MANAGING INNOVATION IN A HIGHLY COMPETITIVE ENVIROMENT

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The effects of globalization are of such a nature that they exert increasing pressures on companies to develop new products more effectively and efficiently. In order to meet this challenge, the organisation of the new product development process has received ample attention both in the academic literature and in the practitioner literature. As a consequence, a myriad of methods to design new products better, faster and cheaper has been developed. These methods aim at facilitating concurrent product design and engineering, integrating both organizational and functional aspects of the design process so as to maximize value creation. Thanks to the advent of families of novel design technologies, concurrency at the technical and functional level has become a reality at last. In this contribution, recent insights on the use and the impact of design technologies in meeting economic challenges and pressures are reported and discussed.

1. TECHNOLOGY AND THE BLACK BOX OF INNOVATION

This contribution is about the ways in which companies develop both the technical and the functional innovations that become embedded into their products. More specifically, I want to discuss the ways in which design technologies such as virtual product design and prototyping, known as parametric design technologies, in combination with design methodologies and appropriate organizational approaches, are shaping and reconfiguring the organisation of the product development process. As a consequence, this contribution is concerned with innovation operations rather than innovation strategy. Only an in-depth understanding of these operations allows to gradually open the black box of the new product development process. However, this does not mean that these operations are devoid of strategic significance. I therefore will conclude the discussion by arguing that the integration of these operations into an 'Integrated Design Capability' can sustain a firm's competitive position, and hence, turn innovation into a formidable strategic weapon for the company.

1.1. THE DESIGN HIERARCHY: MANAGING 'FORM' AND 'CONTEXT'

At the roots of each new product development lies a design hierarchy, breaking the product's architecture and respective functionalities down into technical specifications and components (e.g. Clark, 1985; Iansiti, 1997; Ulrich and Eppinger, 1995). This design hierarchy does not come about at random. It is the result of two related processes. The first process reflects the logic of problem solving in product design (e.g. Allen and Frischmuth, 1969; Petroski, 1996; Weber and Perkins, 1992). The second process is the creation of product concepts that underpin and fullfil customer needs (e.g. Cooper, 1993; Cooper and Kleinschmidt, 1996; ReVelle, Moran & Cox, 1998; Souder, 1987; Thomas, 1993; von Hippel, 1988). As suggested by Petroski in his 1996 book 'Invention by Design', design is a process of understanding what the product's form is and how it might 'fit' the context in which it is to function and to be used. The outcome of the design process is the result of iterative cycles of experimentation and analysis that gradually define and refine the form of the product. Components and design rules are identified, major systems and sub-systems are conceptualised and selected, and their interrelationships are examined. Physical, chemical, mechanical, electrical and other engineering 'laws' impose specific technical constraints on the design hierarchy (Gevirtz, 1994; ReVelle, Moran and Cox, 1998).

However, form is not sufficient. As mentioned, the primary task is to choose design concepts that result in a form that 'fits' the context of use well. Goodness of fit between form and context therefore is at the heart of the second process shaping a design hierarchy. The 'fit' of the product form with its context is most often conceptualised as a set of functional specifications or requirements (Gevirtz, 1994; ReVelle, Moran and Cox, 1998). Methodologies like Quality Function Deployment aim at aligning form and context precisely by linking technical and functional parameters (Bossert, 1991; Hauser and Clausing, 1988; Debackere, Van Looy and Vliegen, 1997). Thus, the cycles of experimentation and analysis referred to previously are necessary to develop a 'form' that is aligned to its 'context of use.'

1.2. UNCERTAINTY AND AMBIGUITY: MEDIATING THE 'FIT' BETWEEN FORM AND CONTEXT

In fitting 'form' to 'context,' ambiguity and uncertainty play a central role (Debackere, 1998; Schrader, Riggs & Smith, 1993; Van Looy, Debackere & Bouwen, 2001). Although both concepts are related, they are not completely overlapping.

Reducing levels of uncertainty has been the primary concern in many management approaches regarding the new product development process. Uncertainty is characteristic of a situation in which the problem solver considers the structure of the problem (including the set of relevant design variables) as given, but is dissatisfied with the knowledge available on the value of these design variables. This is in line with information theory and decision theory that have both defined uncertainty as characteristic of situations where the set of possible future outcomes is identified, but where the related probability distributions are unknown, or at best known subjectively.

Research on organisations has broadened those definitions to better fit with the organisation's setting. Galbraith (1973) defines uncertainty as the difference between the information an organisation has and the information it needs. This coincides with the early definitions of uncertainty provided by researchers on the psychology of problem solving (e.g. Miller and Frick, 1949), as derived from the mathematical theory of communication (Shannon and Weaver, 1949). Duncan (1972) defines uncertainty as follows:

'(1) The lack of information regarding environmental factors associated with a given decision-making situation, (2) not knowing the outcome of a specific decision in terms of not knowing how much the organisation would lose if the decision were incorrect, and (3) inability to assign probabilities with any degree of confidence with regard to how environmental factors are going to affect the success or failure of the decision unit in performing its function.'

The first two components are quite similar to the broad definition by Galbraith (1973), while the third component is similar to the more narrow definitions that stem from information and decision theory. The common theme behind all those definitions is that uncertainty is related to asymmetry and lack of information. Consequently, if problem solvers want to reduce uncertainty, they should gather information on design variables that are known to them.

This finding has been at the heart of many models and instruments designed to manage the new product development process, which is in essence a process of uncertainty reduction through problem solving activity (Allen, 1977; Brown and Eisenhardt, 1995). Uncertainty reduction has therefore been a central theme in many seminal writings on the need for cross-functional integration and intensive information exchange during new product development endeavours (Allen, 1977; Wheelwright and Clark, 1992).

'Effectiveness' in uncertainty reduction imposes a need for reducing information asymmetries between the different partners involved in the new product development effort (suppliers, customers, owners of complementary assets, and the different intra-company functional groups such as R&D, marketing and manufacturing that need to coalesce during the innovation effort).

However, there are limitations to this integrative approach as well. Several authors have argued that models of decision making under uncertainty often do not adequately reflect real-world decision making (e.g. March, 1978; Daft and Lengel, 1986). They propose that often possible future outcomes are not identified or not well defined and that there may be conflict with regard to what these will or should be. These authors state that decision-making and problem solving are often carried out under conditions of ambiguity, rather than uncertainty. Ambiguity is defined as lack of clarity regarding the relevant design variables and their functional relationships. Ambiguity relates directly to Daft and Lengel's notion (1986) of equivocality, which they define as '… ambiguity, the existence of multiple and conflicting interpretations about a situation.' As a consequence, coping with ambiguity is one of the foremost issues in new product design as the final design is inherently a synthesis of multiple perspectives and views on what the ultimate product should offer to its user.

Allen already alluded to this in his 1977 book, when he explained why direct face-to-face contact is the most effective information channel in innovation settings. It is, he argued, because face-to-face contact does not only help to reduce uncertainty via the sharing of information, but more important still, face-to-face contact makes it easier to unveil and discuss divergences in interpretation on the information being shared. In other words, in an innovation context, we do not only have to consider situations of asymmetric information, but also, situations of asymmetric interpretation of that information. In order to reduce asymmetries in interpretation, the richness of the information and information channels available is of crucial importance.

Face-to-face information exchange is characterized by a high level of media richness. As I will argue later on, three-dimensional parametric representations and models of product designs also carry higher levels of information richness than their traditional two-dimensional representations on calculation sheets and paper drawings. And, this is precisely where the novel design technologies come in. Today, an increasing array of technologies is available that allows for the quick experiential design and development of three-dimensional representations of product forms. This implies that in fitting 'form' to 'context of use' via the development of the product design hierarchy, we now dispose of techniques that allow us to quickly define three-dimensional forms of the product (either on computer screen as happens with three-dimensional CAD systems such as CATIA, ProEngineer and Unigraphics or in 'hard' copy as with three-dimensional Rapid Prototyping techniques as stereolithography, selective laser sintering and 3D inkjet printing).

These experiential product designs can then be confronted with the various stakeholders belonging to its context of use, amongst whom users figure predominantly. In doing so, it is possible to organize a new product design in a most experiential mode, consisting of cycles of iteration based on multiple 'real' representations of the product design. It therefore is important to introduce and to emphasize the role of experimentation during the new product development process. Many writings on managing this process have almost exclusively focused on the role of information and information exchange (see for instance the management of part-whole relationships as described by Van de Ven, 1986). However, as observed by Allen (1977), information exchange is (notwithstanding its importance), only a smaller part of the total activity of product designers and engineers. In Table 1, I summarise the activity patterns of designers and designers in innovation projects as Allen observed them.

TABLE 1: THE IMPORTANCE OF EXPERIMENTS DURING PRODUCT DESIGN AND DEVELOPMENT (ALLEN, 1977)

SOURCE OF TIME ALLOCATION	PERCENTAGE OF TOTAL TIME ALLOCATED ACROSS 12 PROJECTS
ANALYSIS AND EXPERIMENTATION	77.3%
LITERATURE USE	7.9%
ALL COMMUNICATION (INCLUDING LITERATURE)	16.4%
OTHER ACTIVITY	6.4%
TOTAL TIME REPORTED (MAN-HOURS)	20,185 HOURS

As is clear from Table 1, analysis and experimentation account for about 77% of the activity pattern of the designers and developers involved in product design and development. Sofar, we have largely neglected the organisation of these 77% in the context of new product development. If we want to arrive at a more effective and efficient design and development process, we thus will have to better handle and understand the management of 'analyses and experiments.' In a very interesting paper, Eisenhardt and Tabrizi (1995) argue that in complex new product development projects (i.e. projects marked by high levels of ambiguity), traditional project management approaches fail and should be replaced by experiential project management, consisting of a rapid sequence of design-build-test-redesign cycles in which the subsequent users of the product can be deeply involved.

This finding is precisely at the heart of the argument made in this contribution: in situations marked by high levels of ambiguity, when defining and designing a product's form to fit the context of use, we have to bring in modes of managing new product design and development that explicitly recognize the value and the contribution of experimentation and analysis. This implies we arrive at 'intelligent' experimentation strategies that move beyond 'mere' trial and error experimentation. This is where the integrated design capability, combining design methods, design technologies and organizational approaches, enters as a new focus in product development organization, not in the least because of increased pressures on speed-to-market, shortening product life cycles and rapid erosion of design advantages due to intense competitive rivalry in new product design.

It is therefore an important finding that design technologies (I tend to call them meta-technologies or 'technologies to develop technology') add a new dimension to the management of the new product development process as they explicitly allow to better control cycles of experimentation in product definition and design given their ability to cope with both ambiguity and uncertainty. Ambiguity is thereby linked to reducing differences in interpretation on the product form and design (for instance, on the definition of the relevant space of functional parameters), while uncertainty is linked to arriving at acceptable target values for the chosen functional parameters via the reduction of information asymmetries on the context of use of the product.

2. MANAGING INNOVATION PROCESSES IN A COMPETITIVE ENVIRONMENT: INSIGHTS

Decades of research into the management of new product development have led to an insight into fundamental critical success factors (for a good summary overview, I refer to Tidd, Bessant & Pavitt, 1997). In Figure 1 (page 31), a (simplified) summary overview of the key performance variables relevant for new product development performance is therefore provided. The critical influence of information flows and communication patterns on the performance of new product activities has been well-documented and subject to major research attention (see Brown and Eisenhardt, 1995, for an excellent overview of the different research studies on this topic). These flows are at the heart of the performance model. The attention paid to information flows and communication networks is not astonishing given the need for uncertainty reduction during the new product development process. In addition, the various methodological avenues that complement and sustain those information and communication processes and that have received ample attention, include:

1. the use of flowchart-based decision and monitoring models of the new product development process (e.g. the phase models and stage-gate models as described in Souder, 1987 or in Twiss, 1994) taking into account both the fuzzy front end phase of every product design endeavour as well as the need for learning between projects as manifested by the presence of a 'post'-project phase (Debackere & Vandevelde, 1996; Deschamps & Nayak, 1995);
2. the introduction of creativity-stimulating and idea-generating techniques like brainstorming and mind-mapping (e.g. Povel, 1993; Terninko, Zusman & Zlotin, 1998);
3. the use and the design of grid-methodologies and techniques to identify, to define and to monitor innovation opportunities (e.g. SWOT-assessments, product maturity grids, business growth matrices, Quality Function Deployment matrices; I refer to Clark & Fujimoto (1991) as well as Wheelwright & Clark (1992) for a good overview);
4. the development of selection methodologies that respond to the need for funnelling, i.e. filtering and tunnelling a wealth of ideas into a more limited set of new product-technology concepts toward a still more limited set of 'successful' products (for an excellent overview of the funnelling concept, I refer to Wheelwright & Clark, 1992);
5. the application of project management techniques to follow-up on new product development endeavours (see for instance Duncan, 1996).

The interaction and the co-evolution of work organisation, design methodologies and information flows are at the heart of the operational management of the new product development process. As can be seen from Figure 1, the advent of design technologies such as three-dimensional computer aided design software and rapid prototyping techniques as well as rapid tooling techniques adds yet another dimension to the core of a high-performing, new product development process. As argued in the previous sections, the advent of these technologies has a profound impact on the principles of concurrency and time-compression that represent a key trend in the management of new product development processes (Loch and Terwiesch, 1998).

They are instrumental in making 'experimentation' a core activity of managing the new product development process. By their very nature, design technologies allow to integrate the new product development process by enabling participants involved in upstream decisions to consider downstream and external design requirements, including the timely and relevant involvement of the downstream and external decision makers themselves.

Information flows are mediated and supported by an appropriate work-organisation format and design methodology. However, in order for these modes of organisation and design methods to be deployed successfully, the necessary informal as well as formal information flows and communication patterns have to be put in place and have to be sustained. Hence, there is a direct two-way interaction between structural variables such as organisation, design methodology and design technology on the one hand and information flows on the other hand. This two-way interaction is at the heart of the process of coping with ambiguity and uncertainty as discussed earlier. The two-way interaction also is at the center of what I will later call the 'Integrated Design Capability' of the innovative firm.

As further shown in Figure 1, innovation performance is a complex and multi-dimensional construct. Performance relates to such rational, financial indicators as market shares and revenues that accrue from new product development activities. However, market shares and revenues are only one dimension of the performance concept. The second route toward measuring performance refers to the internal efficiency of the process. It considers the extent to which the development process is efficiently managed in terms of, for instance, throughput times during the various phases of the innovation trajectory (e.g. time-to-concept, experimental problem-solving cycle times, time-to-ramp-up). A third type of performance dimension relates to 'perceptual' indicators such as the innovation's contribution to the competitive edge of the organisation.

It is important to accept the multidimensionality of the performance construct. Early studies on innovation performance have indeed focused quite heavily on the market and financial performance indicators. Even today, many project management techniques that are used to follow-up on new product development projects still use this rather linear approach. In an era where the capability to quickly learn from failure and experimentation is probably one of the hallmark characteristics of successful innovators, this traditional, rational performance approach may be dangerous, as it tends to focus on single-loop learning rather than double-loop learning.

These dimensions of innovative performance (often operationalised at the project-level and aggregated at the portfolio-level) are influenced and leveraged by a myriad of parameters, as is further shown in Figure 1. As mentioned, communication patterns, information flows, and work organisation techniques are at the core of this framework. In addition, there are important roles to be assumed.

Senior management attitude and commitment, project leader traits and behaviour, as well as team member characteristics exert a strong influence on the performance of innovation activities. Moreover, these have to be embedded in an appropriate motivational context, using incentive mechanisms that foster 'project ownership' rather than 'performance control.' Incentive mechanisms fostering entrepreneurship and 'ownership' in innovative contexts therefore have to be related to the project process (Philips goes as far as calling the project process a Business Creation Process rather than a Product Creation Process) as well as to the overall success of the project in the eyes of its customer (e.g. by providing substantive bonus-schemes for the project members if they achieve a successful project result). These incentive mechanisms have to stimulate project teams to remain attentive and open to new insights and information originating outside the boundaries of the project team. This openness is required to prevent the Not-Invented-Here syndrome from blurring the project team's boundary spanning activities.

Of course, as suggested in Figure 1, the complexity of the project (research projects versus breakthrough, platform or derivative product development projects as defined by Wheelwright & Clark, 1992) has an important impact on the relationships just described. More specifically, in the case of derivative (i.e. highly incremental) projects, the performance relationships can be managed in a much more structured and formalised way than in the case of a more ambiguous research activity or a highly uncertain breakthrough project (where the product is entirely new to the organization). For instance, in a breakthrough project, creating 'ownership' may involve the development of highly visible bonus schemes that give the project members significant stakes in the project's success. For derivative projects this should not be the case. Here the incentive system should evaluate such 'classic' performance control criteria as the responsiveness and the timeliness of the project members' activities to customer needs and approved schedules.

The involvement of external parties, more specifically suppliers and customers, is yet another well-known determinant of new product development success (see for instance Eric von Hippel's research on the role of 'lead' users during the innovation process (1988)). The relative importance of their impact varies depending on the party that obtains the highest returns from investing in the innovation. Although this is a simple criterion, it may be hard to figure out who will benefit most from a particular innovation, certainly when it pertains to emerging technologies and product platforms.

As can be seen in Figure 1, the structure of the market or the degree of competition in the marketplace are other important parameters influencing the success of the innovation journey. Turbulent market structures, marked by high degrees of monopolistic competition, strongly moderate the 'optimal' organisation of the innovation process. Examples abound, such as the case of Quantum Corporation (1992). Quantum, active in the area of computer disk drive design and development, experienced a turbulent, fast-evolving marketplace with fierce competition based on slightly differentiated product characteristics.

This competitive environment necessitated an innovation function that was highly responsive to frequent changes in the marketplace. As a solution, Quantum based the organisation of its innovation process on flexible lateral (team-based) structures, state-of-the-art functions or competencies, and appropriate incentive systems. These required each team member to act as a 'cross-functional specialist' (which of course may seem like a contradiction 'in terminis'). As those 'cross-functional specialists' had to strike a balance between team performance and individual performance as well as between expertise and experience, appropriate incentive systems were developed and implemented.

This need for 'cross-functional specialists' points to the dilemma or the tension present in the innovation matrix type organization; an organisational tension which is characteristic of most innovative companies. Any innovator needs to balance the development of competencies (i.e. the development of a sufficient absorptive capability) with the imperative to achieve the results expected from the projects and programs in the new product development portfolio. The creation of a matrix type organisational structure, in which functional competence areas and cross-functional project teams are intertwined and balanced, often attempts to solve this dilemma. The successful innovation organisation therefore requires a matrix structure balancing a clear

division of influence, power and authority between its project management component and its competence management component.

In order for competencies to be allocated to and deployed in a breakthrough new product development project, they need to be up-to-date and state-of-the-art (I intentionally leave out derivative projects, since they often require only minimal forms of project organisation). Hence, successful breakthrough projects will have to be embedded in strongly developed competence areas. This calls for a 'strong' matrix structure, where competence areas and project management both are allies in resource accumulation and deployment, rather than the one being dominated by the other. Both components of the matrix structure have to be state-of-the-art in their respective domains of expertise and experience. It is obvious that this presence of two strong organizational components carries the germs for conflict situations. Hence, there exists a clear need for professional 'conflict handling and resolution' capabilities and strategies in the innovation matrix.

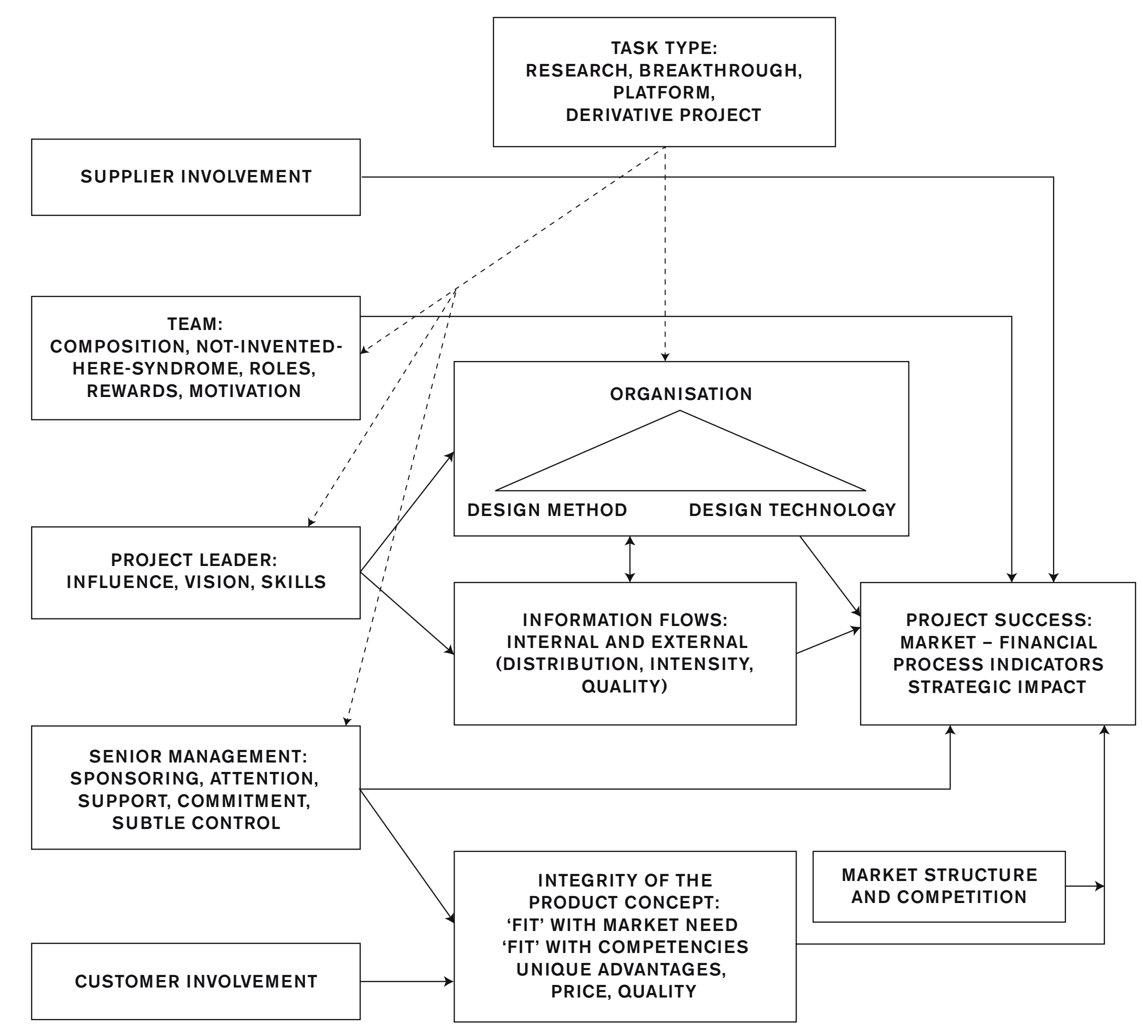

figure 1: An integrated summary model of new product development performance

3. BOEING: A CASE STUDY ON A COMPETITIVE DESIGN CAPABILITY

Boeing has received much attention as an example of the application of advanced design capabilities (Sabbagh, 1996; Petroski, 1996). Throughout its history, the company has demonstrated a capability for both product and process innovation that turns it into an interesting case study subject. Boeing is known for the rigor with which it has come to apply project management principles throughout its development and manufacturing process. As it comes to product development, Boeing is reputable for designing platforms or families of aircraft. This design flexibility allows for several variations, drawing on the same base airframe concepts. Modifications such as a stretched fuselage to increase capacity can thus be accommodated without wholesale revisions in design or without the need to start up entirely separate development programs. The company has also been a pioneer in building co-development and outsourcing relationships. Boeing further became a role model in applying concurrent engineering principles and new design technologies to the design and development of the 777 airplane.

As early as the mid-1970s, the European Airbus consortium began challenging the American dominated aircraft industry. By the mid-1980s, Airbus had become a recognized player on the world commercial aircraft market. As a consequence, by the late 1980s, Boeing began to look to design a new aircraft that would fill needs that planes like its 747 and 767 did not. More specific, Boeing needed to fill a 'gap' with respect to seating capacity and range of its commercial jets keeping in mind economic development in the Pacific Rim area. The company needed a large body aircraft able to cover distance ranges between 7,000 and 8,000 nautical miles.

At first Boeing thought of stretching the existing 767 design. This would be a safe, quick and low-cost way of providing a plane with an increased seat capacity. In the meantime, though, both McDonnell-Douglas and Airbus were expected to offer new large capacity, long range aircraft. With such competition in view, Boeing decided that it would be better to develop a plane that could compete in a more direct way with the new competition. After United Airlines provided a firm 'baseload' order for the new plane, Boeing was able to launch its 777 design in the second half of the 1990s.

In order to increase the 'fit' between form and context, Boeing invited eight airlines to get involved with the design of the 777 in the early conceptual design phase, when little of the design parameter space was firmly decided upon. This allowed for taking into account customer requirements. Although eight airlines had to agree upon some basic design concepts (an almost impossible job to accomplish), Boeing was able to work toward a consensus with them that enabled its engineers to arrive at a solid basis for more detailed engineering work.

In traditional aircraft design, many engineers and draftspersons work individually and in team on various parts and subsystems of the plane. As explained in detail by Petroski (1996), there were over 130,000 unique individual parts to be engineered in the 777, and when rivets and other fasteners were counted, over 3,000,000 parts were to be assembled in each plane. The 747, which had a total of 4,500,000 parts, required about 75,000 individual drawings to specify. This great number of drawings all had to be internally consistent if the various parts and subassemblies were to fit. This required a lot of interface work between engineers. Whenever a design change occurred, all drawings had to be checked in order to assess its impact and to adapt the existing design to the new one. This obviously was a slow and tedious process.

Even with lots of checking, cross-checking, and double-checking, human error could never be totally excluded and as a consequence, mismatches occurred frequently. In order to trace incompatibilities across parts, subsystems and systems, physical prototypes were built. This approach was of course expensive and time-consuming. In the past, Boeing had tried to minimize these problems through an intensive quality management approach emphasizing the need for intensive co-operation throughout the design process.

In order to remedy the aforementioned drawbacks, Boeing opted for a paperless design of the 777. Computers would be used in the design, testing and manufacturing process to a greater extent than ever before. Three-dimensional CAD systems would prove to be the solution to this challenge, enabling Boeing to achieve maximum concurrency during the design of the new plane while at the same time aiming at a high-quality robust design.

Boeing already developed some experience with CAD when designing engine parts of the 767. Both from a cost and throughput time perspective, the CAD approach proved a significant improvement over the traditional 'drawing' and 'interfacing' approach. Also, Boeing had experienced a sharp decline in Engineering Change Orders once the 767 CAD designs were released. The CAD system used during this pilot was the Computer Aided Three-dimensional Interactive Application (CATIA) developed by the French software firm Dassault Systèmes.

In order to be useful for the design of the 777, the CATIA system had to be scaled-up, which was in itself a major engineering effort. Just some numbers help to illustrate the task at hand. Total storage capacity for the overall system reached 3.5 terabytes (the equivalent of 2,500,000 million 3.5-inch high-density disks). As many as 238 teams, including up to 40 engineers, were involved in the design, development and manufacturing of the 777. All engineers needed access to all of the computer data. A paperless design meant that instead of waiting for drawings, any engineer working on any part or subassembly could call up all connected parts and subassemblies on any library of the 7,000 workstations that were scattered across 17 time zones. In order to make this possible, Boeing laid dedicated data lines across the Pacific Ocean. About 20 percent of the fuselage structure was being designed and developed by a consortium of Japanese partners including Fuji, Kawasaki and Mitsubishi Heavy Industries. Their engineers had to be logged into the worldwide 777-workstation network (Petroski, 1996).

Via an electronic pre-assembly program, interference between parts and systems was continuously identified. To be sure that the newly developed CAD-system was itself reliable, an integrated prototyping strategy was developed. As soon as possible, physical prototypes of aircraft subsystems were developed that allowed checking the design rules that rolled out of the CATIA system. In addition, Boeing developed a simulated mechanic, CATIA-man, who could be manipulated to crawl around inside the assembled digital plane to check manoeuvrability during construction and maintenance operations. As a consequence, the keyword for the design revolution we witness at present is improved communications.

These improved communications, and the 'virtual' and 'physical' visualisations that accompany them because of the three-dimensional parametric character of most new design technologies (just think about CATIA-man), are ideal vehicles to help reduce both the ambiguity and the uncertainty that underlay all new product development trajectories. This is possible because of the potentially 'rich' character of the information that becomes available via the use of the 3D technologies, thus benefiting the reduction of information as well as interpretation asymmetries. Moreover, as argued earlier, these technologies can be at the centre of the development and management of fast experimentation strategies that result in highly effective cycles of design-build-test-redesign that are crucial in fitting product form to its context of use (Debackere, 1998; Loch and Terwiesch, 1998; Thomke, 1997). This, of course, brings us to the need to define the new design environment that fits today's highly competitive innovation imperatives.

4. THE NEW DESIGN ENVIRONMENT: ORGANISATION, METHODOLOGY AND TECHNOLOGY

Design technologies have occurred in many different application areas. Although their history and variety is most well established in mechanical applications, they start making significant inroads into other areas as well (e.g. rational or structured drug design and molecular modelling in pharmaceuticals, simulation and testing of circuitry in electronics). In this section, we reflect on the benefits and the pitfalls in introducing this new design environment.

4.1. A COLLECTION OF TECHNOLOGIES

In the engineering literature, the information and evidence on the potential impact and the use of new design technologies are tremendous (e.g. Ertas and Jones, 1996; Jayaram, 1995; McMahon and Browne, 1993; Van der Schueren and Kruth, 1996). In this brief summary, I intend to highlight some of their major features and characteristics, without entering into all the technical details of the tools and techniques involved.

First of all, the advent and the presence of analytical techniques that allow for 3D visual representations and simulations of product concepts linked to such calculations as kinematic modelling, dynamic modelling, stress modelling and thermal modelling have a direct impact on the product design phase of the innovation process. One of the basic mathematical techniques supporting this evolution has been Finite Element Analysis. It has become the primary tool in stress analysis and structural dynamics, and the ability to adapt it for use with CAD has contributed greatly to the proliferation of CAD systems in industry. Because of its parametric character, Finite Element Analysis can be used in analysing designs involving varying geometric shapes as well as non-homogeneous materials. It also provides considerable flexibility in the setting of loading and support conditions. It is also used in the solution of heat transfer problems and the analysis of fluid flow and electrical and magnetic fields.

Although 2D draftings continue to be the most widely used CAD application, many manufacturing firms have chosen to shift to solid 3D modelling. Solid modelling provides a complete geometric and mathematical description of part geometry, which is important if the model is to be used for design analysis, simulation, generation of mass properties, or for developing NC (numerically controlled) data to machine the part. Second, a variety of physical techniques allow for the rapid development of 3D physical prototypes and tools. For instance, just to name a few, stereolithography, selective laser sintering, laminated object modelling and manufacturing, holographic interference solidification, photochemical machining, selective area laser deposition, selective metal powder sintering, fused deposition modelling, multiphase jet solidification, ballistic particle manufacturing, direct shell production casting, etc. Rapid prototyping (and tooling) techniques thus produce physical models from CAD data either by material layer deposition or (also increasingly today) by material layer removal.

Most rapid prototyping systems electronically divide a 3D CAD model of the part into thin horizontal cross-sections and then transform the design, layer by layer, into a physical model. Rapid prototyping (and tooling) techniques are increasingly being used during the product development cycle. For instance, Ford Motor Company uses stereolithography as an integral part of concurrent product and process design. Developing new automobile components is expensive, traditionally requiring many design iterations and significant schedule time. Stereolithography allows the production of models of the part in a single day, using the same CAD data needed for structural analysis, kinematic studies, NC programming, etc. An example of the use of this technology occurred when Ford sought a supplier for a newly designed internal combustion engine rocker arm. When different suppliers had difficulties in interpreting the 2D drawings of the rocker arm, Ford turned to stereolithography to produce a model of the part in one day. When the model was made available to bidders, Ford received a quote that saved up to 3 million US$ annually in production costs.

Although rapid prototyping and tooling technologies are evolving at great speed, there are of course still limitations as to their use. These include limitations due to the use of rapid prototype materials different from those specified for the part being designed, restrictions on the number and variety of test conditions that can be applied to the prototype, and difficulty in using test data from the prototype in performing Finite Element Analysis. In addition, even if the tools are available, my own research shows that it takes some time and change of mindset before designers and engineers are able to make the switch to the new design approach. Training and developing familiarity with the new tools is crucial. However, even when training and guidance are provided, it takes time before the tools are being used in an effective and an efficient manner. Moreover, it is obvious that the introduction of those design tools may have a quite disruptive impact on the 'established' design expertise and experience at the company. As a consequence, 'Not Invented Here' syndromes and resistance to change phenomena may well occur and may thus put a strain on the deployment of the new tools and techniques.

To conclude this brief overview, virtual prototyping is a term that describes the computer analysis and testing of CAD models before the commitment is made to produce the physical prototype. In virtual prototyping the CAD model is evaluated by iterative dynamic simulation before making the physical model. This technique allows testing of the model under various kinematic and dynamic conditions that would be expensive and complex to duplicate in the laboratory.

These last reflections suggest that the use of virtual and physical prototyping should be intertwined and integrated. Prototyping strategies aim at using virtual and physical prototyping in an intermittent and iterative manner in order to arrive at an intelligent experimental program. In this way, the organisation of the design process becomes a rapid sequence of design-build-test-redesign cycles. The 'build' phase of the cycle then uses the prototyping approach that offers most added value in terms of design changes and improvements (or for that matter, elimination of design errors) at any moment during the design process.

This puts a strain on 'traditional' phased project planning approaches as it almost becomes impossible to have detailed milestone planning and reviews in such a fast prototype design and change cycle approach. In other words, the 'traditional' (phased and planned) project organisation format is being replaced (or complemented?) by a more adaptive approach. This adaptive approach allows for a quick sequence of experimentation and analysis cycles, as extensively described in the previous sections of this contribution. Eisenhardt and Tabrizi (1995) coined this organisational approach as 'experiential project structures.'

4.2. THE INTEGRATED DESIGN CAPABILITY

By now, it has become obvious that companies that want to deploy new product development processes in support of their competitive position might consider investing in an Integrated Design Capability that supports a fast-cycle design process. This Integrated Design Capability 'fuses' organisational approaches (traditional and experiential project structures, competence versus project organisation in the innovation matrix), design methodologies (such as Quality Function Deployment, Value Analysis, DesignForAll methods, Product Life Cycle Assessment) and the aforementioned design technologies into one consistent support infrastructure for the company's new product design and development process. This integration, of course, implies a serious investment and hence, becomes a strategic decision for the organisation. It also implies a clear strategic choice toward which market segments and application areas the company decides to turn its innovation attention. This is mainly because investments in design technologies are not fully application-independent, as illustrated by the arguments and discussions in the previous sections.

To this end, for example, the Dutch steel and aluminum company, Koninklijke Hoogovens (now part of Corus Group), has developed two Integrated Design Centres in the 1990s: the Centre for Packaging Technology and the Centre for Product Applications in Transport and Building Applications. Each of these centres creates and sustains an environment in which appropriate organisational approaches, combined with a set of design methods and techniques, are geared toward an effective and efficient new product design process for specific product-market combinations (e.g. packaging solutions, construction applications, automotive parts).

5. CONCLUSION

In this contribution, I have attempted to provide an insight into the major components of the integrated design environment that companies might deploy to support their new product development process. Core concepts that have been discussed in support of the arguments in favour of the integration of design technologies into a systematic management approach of the innovation process were: ambiguity, uncertainty and learning via experimentation and analysis. Of course, as argued, implementing this 'Integrated Design Capability' is not without difficulties and problems.

The building blocks that constitute this 'Integrated Design Capability' are threefold (see Figure 2 for a summary representation):

- Project modes of organisation in which teamwork, milestone management, and output-oriented work definition and follow-up are predominant and supported by appropriate senior management commitment and incentive systems;
- Methodologies that foster interdisciplinary problem-definition and problem-solving activities during design and development projects;
- Technologies that foster the efficient cross-disciplinary analysis as well as the systematic and intelligent experimentation and representation of new product designs.

As mentioned, introducing an 'Integrated Design Capability' in an organisation may be quite disruptive with respect to the design expertise and experience currently available. However, the integrated design environment also allows for a more adaptive and responsive interpretation of the 'traditional' (phased and rational planned) project management structures that have been deployed in new product development contexts in the past (see for instance Clark and Fujimoto, 1991). As a consequence, the 'Integrated Design Capability' introduces a degree of flexibility in design that is badly needed in today's competitive new product development environment. This environment is characterized by increased time-to-market pressures and shortening product lifecycles. Hence, the creation of an 'Integrated Design Capability' is to be considered an important and critical strategic investment by any company.

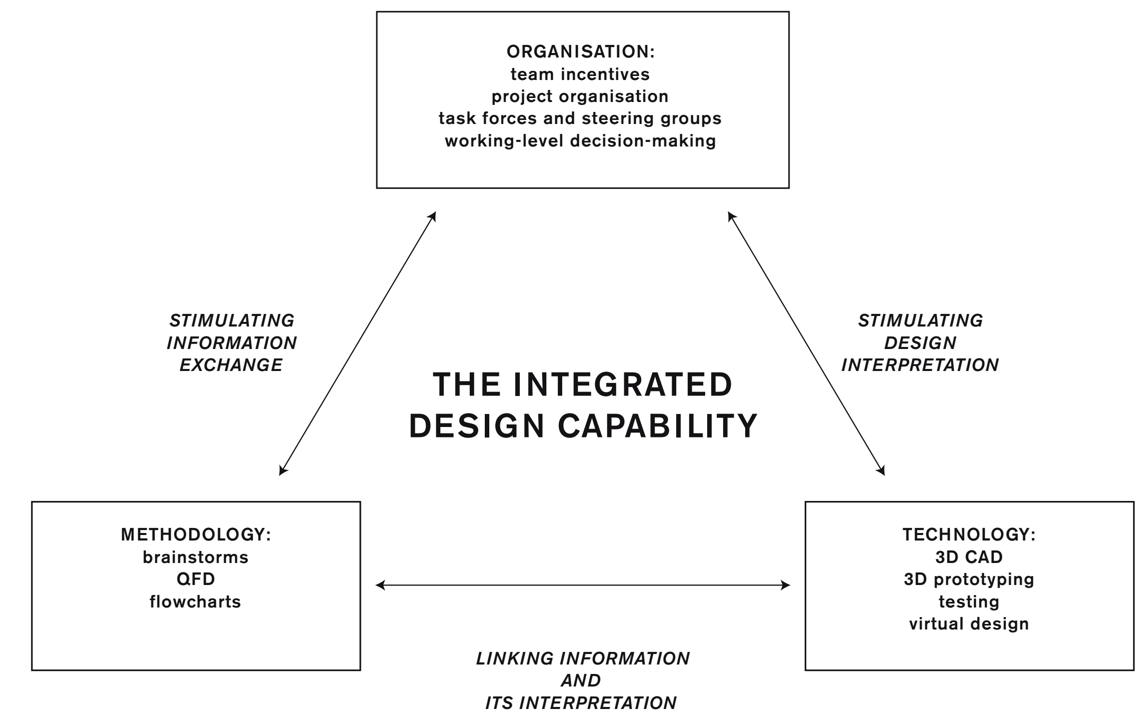

figure 2: The three building blocks of 'Integrated Design Capabilities'

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