THE DEVELOPMENT OF SCIENCE BASED PRODUCTS: MANAGING BY DESIGN SPACES

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Abstract

The design of Science Based Products (SBPs) combines three main issues: i) to explore a functional space; ii) to produce scientific knowledge on key phenomena of the concept; and iii) to be manageable. The literature usually considers these objectives as difficult to reconcile: a project involving functional exploration and phenomenological exploration should be unmanageable. However, based on two SBP cases, we show that this point of view is mainly due to a lack of relevant theory of design management. In this paper we introduce the notion of design space as a collective working place where designers can "act to learn on what has to be learned". We show that the design of a SBPs is managed as a sequence of design spaces.

Introduction

An increasing attention is paid to innovation management as many businesses face a severe competition that demands more than cutting lead times and updating existing products. The literature on the subject has grown along three main issues:

1- *A growing need for new scientific knowledge*. Scientific knowledge production is often seen as the task of basic research centres where researchers should be free to launch there investigations. However since the 80s and 90s, several firms have renounced on having their own basic research labs [1] and there are today questions on how to manage this production of scientific knowledge: how to acquire it when needed ? How to maintain research partnerships with public labs?

2- *A need to break with the traditional functional spaces*: when industries are following dominant design, it is enough to compete along the well-established functions of the products [2,3]; today competition requires to investigate new functional spaces and anticipate on disruptive innovations [4].

3- *A need for control over the costs and risks of the innovation processes*. After rationalizing production costs, managers are today looking at R&D costs [5]: how to reduce them to increase the company's profitability? This occurs in the above described context where more R&D would have appeared as a good solution. As a consequence it appears that one has to look for managing the process and not only demanding more resources.

Even if these issues might be more or less separate, one interesting research approach consists in focusing on projects where all three issues are simultaneously involved. That's why we focused our work on the development of Science Based Products (SBP), i.e. developments of products requiring both scientific knowledge production and functional space exploration.

This paper shows that the management of SBP can be only partially interpreted within the classic management concepts, and that it requires new ones. We will introduce both theoretically and empirically the notion of Design space: *a Design space is a collective working space where designers can act in a way that enables them "to learn on what has to be learnt*". The notion of design space helps to clarify what can be observed in several SBP processes, it explains pitfalls, difficulties but also successes in the management of SBP. Our aim is to show how design space management works in specific cases and to why it is a framework based on SBP's introduces a new wider perspective for product development management.

The paper is organized into four sections: we first define what is a SBP and summarize what is already known about them and what are the main issues. Using design theory to analyse SBP development we explain in part II why a new model is needed; in part III we define more precisely the notion of design space and shows how it supports the development of SBP. We then conclude by addressing the main issues in the management of design spaces and by showing how the notion of design space can be extended well over the strict limits of SBP.

1 Part 1: Science-based products: crossing several literatures.

1.1 SBPs: an actionable definition.

In this paper we define Science Based Products development by two related issues that are well recognized at the launching of the project :

– i) the product concept still requires *functional definition.*

– ii) the development requires a program of *scientific research* about *the main phenomena* associated with the product;

This definition implies some distinctions:

– *A SBP is different from applied research in NPD*. Applied research is usually considered as the application of scientific results already obtained by basic research. In SBP the scientific research work has yet to be done as learning is needed on largely unknown phenomena that are essential to the project. Also usual ”applied research” addresses well identified functions; in our definition of SBP, functions are also unclear and the investigations on the phenomenon are suppposed to help to clarify them.

– *A SBP is different from basic science program*. A basic science program is usually considered as a program that works on a given phenomena without clear identified application goal. A SBP clearly aims at developping a product: some functional goals can be formulated yet only very partially [See 6].

Let's give some examples of SBP projects. *The design of new drugs* in pharmaceutical industry: it involves scientific research in chemistry, biology, biocomputer science,... with large debates around the functions (the disease to be cured is just a broad target). In the literature, *the cochlear implant development*, described in the ”Innovation Journey” book [7]: it involved research in electronic, acoustics, physics, speech processing,... and the functional space was clearly unknown (deep or partial deafness, more or less adaptable, more or less invasive,...). The developemnt of *Nylon hosiery* [8]: the design of a new textile fiber involved basic research on polymers while the intended functions were unclear at the beginning of the projects when it wasn't even question of hosiery!

Thus our definition of SBP's is easily *actionable*: it is possible to operationnally identify a SBP, and identify it ex ante. It is not necessary to wait the end of the project to known whether it was a SBP or not. This approachs differs from the classic definition of innovation inherited from economic statistics [9]: a successfully sold invention as success can only be assessed ex post. This operationnal aspect is a necessary to assess that it is a notion acceptable for management theory.

1.2 SBP in the literature: what do we know about SMP?

SBP is not an existing notion of the literature. However the literature on NPD offers important amount of knowledge concerning SBP's. This literature can be classified into two main trends: on the one hand, authors criticized classic NPD for being poorly adapted to innovative products and tried to improve it in this direction ; on the other hand, authors studying innovation processes try define some framework for the management of these innovation processes without reference to NPD. Studying SBP crosses these two main trends.

SBP and NPD: the management of knowledge production

a) Authors have already pointed out that “traditional” project management relies on strong hypotheses that are not suitable for innovation. Wheelwright and Clark [10] spoke of “pizza bins of proven technologies” (p. 40) and Clark and Fujimoto [11] underlined explicitly that “ Basic research or advanced engineering aimed at searching for technical possibilities is generally outside the scope of [their] study” (p.26, footnote). In NPD, there is a clear and identified goal of the project. This hypothesis does not exclude innovation but it restricts it to well identified areas, for instance through the division of the product in separate modules where innovation is accepted whereas it does’nt change the division [12]. But how should one organise when the main goal is unknown or when it is not possible to divide the design work into modules and sub-systems? Recently Lenfle and Midler [13] identified new types of project called “innovative proposal projects” (IPP) [14]: contrasting with the traditional project management, based on proven technologies, an IPP has to introduce a new technology and as a consequence, different opportunities must be experimented and studied carefully.

b) To foster innovation, authors focused on the beginning of the projects, managing the “fuzzy front end” (FFE) was as a way to reduce the time to market (as said by Reinertsen: “to beat an Olympic Runner in the 100-metre dash, start running a minute before he does”, [15]), or as a way to stepwise refine early business analysis (assessment, detailed market studies, competitive analysis, concept tests [16]). Khurana and Rosenthal [17] saw FFE as a process that integrates “product strategy formulation and communication, opportunity identification and assessment, idea generation, product definition, project planning and executive reviews”. And Koen et al. [18] proposed to speak of Front End Innovation (FEI) focusing on two main issues: idea generation and opportunity recognition. Brainstorming and creativity appear as ways to enhance the idea production [19]. Christensen [4] and Leifer and Rice [20] insist on alternative ways for ideas and projects portfolio screening to avoid rejecting breakthrough innovations [21]. These studies underlined the difference between “front end”, or other pre-project phases, and the project development itself. In these upstream phases science is not excluded but it can only be a provider of “ideas”. Hence, these works suggest that innovative concepts have to be prepared upfront but there is no specific role dedicated to science. We will then more specifically focus on *how the scientific way of producing knowledge can be used for structuring and enriching the fuzzy front end phases*.

c) Instead of focusing at the “front end” of product development, authors have already stressed the fact that research activity is not at the beginning of the process, but all along the development process [22]. Myers and Rosenbloom [1] broadened the view: the design process needs also firm specific knowledge, communities of practice and technology platform joining the core competencies and technology management [23-27]. Teece and Pisano insist on the “dynamic capability of the firm” [28], the ability of the firm to integrate new competencies. Yet, this literature maintains a very abstract way of looking at the innovation process: the organization scans and searches its environment to pick up signals about potential innovation, it selects an option, resources it and then implements (Tidd et al. [27]). The innovation remains an “exogenous” process which is only managed by resource and knowledge acquisition. By contrast, *studying SBP’s allows to investigate in detail the issue of knowledge production for the design process*: it mobilizes extremely controlled ways of producing knowledge in order to understand how the knowledge production interferes with the design process. On this point, we will build on the works of Thomke and his colleagues on the experimentation techniques and their impact on the experimentation strategies [5,29,30].

They model the design process as an iterative trial and error process in which managers have to identify what are the most useful (say "learningful") trial techniques for each phases. Yet, this approach still do not address the *issue of functional space exploration also important to* SBP's.

SBP and innovation processes: what is managed?

Innovation processes have been seen as distinct from any "development". Burns and Stalker [31] insisted on the "organic" features of innovative organizations, as compared to "mechanical organizations". Innovation activity is often described as "skunk work" or by processes that need alternative managerial principles [20,32]. Tushman and Anderson speak of "ambidextrous management" that protects and enhances "entrepreneurial units". Leifer and Rice insist on "incubating arrangements" for innovation. Nohria and Gulato studied how slack can be useful for innovative organizations [33]. Van de Ven et al. [7] led in depth studies on the "innovation journey". They underlined how "events" pace the innovation maturation. However, these authors do not address the issue of innovation *management*. Van de Ven et al. describe innovation as an "inherently uncontrollable process"; managers can only "enable" and take "pragmatic decisions" to react to changing conditions. *The process appears as largely unmanaged and chaotic*. Thus, it seems that the richer the authors describe innovation processes, the less they recognize their management principles.

Yet, Jolivet et al. [34] proposed a methodology for managing breakthrough innovation. Based on Van de Ven et al. descriptions, they proposed (1) to describe "internal scenarios" that are embedded in the project and (2) to reach collective agreement on breakthrough innovation. Relying also on "Actor Network Theory", they suggest to map the emerging innovation journey. Yet, network building or activity is not specific of the innovation journey, it could also map the practice of a salesman. Selling and idea is part of the job but it ignores the content and emergence of the idea : i.e. the design work itself. Mapping the innovation network could partially help, but it does not investigate on how alternatives design and learning choices are made. These works on innovation processes describe a sequence of actions but the way they interpret them do not help us to investigate the issue of managing these actions*: should we accept the underlying hypotheses that it is a non manageable process? Or is it the theoretical lenses of the authors that prevents them from recognizing management processes?*

Our empirical work on SBP's confirms largely the descriptions of this literature. However we will also show that, with a new managerial model –i.e. with revised lenses- it is possible to find how SBP are manageable.

1.3 Main hypotheses on the management of SBP development:

We can now formulate our main hypotheses:

- **Proposition P1** : SBP management requires a new managerial model.
- **Proposition P2** :We introduce the notion of Design space, a space of collective work where knowledge is produced in relation with the overall SBP process. *We claim that building design spaces enables management and the knowledge production in relation with the design process).*
- **Propositions P3**. A design space is characterized by different types of initial knowledge and hypothesis (knowledge on functions –F-, on phenomena –P- and on the devices themselves and more generally on the way that the P-space and the F-space are coupled in the design space –L for likelihood). Within a design space, the design process can be *traced* by the knowledge increase on F, P and L. From this model we will derive some principles for the management of design space and SBP development.

1.4 Research methodology: wearing the good lenses.

In this paper we present two specific SBP projects where we pay a particular attention to the way the scientific knowledge production is stimulated and to the parameters and dimensions coming from the definition of design space. *This will clarify what is managed in both projects and what are the main pitfalls in SBP management*. The cases are used for illustrating and testing the theory. In the following, Part 2 presents two cases of SBPs and underline the need for a new managerial model to overcome the "seemingly chaos" of SBPs. In Part 3 we will define in detail the notion of design space and discuss its interpretative and managerial power about SBPs development (difficulties, reasons of success…). We will discuss some specific : what is an "ill-configured" design space? What are the human resources of a design spaces? What can actually be learned in a design space? In part 4, we discuss the generalization of our model to innovative design projects.

2. Part 2: Two case studies of SBP development : in search of management actions.

2.1 Checking our cases: do we have SBPs.

Case 1 WITAS. It is a project, funded by the Knut and Alice Wallenberg foundation, and monitored by universities and one big aerospace company. WITAS was initially considered as a "moon lander" project, i.e. a big challenge that may catalyse research. Looking at "robots that fly" appeared as a good vector both for basic research and applications-rich advances. The project intended to prototype a fully autonomous flying vehicle (Unmanned Autonomous Vehicle, UAV) with one application area. Because of possible civil applications, traffic surveillance was chosen (emergency service assistance, catastrophe management, traffic management). This project was sufficiently challenging for research disciplines and there was simultaneously a clear demonstration focus, to prove results, not only in an academic research matter.

What are the main results of WITAS?

– Several research papers and thesis in the fields of computer science, image processing and control;

– Innovative architectural software solutions for autonomous flying objects: researchers addressed the important question of interaction and interplay between traditionally separate "control", "reactive" and "deliberative" layers. This division relies on different computational paces: 100ms / 100 to 1000ms / more than one second; it also relies on science division: control science for the first one; computer science and AI for the other two. Researchers were led to address the issue of switching from one layer to the other and having an architecture that support this kind of boarder-crossing phenomenon (deliberative / reactive and reactive / control).

– Researchers also discover that an "autonomous flying object" is not a clear function and the first prototypes helped to investigate the issue: *what is an "autonomous flight"?* It appeared that a 100% autonomy was not relevant: WITAS had rather to investigate a spectrum of types of interactions between operators and the helicopter platform, addressing indeed "basic" functions like "autonomy and functional degradation" or "autonomy and goal setting".

Case 2 ENERGY, involved a public research lab on energy and a car maker that jointly explored how to provide a car with thermal comfort via vertical slow airflows from the ceiling. The idea was to provide new types of thermal comfort, not being limited to a mean value of thermometers measurements.
What are the main result of this ENERGY project?

– Knowledge on vertical airflows and their cooling capacities. Researchers and engineers learned on several architectural principles, on filtering and diffusing technologies, on aerodynamics behaviours of vertical airflows in car interiors,…

– Researchers and engineers were also led to revise their understanding of the thermal comfort. They identified two thermal regimes: the first consisting in fast decreasing the interior temperature; the second in keeping low temperature. It also appeared that the traditional air conditioning systems were adapted (and designed) for the first regime whereas the vertical airflow cooling system rather addressed the second regime.

One can first notice that these cases correspond to SBP: "autonomy" and "thermal comfort" appeared both as uncertain functional spaces; science appears in both cases and addresses the main phenomena (control and AI in WITAS, energy studies in ENERGY) and in both cases there was new knowledge produced on these main phenomena. Last, these weren't only "stories" without control: the projects were managed (in the WITAS project, by the WITAS steering committee and the project manager; in the ENERGY project by the car maker exploratory team on energy).

However one can observe that WITAS and ENERGY are more precisely parts of broader SBP: neither WITAS nor ENERGY gave immediately birth to a new product. The cases address more precisely the initial phases of the related SBP, where the list of specification is still unknown and the competencies are largely unknown.

2.2 What do we describe ? From "seemingly unmanageable" to a sequence of managed phases.

How should then one describe the history of these projects? Confronted to this question we have been led to assess the limit of the traditional models for SBP description and management.

a) Following Van de Ven et al. an "the innovation journey […] is modelled as : "new IDEAS that are developed and implemented to achieve desired OUTCOMES by PEOPLE who engage in TRANSACTIONS (relationships) with others in changing institutional and organizational CONTEXTS" [7, p 6-7]. In this author's methodology any change on one of these five dimensions is an "event". If we use this methodology, for instance in WITAS, one actually finds regularly new ideas, evolving outcomes, changing research teams and project leaders, evolving contracts with the steering committee and with other contributing research teams from Europe and the US,…The same holds for ENERGY. However, if this model captures in detail a set of events, it is obvious that its own logic will easily shape the observations in such a way that a seemingly chaotic picture appears, with a lot of diverging events and no managerial logic or impact. How to account for the type of management that supported the projects?

b) Let's try the NPD model. Obviously, we don't expect a pure NPD process, since functions are initially unknown and competences are not available. However, can we recognize FFE or "scan and search" strategies?

- In WITAS, we were surprised to observe *not one but several repeating FFEs* where functions were discussed and new architectural alternatives were investigated; these phases were also closely linked to several cycles of knowledge production in research experiments. We identified indeed two main phases: at first a work division occurred and image processing and computer science teams worked independently on issues around autonomous flights; in a second phase, under a new project leader, one prototype was built, several test campaigns gave new ideas and new knowledge, and they paced the investigations of the labs.

- In ENERGY, we observed similar patterns: three phases of FFE appeared and each of this phase required idea generation, functional exploration or at least functional definition, and knowledge production or acquisition.

b) We then remark that each FFEs gives birth to a *learning phase*, each of these phases being a kind of "moment of equilibrium". We were first struck by the fact that facing broad issues, like UAVs or innovative thermal comfort in car, the exploration occurs first by addressing a "confined" issue: "demonstration of an autonomous flying helicopter for traffic surveillance", "a demonstrator of vertical slow airflows"… Second, there was not only one single prototype, but a sequence of prototypes or demonstrations: a sequence of WITAS demonstrations, a sequence of trials around vertical airflows,… And the prototypes were linked together: from one prototype to the other, the functions of UAVs or thermal comfort are explored and enriched, and several scientific phenomena are investigated and better understood.

2.3. Reshaping the interpretative model.

These observations led us to the hypothesis that both projects required a new model: a new interpretative model (see proposition P1) *that allows to unveil management issues and interventions*. Note that his result is not only true for these two projects: any SBP will include at least one specific learning phase (and more generally a sequence of learning phases), namely the one related to the scientific knowledge production. Explanation: scientific research needs a controlled process, it requires specific types of confinements (be it laboratory bench or ethnographic observation); while the SBP issue addresses broad issues where objects are not confined (if they are even known…) and have to be explored. Therefore the SBP development requires that a restricted area for scientific research is selected. In this area, knowledge will be produced. This knowledge will then be used back into the SBP design process. This process of area selection, knowledge production and knowledge use in SBP is crucial for the SBP management operations: who selects the learning areas? How do learning reacts on the SBP development?

Therefore we have necessarily *two management processes* acting simultaneously: one which can be described as the repetition of FFEs and one who is formed by learning phases. *It is the combination of these two processes that produces a seemingly chaotic, unmanageable process if we do not recognize that this combination corresponds exactly to a sequence of design phases that we are going to model in more detail now.*

3. Part 3: Managing by design spaces: a model for managing SBP.

To describe more precisely this sequence of learning phases. We introduce now *a model of Design space* and its main dimensions.

3.1. Defining a design space and a transition between design spaces.

Broadly, we define a **design space** as *a collective work space allowing design activity i.e. aiming at enabling designers to learn on what they want to learn for their overall design process*. Let's model that more precisely: if one represents the designed object as a set of properties, the design process consists in step by step defining these properties. In this model, a design space is an action space for a group of designers, in which they can drive a design activity, this design activity *doesn't necessarily address directly all the properties of the target product but does address a limited number of properties (or constraints) that will help to design the future product*. More precisely one can notice that there can be several types of properties: (i) the specifications that have to be met (functions) and (ii) the design parameters that are defined by the designer and the implied constraints [For examples of this modelling, see 35,36]; moreover, the link between design parameters and functional requirements is based on phenomenological laws; last, the evaluation of the designed object performance requires specific evaluation devices. This indicates three main spaces: a functional space (and its related space of design parameters) **F**, a phenomenological space **P**, and a device space, to which one refers by **L** (for likelihood function, since this device space is equivalent to a likelihood function L(F, P) of an event having F for function and P for phenomenon).
In traditional NPD, P, F and L are well-known. In SBP, P, F and L require deep investigation. And any SBP implies *a scientific design* space for investigating F, P and L. In such a design space (design space 1 in figure 1 below), knowledge is produced in a highly controlled way. We can then distinguish three main dimensions of this learning:

– the space of phenomena addressed by this design space (P1 in figure 1). These phenomena are the main objects of science. A “pure science” design space will tend to increase knowledge on phenomena **(δP1**). We can mention well-known phenomenological knowledge: mass conservation, electronic charge conservation (Maxwell Gauss law), energy conservation (or first thermodynamic principle),…

– the space of functions (F1), i.e. some functions of the SBP (and occasionally others) that are addressed in the design space and are increased in the exploration **(δF1**).

– a set of functions (L1) which represents the previous knowledge (principles, experts) and techniques that allow to couple both spaces of functions and phenomena. As an example an experimentation device on the cooling capacity of a vertical airflow will link a (partially unknown) family of phenomena and a (partially unknown) family of functions, and the link will be adjustable, depending on the capabilities of the device (adjust airflow temperature, airflow speed, airflow direction…). New knowledge on L will be noted **δL1.**

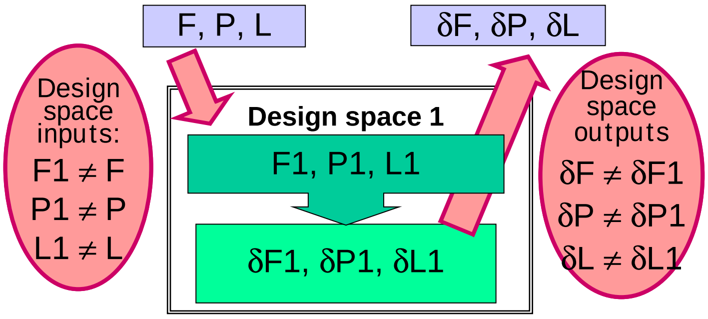

Figure 1: design space management process and design space management principles

We also define the notion of **transition between design spaces** as a reformulation of the SBP concept (see illustration in figure 1). This reformulation can address the functions of the SBP (F, increased by δF), the phenomena involved in the SBP (P, increased by δP) and the evaluation processes related to the SBP (L increased by δL). This reformulation will support the identification of a new design space.

With this model, we will reinterpret our two cases and show how design space management actually helped to overcome the traditional traps of innovation processes.

3.2. design space and design sequence in WITAS and ENERGY.

<u>ENERGY case</u>

The ENERGY issues concerned a functional exploration on thermal comfort, a phenomenological exploration on vertical airflows and an exploration of the coupling between energy phenomenon and thermal comfort. We summarize this in the upper left cell in the table below.

In a first phase, the ENERGY partners decided to build a prototype for vertical cooling airflow in an existing vehicle. They intended to test whether there was a reasonable cooling capacity (F1), to learn on vertical airflows in car (P1) and to tune aero-thermal models (L1). This leads to the first design space. Designing the prototype helped them to learn on the three spaces (F1, P1 and L1). This learning was then transferred to the overall ENERGY project. We represent this loop in figure 2 below. One can notice that this first phase is P-oriented (produce the phenomena) and F is reduced to a type of “killing” criteria: the phenomenon should at least meet a limited performance for deserving further exploration. This design space here avoids the classical trap of immediately trying to be representative and evaluating whether the phenomenon meets the whole set of car specifications. The research lab claimed his prototype not to be car representative but rather to be a “phenomenological” prototype. This preserved a P-exploration in design space1.

Design space 2 and 3 were actually launched in parallel. Design space 3 was intended to further explore functions. But a new opportunity appeared in between: by the car maker, the Air Conditioning engineering department heard about the new concepts studied by their colleagues from the thermal exploration team. They were interested and offered a possibility for testing the technology. Both the research lab and the thermal exploration team were happy to catch this (apparently) good opportunity for quickly testing and hopefully developing their concept.

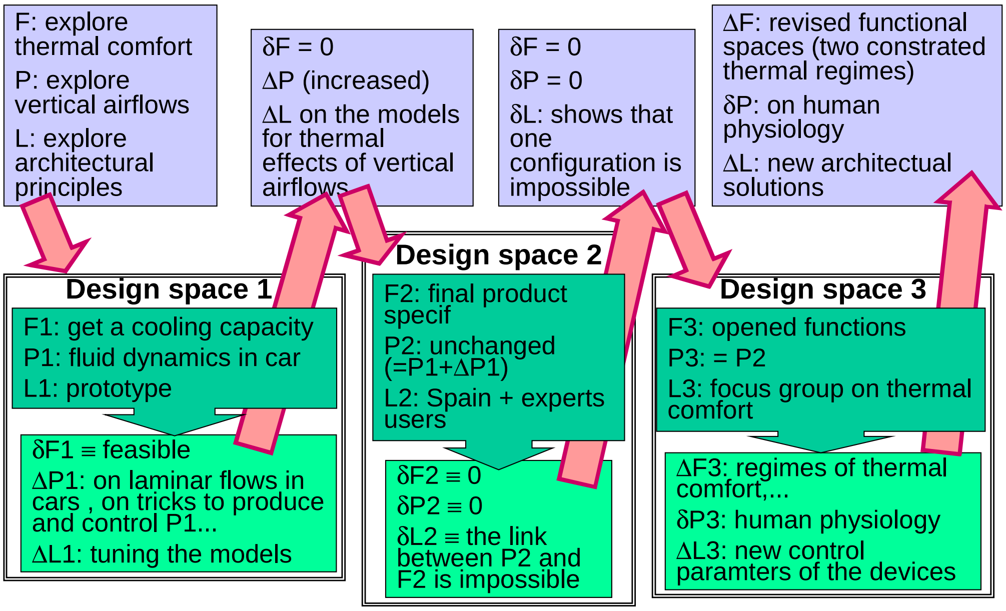

Figure 2: ENERGY design spaces (red arrows indicate how to read the table)

This design space2 was clearly built as a validation: the functional dimensions were strictly fixed in accordance with the set of specification that has to be met by a traditional air conditioning system. Since the traditional system consists in a cold turbulent airflow that is supposed to quickly cool down the car after a long park time in the sun, one criteria was for instance a minimal speed. The vertical slow airflow system couldn’t meet this requirement since it was on the contrary built on laminar regimes that require extremely slow flows. The prototype was taken to Spain and evaluated by experts users that check whether the car (among several others) met the traditional specifications. The result was unsurprisingly negative! This implied two conclusions: this design space 2 led to very few learning; this design space 2 could have killed the whole SBP. Actually it led to conclude that vertical air-flow system weren’t “car-worthy”. Design space2 embodied the temptation of the “realistic” trial and it had failed. How to go out from this trap?

There were then two main solutions: either revise P or revise F. A design space 3 explored the second issue. It was oriented towards functional exploration. A focus group was organized to analyse, describe, criticize and propose improvements for the types of thermal comfort provided by the vertical airflow system and the traditional air conditioning system. This didn’t intend to explore the airflows phenomenon but it led to new knowledge on human physiology. However it mainly supported learning on what could be thermal comfort. Among several results, this design space 3 gave the main result of the SBP: one can differentiate between two regimes in thermal comfort, the “cooling down” regime and the “low temperature keeping” regime. This also led to revised the architecture for a dual system. Therefore, this design space 3 opened new horizons for vertical airflows.

What are the lessons to learn from the ENERGY case? First one can now *understand* where the results come from, what were the main failures in the management (the temptation of the design space 2) and how the success relied on carefully managed design spaces (design space 1 and 3). Second this also *supports management reasoning*: when should P be investigated, when should F be explored. The sequence of design spaces shows how P is first explored with little functional learning and then

F is explored (with limited phenomenological learning).

Design spaces in WITAS case

Designed as a ”moon lander project”, WITAS aimed at exploring functional spaces around autonomous flight (with traffic surveillance) and at exploring new phenomena in such sciences as computer science and image processing. It was clearly said that the ”flying object” didn’t have to be airworhty, so that competences on control weren’t concerned at first.

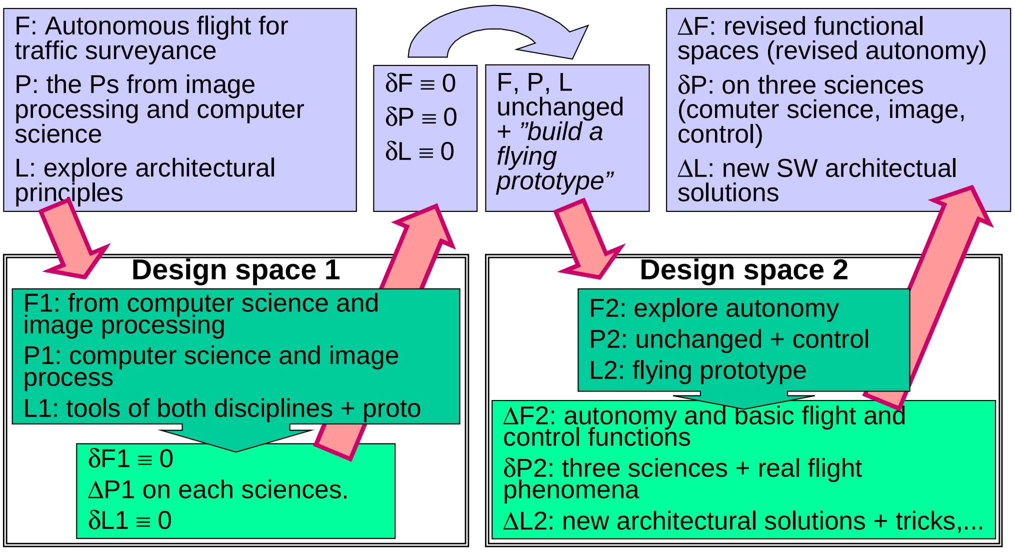

Figure 3: WITAS design spaces (read arrows indicate how to read the table)

The first phase consisted in parallel sub design spaces, each of them being close to a scientific discipline (computer science or image processing). The integration was limited to a simulation. This P-oriented design space gave birth to new knowledge on each disciplines, but it didn’t enrich the functional space; moreover it was difficult to learn on the SBP itself: the phenomena studied in disciplines were not easily transferable to the SBP level. After several months the WITAS steering committee finally decided that the simulation was not enough and that a reconfiguration in design space was needed. It prescribed the following design space: build a flying prototype. This provoked strong changes in the project: a new project leader arrived and decided to integrate completely new knowledge, in particular control skills... design space2 was then oriented towards a flying prototype, that the research team should provide with different softwares and components. This design space 2 was then intended to be both P and F oriented: this was P oriented for understanding new phenomena in autonomous flight; this was F oriented for the exploration of the notion of autonomy.

The result of this second design space has already been mentioned: people learned on F (from ”100% autonomy” to new scenarios with more or less autonomy); there was also learnings on P (new types of programming) and on L (architectural notions).

What can be learnt from WITAS? First it explains the initial difficulties: instead of exploring the functions, and the related phenomena, the project leader organized work division, targeting phenomenological knowledge in each research discipline. It also explains how the project changed: the initial shift was due to restricted P-oriented design spaces… the second design space, on the contrary, supported the functional exploration strategy. Actually both design spaces represented strong differences: a simulation is a model for integrating data; a flying prototype is a much more concrete object (more expensive,…). This once more gives insight one the design space configurations and their link to the functional explorations.

3.3. The design space management process: its steps and the implied work division.

In WITAS and ENERGY we have shown how the design space analysis helps to capture the evolutions, the successes and the risks of the projects. It also appears as a managerial tool: the design space notion helps to identify what has to be learned, in which conditions, with which means and resources,…

We can now mention some managerial action at each step of a design space exploration:

- The *inputs of the design space* have to be given, related to the SBP: it consists in a restriction from the F, P and L of SBP to get the F1, P1 and L1 of the related design space (see figure 1 above). This restriction can respect certain constraints:
  - keep "killing criteria" inside: the initial design spaces are supposed to validate that the broad concept will resist the first tests.
  - avoid "validation": requiring the design space to be representative, it increases the costs (more controlled F1, P1 and L1) and, moreover, leads to restrict the F1 exploration (see the trap of design space 2 in ENERGY and the advantages of design spaces 1 of ENERGY and 2 of WITAS)
- The design space is used for learning from F1, P1 and L1. This exploration is constrained by resources, and particularly by time. Design space managers have to find an optimum for the ratio: value-added (DS1) / duration (DS1). A *work division* is possible: the design space manager can be different from the SBP manager. For instance, in case of well-defined F1, P1 and L1, the design space manager can be a pure scientist, whereas the SBP manager will have to conduct complex reasoning on the objects, combining functional, phenomenological and architectural reasoning (see design space 1 for WITAS).
- Last, design space outputs are transferred to SBP where they are used as learning on F, P and L spaces. The learning might then be extremely heterogeneous: at different conceptual levels, concerning different aspects of the projects (users, economic models, technical issues, scientific questions, collaborations,…). This requires what we called elsewhere a strong value management and a strong competence management.

What is the relation between this management process and the more classical managerial processes in design, like cross functional team and work breakdown structures (WBS)? First we already underlined that the latter are *not possible immediately in the SBP* (competences, architectures and functional targets are largely unknown). But the design space model enables them: in WITAS and in ENERGY we find cross functional teams and WBS *inside* each design spaces (see a clear work division in WITAS for the prototype building), where F1, P1 and L1 are designed so as to enable collective work (functions, competences and targets are better identified). Note that from one design space to the other, cross functional teams and WBS can be completely changed, so that following *only* them, one draws a chaotic pattern.

We can then conclude that this managerial model on design space helps for understanding and managing SBP (proposition 2).

4 Part 4. Discussion and conclusion

4.1 Towards principles for the management of design spaces.

We propose some principles for the design space (proposition 3). These principles will be exemplified by the two previous cases and they help to characterize ill-defined design spaces.

<u>Design space input management.</u>

The principle for input management is intended to guide SBP managers in the restriction from {F, P, L} to {F0, P0, L0}. It can be formulated as follows:

The less you know on F, P, L, the more you add new variables not included in the initial F0, P0, L0 ("embodiment" variables).

Explanation: in dominant design, where F, P and L are well-known, it is quite easy to have models related to F, P and L; this enables highly refined and abstract knowledge production tools based on known F0, P0 and L0 variables. On the contrary, when F, P and L are largely unknown, it is necessary to work wit design space variables which relation with F, P, L (and F0, P0, L0) is unknown: this principle is actually related to poor confinement capacities (it is impossible to confine situations where control variables are unknown). This principle is also linked to learning strategies: one tests in a given environment in order to make new F, P, L variables appear. I.e. the new variables are candidates for learning on F, P and L; they might be involved in models of F, P or L). *In SBP, this principle leads to "physical", highly embodied prototypes*, as it was done in WITAS (flying helicopter) or in ENERGY.

When this principle is infringed, one gets some ill-defined design spaces: modelling without any physical reference (the "virtual" syndrome) or conversely paying for costly physical prototypes when modelling would be possible and far enough for the design process (the "prototyping" syndrome).

Design space output management.

The principle for output management is intended to guide the SBP manager for learning from a design space, i.e. for going from {δF0, δP0, δL0} to {δF, δP, δL}. We assume:

The less you know initially on F, P, L, the more you prize learning on F, P, L variables and models from δF0, δP0, δL0

This could sound quite paradoxically: in SBP one builds design space with numerous physical parameters for modelling and in dominant design on builds modelling design space for learning on physical parameters. However this is the usual practice: physical prototypes are useful for the principles and models that can be deduced to generalize from one single case; conversely a good model help to target one single relevant trial for maximizing local learning. In ENERGY, the most valuable learning is less on the details of the prototype than on the models for vertical airflows and their design. In WITAS, the value is neither in the helicopter, nor in the software but it is in the software architectures.

Once more, what are the design space diseases related to this principle? In SBP: take all the tips and tricks used in prototype building for "development solutions" (the "solution" syndrome). In dominant design: take a modelling hypothesis for a demonstrated truth (the "tautology" syndrome).

Design space learning interdependencies.

A third rule concerns the learning logic inside a design space. One case states that:

There is no possible independence between the learning dimensions F, P and L

Demonstration: the negation would be: it is possible to learn purely on one single dimension, i.e. the dimensions would be independent. For instance there would be a functional language independent from the phenomenology: this means either that the functional language has no real substrate or that the phenomenology behind the functions is not addressed in this design space. In both cases there is no need for the exploration of such a design space.

The principle corresponds to traditional problems in design: (i) a functional exploration without any work on the phenomenon is the "application" syndrome (one P emerged from basic research and looks for applications); (ii) conversely a phenomenological exploration without any functional work is a "substitution" syndrome: one hopes that a new technology will be able to beat the existing one on the same battlefield.

4.2. Generalization and further research

The notion of design space is useful and easy to identify in a SBP, since science requires highly controlled spaces for knowledge production. However the notion is more generally interesting in all design processes, where knowledge has to be produced and not only mobilized. An innovative design process appears as a two layers process: in the above layer occur the reasoning on the overall project (value structuration,…); but this process can't go on without knowledge production and this knowledge production is more fruitful in confined areas, which are the design spaces. We can represent the innovative design process as in figure 4 below (Note that the value structuration process requires specific tools for sustaining and controlling collectively the innovative design reasoning. We don't address herein such tools that might be based on the C-K theory developed by Hatchuel and Weil [37]).

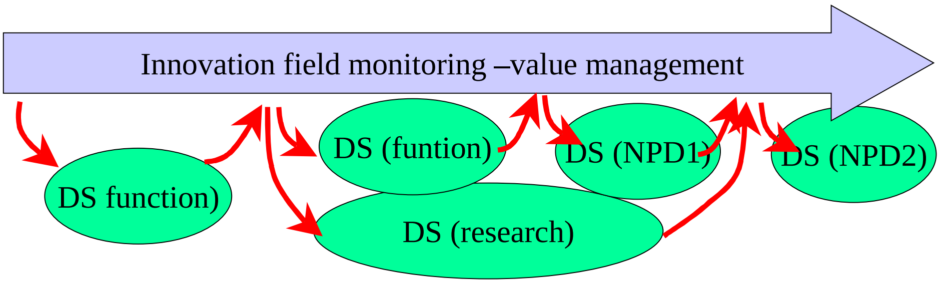

Figure 4: Managing by design spaces (research oriented at the beginning; more and more product development in the end)

The notion of design space helps also to define roles for the actors of a SBP (and more generally an innovative design). Actually one clearly distinguishes the role of the value management, in the above layer, from the role of the actors inside one design space. In-between is the design space leader: he can be confined to the design space or be closer to the to value managers, while being drowned into action.

This notion also helps to understand the overall process that leads from a broad innovation field (with a lack of competencies and high uncertainties on the value) to several structured development processes, based on established skills and well adapted lists of specifications. It would be interesting to characterized some strategies that enable to explore and structure an innovation, maximize the business value and minimize the investments.

4.3. Conclusion.

The main results of this research studies are the following:

- As described by other authors, these processes show a sequence of important changes that redefine the identity, meaning, knowledge, scope and main actors of the project. However, these changes are neither chaotic, nor random, nor unmanageable in terms of design theory, we interpret them as changes of the "**design spaces**" of the project: we define a "*design space*" as a *consistent configuration of a set of functions (F), a set of scientific phenomena (P), and a group of learning devices adapted to the exploration of the relations between (F,P).*
- Defining design spaces allows project leaders, scientific researchers, managers an sponsors to cooperate in spite of the important uncertainties unavoidable in SBPs: for example, work breakdown structures are dependant of the definition of the design spaces. Thus design spaces reconcile, in a transient but operational way, the logic of scientific inquiry and the product development logic.
- The *transition* from one design space to another (or to several ones) appears as the main driver and strategic issue of the project ; in each case, it has been possible to represent and trace these design spaces.
- Often, design spaces are associated to some well known types of "realization" (like

computational models, mock-ups, prototypes, demonstrators..); yet this research shows that these realizations have no value per se but only relatively to the design spaces of the project. The notions of critical issue, critical event, or bifurcation used in the literature of innovation (Van de Ven [2]) can be fruitfully revisited within the "design space model".

– Many of the paradoxes of the literature can be tempered: the development of SPB's appears as actually managed and organized, but in a very specific way : namely, managers (project leaders) play an important role in the *formation* (resource allocation, design strategy), *transition and abandon* of design spaces but not in the management of the design space themselves. Unlike standard development models, the sequence of design spaces is nor necessarily *convergent* nor *divergent* as the shape of the transitions depends of a managed design strategy that can be defined as a ***value building trajectory** of the process :* ***valuating, determining the judgment of failure, success, or the outputs of the project****.*
Misunderstandings about the genesis and definition of the design spaces could explain the high mortality of SBP's more than the existing uncertainties.

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