growing returns indefinitely, ensures its long-term survival. The notion of repeated innovation therefore describes a new approach to the trajectory of firms: neither a technical trajectory, nor a market-based trajectory, but a combination of the two, by well thought-out sequences of successive innovations. Such trajectories are neither fully programmed, nor entirely random: they express the workings of design activities that combine creativeness under constraints, strategic decision-making and learning processes (Hatchuel 2002).

Hence, the firm develops by linking knowledge production processes and product development processes: it organizes (or at least benefits from) a co-evolution of knowledge and products that serves to innovate on a continual basis whilst limiting the risks inherent to innovation. It is these "design strategies" (Hatchuel and Le Masson 2000) which are expressed in product lineages (modules, standard architectures, exploratory concepts) and in lineages of competencies (professions, technologies, knowledge, areas of exploration, etc.).
II. A new model of the firm: the design function

A. Definition of the design functions: symmetry of inputs and outputs

To understand innovation, we therefore need a model for design activities. What resources do they require? As we have seen, the design activity requires knowledge that can be activated or competencies\(^2\). What are the results of the design activity? Its initial outputs are the definition of products and of the firm's internal or external production functions. But we have seen that the outputs of a design activity are also new competencies, which will not necessarily all be used in the product in question. Let us compare a "design function" defined in this way and the traditional micro-economic production function.

The production function models the way in which the combination of quantities of production factors, usually goods (including capital) and labour (or competencies), serve to make a quantity of one or several goods. The nature of these goods is implicit to the production function itself and, in principle, the list of goods given \textit{ex ante} is not modified by the production activity.

In contrast, the design function has the following characteristics:

- **The inputs of a design function** are goods (including capital) and competencies,
- **The outputs of a design function** are:
  - A definition of the goods to be produced (which can also be a revision of existing goods or can involve the withdrawal of these goods).
  - A definition of the processes required to produce and distribute these goods (production function of the goods; once again, this may be a variation on existing processes, or may involve the withdrawal of the processes).
  - For each type of competency, the learning which results from the design work and feedback on experience from the product (in manufacturing, in the market, etc.).

This list matches the frequent empirical observation whereby a company can sell either products (goods or services) or production functions (design of turnkey factories), or design competencies that can be as abstract as a patent, a name, a drawing or a brand.

- In formal terms, we can define a design function over two spaces, and two alone: the space of goods (including capital) \(G\) and the space of knowledge \(K\); the design function is a function of both spaces over each other. It transforms the space of goods and the space of knowledge by "expansion" (Hatchuel 2001).

\begin{equation}
\text{Design F: } G \times K \rightarrow G \times K
\end{equation}

The final space in principle contains the initial space otherwise neither goods nor knowledge have been created).

In comparison, a production function is traditionally written as:

\begin{equation}
\text{Production F: } G \times K \rightarrow \text{Q(G): Q(G) being a function quantified over the space of goods (the space G and the space K are not transformed).}
\end{equation}

\(^2\) For the sake of clarity, we will not make a distinction in the following pages between knowledge and competencies, although, strictly speaking, competencies are series of accumulated knowledge and experience forming a significant unit in the action (design activity in this case).
• The production function is a restriction of the design function: It can be noted that a traditional production function is a restricted design function whose final space is restricted to quantities of goods, and which does not "reproduce" any of the input factors! Yet the distinctive feature of design processes is that they reproduce or deform an initial competency and/or initial goods. In formal terms, we move from the production function to the design function by symmetrizing the initial and final spaces.

• Recursiveness of design functions: This formal symmetry enables us to consider the repetition of design activities as a recursive function within a given firm, i.e. as something that transforms itself by its own action. In order to model the history of the firm, we can thus start with a design function and see how it is repeated over time. Formally, let there be a design function relating to a firm's design project and let the initial inputs be vectors $G_{inputs}$ and $K_{inputs}$, $f(G_{input}, K_{input})$. The general function of the firm after $k$ design projects can be set down as: $f_{firme} = f \circ f \circ \ldots \circ f(G_{input}, K_{input}) = f^k(G_{input}, K_{input})$.

B. Some properties of design functions: lineages, returns on production and design

a) Suitability to stylised facts: It is easy to check that the model accounts for the stylised facts given above. By definition, the output of a firm represented by a design function consists in both products (their design and related production function) and knowledge. At the same time, the design function in no way guarantees that there will be an efficient relationship between the production of knowledge and the firm's growth. The firm can develop knowledge that will never be used correctly if the recursiveness of the design function is not organized properly.

If there is "repeated innovation" it means that two successive innovations from the same firm have points in common. This is the significant advantage of the fof structure. Managing successive innovations can give birth to the lineages of products and competencies mentioned above. The firm has the choice whether or not to keep certain characteristics of its products depending on the learnings gained from the design activity itself and from the results of sales, for example.

b) Notion of design strategies: what is a "lineage"? Hence, the succession of products and competencies stemming from a given design function (or from its own evolution by generating goods and competencies) helps construct series of products, or product lineages, as they have, so to speak, "common genes": this may be a brand, a style, a group of organs, a set of functions, etc. Generally speaking, we can say that a product lineage is obtained whenever there is a sub-set of common design competencies for all the products concerned, which guarantees learning potential throughout the lineage.

c) Returns and design function: the notion of competition effect on product lineage

The traditional notion of returns on factors must now be re-explained for the design functions. In addition, the introduction of learning as an output and a condition of innovation, risks generating returns that grow ad infinitum. We must therefore pose constraints on the

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3 In this framework, how are new lines generated? After a lapse of time $t$, lines can be constructed on entirely new competencies. They are generated as follows: a line is enriched gradually by a new competency (which is possible in the above framework). Then this competency, on its own this time, in turn gives birth to a new line.
design function by clarifying the different returns, which we can define using the formalisms mentioned above, particularly the notion of product lineage. Let there be a lineage of innovations $f_1, f_2, \ldots, f_k$ for a single type of goods $g$. Four different returns can be highlighted, depending on whether we consider the design function, whose returns are assessed with respect to the company's profits, or the production function, whose returns are assessed with respect to the quantities produced; also depending on whether we reason in static terms (returns defined at a stage of innovation) or in dynamic terms (returns defined in terms of the progression made over a lineage). The following returns can therefore be defined qualitatively (models of these notions are given in appendix):

1. **Static return on production**: each production function generated is a traditional function, i.e. with decreasing returns on its factors.

2. **Dynamic return on production**: the move from one function to another by efforts in design can give growing returns for a production factor which is common to the lineage. For example, a regular reduction in energy consumption for manufacturing throughout a product lineage.

3. **Static return on design**: this is assessed for a given competency, but on which output? As we have seen, by definition there can be many different types of outputs of a design function (nature of goods, production functions, knowledge). It can therefore be defined more globally in terms of the profits made at a stage of innovation. Here, we can accept the hypothesis of increasing returns at least on a zone of variation of the competency. For example, higher spending on the style of a new product can turn average sales into exceptional sales, and the marginal gains can increase for a greater part of the investment involved.

4. **Dynamic returns on design**: When repeated innovation occurs, we can also define one, or several, notions of dynamic returns on design. The notion can be assessed for a fixed level of competency but whose return on design improves by repetition (e.g. a firm which hires young people with identical diplomas for a single project, but uses their competencies better and better). A dynamic return on design can also be assessed by taking into account the evolution of a competency throughout the lifetime of the lineage, by measuring the relationship between the difference in static returns on design at two given times and the corresponding variation in competencies. For example, improvements in knowledge of a material means that higher value features can be proposed for the product. Then, these features can themselves be used in design to help raise the value of the following products. This type of virtuous circle makes growing dynamic returns on design. It has been described in the past for the steam engine, where improvements were also to the benefit of the engine manufacturers themselves. But can we really imagine that the impact of increased competency on the profits increases indefinitely over time? This would amount to saying that product lineages can be viable indefinitely or constantly bettered by learning. At the very least, it ignores competition. It is more realistic to claim that the dynamic return on design can grow up to a certain point in the lineage, but that it will decrease after that. We will call the existence of decreasing dynamic returns on design the "competition effect on product lineage", which is the same as saying that the longer the lineage, the greater the intensity of competition. New lineages must therefore be launched when additional learning is no longer sufficient to face up to the competition effect on product lineage.
We can see how the formalism of the design function returns to traditional representations when there is no endogenous learning, but that it also serves to highlight new, particularly useful notions for interpreting stylised facts in micro-economic terms.

It simultaneously identifies management approaches specific to the design process: for example, we can see how the static return on design, however low, makes up for the decreasing nature of static returns on production by provoking a dynamic return on production. The firm would be advised to repeat the innovation during the period of strong learning at the beginning of the lineage, but the learning will be less effective if it lets the lineage last too long. The design function opens up a whole range of interventions that restore the potential strategic wealth of determined, organised policy of repeated innovation. We will now go on to see how this model can be used to shed light on the micro-economic theories of innovation.

III. Rereading firm and growth theories using design functions

The theories of endogenous growth can be reinterpreted in the framework of the formalism developed above. In practice, they mobilise *implicit* design functions, built up without specific learnings within the firm. This inevitably imposed an exogenous development of the learnings outside the firm. The firm modelled in this way designs, but learns nothing from the activity.

1- Introducing a dynamic list of goods: an implicit design function

Whereas economic equilibrium assumed a world in which the list of goods is known and static, the hypothesis no longer holds in the case of innovation. Theories of endogenous growth dealt with this by introducing ad hoc micro-economic models for creating new goods, but without specifying their significance in economic or management terms. Romer (Romer 1990) and Aghion and Howitt (Aghion and Howitt 1992a) claimed that Research produces a "random series of innovations". This type of hypothesis became common in innovation economics, as observed by Jones (Jones 1995). These special functions which, for a given input, do not associate a quantity of goods but a variation in the list of goods, are not production functions in the traditional sense of the term, but in fact *implicit design functions*.

2- Design function and theories of the "regeneration" of production functions (Schumpeter, Abramovitz, Penrose and the evolutionary theorists).

The formalism of the design function takes into account a series of traditional criticisms of the production function. Very early on, Schumpeter (Schumpeter 1964) sensed the need for innovative design activity: "we will simply define innovation as the setting up of a new production function". In other words, thinking on innovation must go beyond established production functions. He also pointed out that forms of "change routinisation" were appearing in firms, as technological research was increasingly mechanised and organised and there was less resistance to change, to such an extent that everything that became objectively possible was being attempted by existing firms. Modelling based on the design function does no more than acknowledge evolutions that took place long ago in firms.
Abramovitz (Abramovitz 1952) also attempted to devise a theory of growth in the traditional framework, although he discretely steps out of it by introducing a distinction between "potential productivity" and "effective productivity". He analyses the role of the firm as the capacity to transform potential productivity (which depends on the level of the factors) into effective productivity. He represented the firm as designing the process that enables factors to be organized. However, building this effective productivity is related to how vigorous the spirit of enterprise is in the firm, i.e. essentially to a series of political and psycho-sociological factors. A similar approach was also adopted by Penrose (Penrose 1959) who saw the firm as a collection of resources mobilised by an administrative framework. But, the way in which this administrative framework or the entrepreneur transforms the resources into production factors has not been studied. All these studies challenge the use of the production function as a consistent descriptor of the firm, but as they ignore design activities (apart from Schumpeter's intuitions) they do not propose a formal framework in which new production functions can emerge.

Evolutionary economic theory also criticised the notion of production function (Nelson 1992), Pavitt (Pavitt 1992). However, the formalism adopted consists in a given list of production functions from which the firm must choose (with the constraints of bounded rationality). This therefore concerns a very special class of design functions which are apparently simple decision-making functions (see Hatchuel 2001 for a critical study of the design activity as a decision-making function).

3- Growth theories for the firm do not model the firm's learning

How do these implicit design functions account for the firm's learning?

Jovanovic's model (Jovanovic 1982) represents the firm as a production function where efficiency is governed by a random variable. The firm only knows what is achieved successively by its production function, but it gradually "learns" the overall limits of its potential performance; if the limits turn out to be too inefficient, it withdraws from the market. This model does account for new product development and learning, but the latter does not help improve the firm's performance. It is as if there was a random design function with no memory, converging towards a predetermined production function. Growth is not a result of the firm's "positive" action.

Pakes and Ericson's model (Pakes and Ericson 1998) is presented as a variation on Jovanovic's model where the firm can "actively" explore new possibilities by investing in R&D. However, all investments are mechanically profitable – apart from a probability function – and the firm gains nothing from the learning rents relating to the repetition of the innovation. The implicit design function can therefore present growing dynamic returns, which obviously poses a problem. If there is growth, this is due to a succession of strokes of luck with no memory. We therefore have a single growth path which does not take into account the different trajectories relating to a repeated innovation model.

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4 This summary is widely used by Nelson (Nelson 1997) in a recent critical article on the new growth theories: he shows that most of the growth factors analysed by the theories of endogenous growth already existed in Abramovitz's article.

5 It should be noted that this only concerns productivity: the nature of the goods is still fixed ex ante. Abramovitz does not mention design activities.
More recently, Klette and Griliches (Klette and Griliches 2000) related the theories of firm growth and endogenous growth, particularly with Aghion and Howitt's and Grossman and Helpman's so-called "quality ladder" models (Aghion and Howitt 1992a; Grossman and Helpman 1991). The firm is modelled as a decision-maker confronted with a decision to invest 1 to have the chance of finding an innovation in time $1/\lambda$ later (implicit design function). Once again, there is no learning from one one-off project to another, and the design process produces no excess knowledge. Growth is therefore entirely based on a hypothesis of profit evolution in the form $\pi(k) = \pi(0) \exp (\eta - \pi \times k)$ in which $k$ is the number of the innovation and $\eta$ is a constant characteristic of the growth. But it is interesting to note that this model amounts to laying down an implicit design function, without memory, but with growing dynamic returns on design (as we have seen, the dynamic returns on design are precisely defined by the firm's profit).

4- The design function: a generalisation of endogenous growth models

Economists working on endogenous growth sought to go beyond the view of exogenous technical progress. They reintroduced parameters such as human capital, learning by doing, public capital and technological research and innovation. In this way, Romer modelled growth with positive externalities (Romer 1986) then with an increase of the list of intermediate goods (Romer 1990). Guellec and Ralle completed this model by adding a hypothesis on obsolescence (Guellec and Ralle 1993), whereas Aghion and Howitt modelled Schumpeterian growth in which innovations follow one another at a Poissonian rate and replace one another at the level of intermediate goods (Aghion and Howitt 1992b).

As they were based on common formalisations (Artus 1993), these models could have led to a general framework for design activities, but they actually resulted in particularly restrictive models: restrictive forms of learning (knowledge is not considered to be an actionable variable and the transfer of knowledge between designers and producers is modelled by transmissions of goods); restrictive forms of division of labour between firms (the models comprise two or three widely "decoupled" economic sectors in which specific goods are exchanged); restrictive forms of innovation (increase in the variety of goods at a regular rate or by a random Poisson process). All these restrictions amount to positing implicit design functions which do not allow for any learning. They reintroduce, at the level of the firm, the phenomenon which they sought to go beyond: exogenous learning. We can demonstrate this by reinterpreting Aghion and Howitt's model (Aghion and Howitt 1992b) using the formalism of design functions.

Let us examine what they refer to as the research sector. Research uses qualified workers ($n\%$ of total $N=1$) and produces innovations at a Poissonian rate of parameters $\lambda, \varphi(n)$ (with $\varphi(n) = n$). These innovations are patents. Research is therefore a design function $f_R$ which assumes as inputs the list of patents already registered (goods $G_i, i=1...n$) and knowledge $K_1$ which is assimilated with the quantity $n$. The output of this function is the patent $G_{n+1}$ which emerges after a random period of time according to Poisson's Law. There is no learning. This amounts to spending the input $n$ whatever happens, to have a chance of obtaining the patent at a later stage (without further expenditure), with probability estimated using Poisson's Law. In the formalism of design functions we can therefore set down:

$$f_R: G_{i,i=1...n} \text{ Poisson } \rightarrow \{G_{i,i=1...n+1}, \delta K_1 = 0\}$$

One can notice that it is not a regular production function since it adds a new good to the set of known goods.
Manufacturers of intermediate goods have a production function for the intermediate good (which we refer to as $G'_{i}$) which in fact amounts to $Q_{G'_{i}} = N-n$ during the period of time $t$ preceding the following patent. The function stops there. Hence, the following design function for the manufacturer relating to patent $G_{i}$:

$$G : \{ \} \quad t \text{ Poisson} \begin{cases} G : G'_{i} \text{ avec } Q_{G'_{i}} = N - n \\ \partial K_{1} = 0, \quad \partial K_{2_{i}} = 0. \end{cases}$$

The manufacturers of final goods (constant single goods) are represented by an aggregate production function $y = A.F(x)$ where $x$ is the intermediate good (which we refer to more precisely as $B'_{i}$), with $A = A_{0}.\gamma_{i}$ where $i$ is the patent's order number. In other words, in the framework of design functions, we have in fact a series of design functions (a function for each intermediate good) which can be set down as:

$$f_{\text{final}, i} : \begin{cases} K_{1_{i}} : N - n \\ K_{2_{i}} : G_{i} \end{cases} \quad t \text{ Poisson} \begin{cases} y_{\text{final}} = A_{0}.\gamma_{i}.F(Q_{G'_{i}}) \\ \partial K_{3_{i}} = 0. \end{cases}$$

Modelling by design functions enables us to reinterpret the meaning of what is described in economic and management terms:

- The approach assumes a permanent design activity: in fact a series of production functions are generated both on the level of intermediate goods (where a new good is designed each time) and for the final good (where a new process and the related skills are designed each time).
- This design "costs" nothing (it appears nowhere in the price equations).
- None of the design activities spark off learning. No excess knowledge is produced either: all knowledge is used completely and directly in the design function concerned. In particular, the research activity systematically leads to a patent.
- No knowledge is lost from one market to the next: the patent is transmitted downstream in its entirety; the intermediate goods are transferred with no problems whatsoever.

We are therefore dealing with very special design functions which produce no excess knowledge, either in relation to the research activity or the other activities. In this context, growth is not related to reusing this knowledge, but springs from the mechanical impact of the research activity on innovation. In other words, the hypothesis of a direct relationship between the level of research and the results consists precisely in exogenizing the learnings as they do not depend on the successive innovations.

We would no doubt reach similar conclusions for other authors. The fact that there is no explicit model for the design function means that the firm's learnings must be exogenized. Hence there are no product lineages and the process described does not correspond to a process of repeated innovation, although we have demonstrated the latter's importance for innovation in the firm.

The above points underline the contribution that a general model of design functions can make, both in general terms and even in terms of simplicity. The expansion of goods and competencies by the design activity can be axiomatized from the outset as a potential inherent to the definition of the firm. It must keep this potential up to date, with its own specific static and dynamic returns, by managing a process of repeated innovation.
IV. Conclusion: The first lessons to be drawn from the design function model

Modelling the firm by design function reproduces the many action levers for the firm's growth by innovation. It restores the microeconomics of innovation and founds the formal basis of innovation management. If we take into account the recursiveness of design functions (fof law) and the different types of returns in play, we can understand how different types of design management arise and tie in with the wide variety of profit strategies observed (Boyer and Freyssenet 2000). It also helps explain why certain particularly "deviant" firms are able to obtain exceptional growth by innovation due to their specific organization.

The model also underlines that the economic result of an innovation or a new product cannot be limited to the revenues created by it, but must also take into account the simultaneous learnings, even if they are not desired. However, their value depends on their use in the future. This, in turn, depends on the design strategies: the value of a new project therefore depends on the ability to use all the opportunities it creates in an appropriate manner. We can call this the "capacity to follow up the innovation". If no use is made of the learnings springing from design, we revert to the traditional growth models.

The design function makes a "prudential" strategy compatible with a sustained innovation policy. A strategy can be considered prudential when, for a single new product, it does not jeopardize the firm's survival (Chapel 1997). The design function allows for the elaboration of "martingales of innovation" for which each stage is prudential (low static return on design) but whose overall trajectory can be highly innovative (very high dynamic return on design for part of the lineage until the competition takes effect). This does not mean that each stage is reversible, but that it makes a transition that creates new opportunities where learnings from the lineage are consolidated.

Managing the learnings at each stage within a lineage, or between different lineages, is a determining factor for repeated innovation. If "excess" knowledge is not reused, or is done so in an inefficient way, the evolution (and the cost) of the design functions will have little impact on the firm's competitiveness or growth.

Hence, this model opens the way to several paths of research that we can only summarize briefly here, but that will be studied in future articles.

- **Repeated innovation and strategy for the acquisition of competencies**: Modelling of repeated innovation by design functions may lead to paradoxes in terms of the acquisition of competencies. When should new experts be recruited? At the start of a product lineage, or when all the potential projects cannot be handled? Could it not be preferable, in some circumstances, to give up certain projects and refrain from recruiting new people, in order to maintain the dynamic returns on design for the projects in progress?

- **The paradox of R&D, a natural consequence of design functions**? Design functions cannot give rise to optimisation strategies in the same way as production functions. This means that the level of investment in creating knowledge has no possible mechanical relationship with growth. As we saw above, the efficiency of the investment depends on four different returns that the firm must consolidate and adjust each time. The paradox of R&D can therefore be expected to increase with the efforts made in terms of design. Only an overall improvement in the ability of firms (or at least a significant number of them) to organize repeated innovation will temper the paradox, without being able to end it
completely. Le Masson (Le Masson 2001) showed by simulation how this paradox immediately arises in economies where design activities exist.

- **Repeated innovation and public innovation policies**

As we have seen, endogenous growth models were based on exogenous learnings. Innovation-related aid is considered as aid to a sector of research, under the assumption that the knowledge produced will be disseminated throughout the economic fabric. Modelling by design functions insists, in addition, on the importance of internal learnings and the rationale of designing lineages. This appears to be confirmed by most historical studies of the industrial revolution, for example. Another type of aid to innovation then emerges that appears to support an improvement in design capacities or in the organization of learnings. For instance, it can be posited that subsidies should not only be given to a first innovation, which is always difficult to assess, but also and above all to the second attempt, on the basis of what has been learnt from the first product, if the results obtained do not allow the firm to get by on its own. Nonetheless, for this idea to be validated, it is essential to analyse the firm's design functions.

To summarize, modelling by design functions re-establishes the profound nature of firms. It fosters innovation strategies supporting sustainable growth. Innovation is no longer seen as an isolated event in the firm's history, but as its central metabolism, although the latter does not guarantee that high investments in R&D will necessarily result in growth. This can only be obtained at the price of appropriate, prudential and continued management of design learnings. Finally, the introduction of design functions explains the paradox of endogenous growth theories which, failing adequate micro-economic representations, have been obliged to reintroduce learnings which are exogenous to the firm.

As the current period is quite obviously characterised by competition by innovation and by unprecedented expenditure on R&D, we might ask ourselves what justifies the persistent use of models that limit research in Economics and Management, and which are clearly out of step with current knowledge on the innovative firm. The model proposed in this article is not the only possible one, but it does enable us to simultaneously improve theoretical unity and realism. It also demonstrates the kind of results that can be expected from cooperation between management research and economic modelling.

**APPENDIX: modelling static and dynamic returns for a design function**

Let there be $f_p(W_1, \ldots W_n)$ a production function with $W_1, \ldots W_n$ as production factors.

Let there be $f_d(G_{inputs}, K_1, \ldots K_n)$ a design function with inputs $G_{inputs}$ and $K_1, \ldots K_n$ respectively as goods and knowledge. The output of $f_d$ in the space of goods, denoted $f_{c, G}$ is a type of good $G_{m+1}$ and the production function associated with this good.

**Notion of static return on production**

The *static return on production* for the factor $W_i$ is: $\frac{\partial f_p}{\partial W_i}$. This term is decreasing with $W_i$.

**Notion of static return on design**

The static return on design is calculated for a competency taken as an input of the design function. It measures the impact of an increase of this competency on the output of the design function in the space of goods. This output is not only the associated production function, but also the possible impact on the usefulness in the eyes of the consumers. It is therefore preferably defined by the profit made on the good $m+1$, noted $\Pi_{m+1}$, thus taking into account the combined effects of changes in the
nature and the function of production. It can be written as \( \frac{\partial \Pi_{m+1}}{\partial K_j} \). This term is not necessarily decreasing with \( K_j \).

**Notion of dynamic return on production**

Let there be \( f_{p,j}(W_1, \ldots, W_n), j=1 \ldots p \) the series of production functions of a given good \( G \), each term in the series being obtained by redesigning the process. Hence a series of functions \( \frac{\partial f_{p,j}}{\partial W_i}(W'_i) \), \( j=1 \ldots p \). For a set level of \( W_i \), the series of values taken by each of the functions is not necessarily decreasing for the number \( j \) of process redesigns. The dynamic return on production can be expressed as the return on the process redesign, i.e. the difference between two successive terms in the series. It can be expressed as follows: \( \frac{\partial f_{p,j}}{\partial W_i}(W_i) \)

**Notions of dynamic return on design**

Similarly, we can define the series of profits \( \Pi'_j, j=1 \ldots p \) relating to the series of goods \( G_j \) over the lineage. Each profit is an indicator of the component in the space of goods of the design functions \( f_{d,j}(\text{inputs}, K_1 \ldots K_n) \). We can obtain the series of static returns for a set level of competency \( K_i \frac{\partial \Pi_j}{\partial K_j} \), \( j=1 \ldots p \). The series is not necessarily decreasing for the rank \( j \) of the product over the lineage. The competition effect on product lineage consists in saying that the series is decreasing as of a certain rank.

It should be noted that there are two possible ways of expressing the dynamic returns between design \( j \) and design \( j+1 \). As we have done above, we can set the level \( K_j \) for the good \( j \) and the good \( j+1 \) and calculate the difference between the terms in the series. But this does not take into account the impact of learning during the design of product \( j \), or the design of product \( j+1 \). It is possible to express a dynamic return on design compared with an effort in learnings. Take \( K_{i,j} \) the level of \( K \) at the start of the design for good \( j \). \( K_{i,j+1} \) is in fact the output of the design function \( f_{d,j} \) in the space of knowledge, on knowledge of the type \( i \). The dynamic return on design throughout the lineage can therefore be denoted as follows:

\[
\left( \frac{\partial \Pi_{j+1}(K_{i,j+1})}{\partial K_{i,j+1}} - \frac{\partial \Pi_j}{\partial K_{i,j}} \right) \frac{1}{(K_{i,j+1} - K_{i,j})} \text{ or } \frac{\partial^2 \Pi_j}{\partial^2 K_{i,j}} \text{ with } K_{i,j} \text{ defined throughout the learning trajectory on the lineage. This gives a form of calculation for returns on learning on the lineage.} \]
Bibliography


