UNIVERSITÉ DE MONTRÉAL

PRODUCT MATURITY AND ARCHITECTURE EVOLUTION IN COMPLEX INDUSTRIES

MICHAEL KAMEL
DÉPARTEMENT DE MATHÉMATIQUES ET DE GÉNIE INDUSTRIEL
ÉCOLE POLYTECHNIQUE DE MONTRÉAL

THÈSE PRÉSENTÉE EN VUE DE L'OBTENTION
DU DIPLÔME DE PHILOSOPHIAE DOCTOR (Ph.D.)
(GÉNIE INDUSTRIEL)
AVRIL 2008

Library and
Archives Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-46105-1
Our file Notre référence
ISBN: 978-0-494-46105-1

NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:
L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

UNIVERSITÉ DE MONTRÉAL

ÉCOLE POLYTECHNIQUE DE MONTRÉAL

Cette thèse intitulée :

PRODUCT MATURITY AND ARCHITECTURE EVOLUTION IN COMPLEX INDUSTRIES

présentée par : KAMEL Michael
en vue de l'obtention du diplôme de : Philosophiae Doctor
a été dûment acceptée par le jury d'examen constitué de :

M. BOURGAULT Mario, ing, Ph.D., président
M. MILLER Roger, Ph.D., membre et directeur de recherche
Mme AUBRY Monique, Ph.D., membre
M. MARTENS Martin, Ph.D., membre externe

DEDICATION

I would like to dedicate this thesis to
God, who has supported me every
moment of my life, to ***Pope Cyril VI***
whose prayers have supported this
work and to my soon to be born child
whose anticipation gives me great joy.

ACKNOWLEDGEMENTS

The author would like to acknowledge in gratitude the help received from the following individuals for the completion of the work in this thesis:

- Dr. Roger Miller, Jarislowsky Chair, for his constant supervision and invaluable help throughout all the phases of this research.
- The members of the jury Dr. Mario Bourgault, Dr. Monique Aubry and Dr. Martin Martens for their invaluable help, their comments and constructive criticism of my research.
- Dr. Xavier Olleros, for his feedback and constant support at the literature review phase.
- The various participants from the industry who have taken the time to fill-in the research survey and provide the valuable data that this research needed.

SUMMARY

Disruptive innovation has been a key concern of managers and academics alike for several decades. In recent years the rapid pace of innovation and change in ICT (Internet Communication and Telecom) industries has caused disruption to be frequent in some industries. Research on products, which have had a rapid lifecycle such as the computer disk drive, has paved the way to a modern detailed version of Schumpeter's creative disruption theory which also extends to aspects such as product architecture and systems integration.

Christensen's disruptive innovation theory, based on a study of the disk drive industry, hypothesized that as incumbent producers attain technological maturity, they tend to surpass the needs of the mainstream clients in favor of their big account clients which continue to push the envelope with their specialized needs. As the incumbents overshoot, low-level entrants enter the market and cater only to non-consumers or those favoring flexibility or cost considerations over technological advancement. As the entrants advance their technological capabilities, they start to attract mainstream clients satisfying their needs but without the price premium that incumbents require for surpassing them. The incumbents' core competencies, focused on technological advancement, are then disrupted and the incumbents' lean and low-cost structures become the basis of a competitive position in the industry. The incumbents are eventually overthrown by the more competitive entrants.

The shift of competitive advantages from technological advancement to cost and flexibility encourages the incumbents to open the product architecture to enable higher efficiencies and increased focus on cost reduction. This results in a change of the product architecture towards openness.

Chesbrough built on this theory further, also based on a study of the disk drive industry, hypothesizing that the openness of product architecture will only last for a limited period of time until the limits of the current product architecture are reached. Once this technological maturity is reached, an entrant often introduces a new technological platform that starts to overtake the market by its technological merits again. The product architecture will switch back towards closure to allow the developers to compete on product features and technological advancement. This phase will terminate by technological maturity, overshooting the needs of the mainstream clients and eventually opening of the product architecture again. This cyclical pattern continues to alternate throughout the lifecycle of a product.

This study aimed at finding if disruptive innovation theory, described above, suits complex product system (CoPS) industries, taking the aviation training industry as an example of such industries. Following observations that the industry has attained technological maturity over the past few years, the disruptive innovation theory's anticipation of product architecture openness was tested. The broad research hypothesis was that the industry diverged from the behavior predicted by the theory for several reasons related to its attributes distinguishing it from appliance consumer electronics industries such as the disk drive industry studied in earlier research.

To approach the study, three sub-industries were defined within the aviation training industry: the simulation product industry, the training products suite industry and the training services industry. The three sub-industries lie in increasing downstream order on the industry's value map. After assessing the industry's technological maturity, the effect of this maturity on the product architecture of each of these sub-industries was investigated.

Case-based research was conducted interviewing industry experts and collecting qualitative and quantitative data as well as reviewing published documents about the industry. The research findings have generally converged to demonstrate that the industry has indeed attained technological maturity as its players have met and even surpassed the product requirements of simulation technologies mandated by regulatory authorities. It was also established that it is these regulatory requirements that dictate the product features demanded by customers through their regulation of all the stages of the pilot training process. The existing simulation technologies readily meet the most stringent fidelity requirements, namely those prescribed for level D full flight simulators. Training conducted in these simulation products is considered by regulators as equal to actual flight time conducted on the aircraft.

Industry incumbents, as predicted by disruptive innovation theory, have also started to overshoot the requirements of the average airline training facility. With advanced laser visual systems and electric motion actuators, the costs of operating and maintaining the simulators are constantly improving although with little effects on their fidelity. Concurrently, a number of low-level entrants started providing lower cost and higher flexibility simulation devices. This trend was especially favored by the parallel increase in the number of no-frills airlines and low-cost carriers. The lean operating model of these new customers favored stringent cost control and a shift on emphasis from technological advancement to cost. So far, the industry has behaved as predicted by the disruptive innovation theory.

However, the divergence between the evolution of the industry and disruptive innovation theory came about in the incumbents' response to the disruption caused by new entrants' cost

advantages. While the theory would predict that the incumbents' market shares should have taken over by the entrants who will then open the product architecture to continue to drive down costs, incumbents actually closed the architecture of their products and services further into an integrated solution as a way to create superior value for their customers.

i) At the individual simulation product level, the incumbents continued to drive their closed architecture around proprietary designs and lowered their costs through increased attention on supply chain optimization and longer-term agreements with their vendors. This helped them achieve significant economies on the costs of data and parts used for their simulators. They also developed lower-cost and higher flexibility LCD-based simulation devices leveraging their existing simulator libraries developed for full flight simulator projects and benefiting from the high computing power available on commercial off-the-shelf personal computers. Innovative pricing agreements were devised with data providers to lower the prices of these flexible procedure trainers enough to drive out a key entrant competitor WICAT Systems Inc.

ii) At the product suite level, the incumbents packaged their full flight simulators and flexible procedure trainers into integrated training suites that ran the same simulation software seamlessly on multiple levels of devices. This feature was valued by many customers who traditionally suffered from the learn-unlearn cycles that were inevitable in the open architecture products suite industry where training providers traditionally acquired different devices from different vendors and provided differences training to bridge the gaps between the simulation fidelity levels. The new integrated training not only increased the quality of the training but also lowered the costs of upgrades and maintenance needed to keep the simulation devices fleet concurrent with the aircraft fleet. The portability of the simulation software on the different product platforms ensured that modifications had to be done only once for an operator's suite of training devices.

iii) At the training services level, the industry had an open product architecture with two distinct training phases: *ab-initio* and operational, consisting of type-rating and recurring. *Ab-initio* training enables a layman to fly an aircraft for commercial purposes. It is often conducted in small flying schools relying on single propeller engine aircraft for complementing classroom instruction of flight skills. Type-rating training prepares a licensed pilot for flying a particular type of aircraft type. Recurring training is the annual training mandated by regulators to maintain a pilot's flight license. Both type-rating and recurring training are often conducted at airlines training facilities and make heavy use of simulation equipment. A pilot's training career traditionally consisted of *ab-initio* training at an independent flight school, followed by type-rating training and recurring training either at the employer's training center or at an independent training center. The objectives, technologies and methodologies of training differed significantly amongst the 3 phases resulting in a longer and more expensive training cycle that initially taught pilots some skills that they had to forget soon afterwards. The 3 phases were governed independently by regulatory guidelines that dictated their contents and desired outcomes.

This open architecture of the training service has been recently changing through two parallel changes: the MPL license and the vertical integration of some independent training service providers into the *ab-initio* phase. The MPL (Multi-Pilot License) is currently being defined by an industry forum mandated by the ICAO (International Civil Aviation Organization). The license aims at training the pilots directly in a multi-crew setting, using increased simulation and on aircraft used by future airline employers from the very beginning of the training cycle. The airlines' industry forecasted growth and serious shortage of pilots over the next decade has provided the impetus for the development of the MPL. The other parallel evolution has been the trend of acquisitions and partnerships that some independent training providers, such as CAE, have made with *ab-initio* training providers for providing more integrated training using synchronized curriculums and therefore reducing the overall cost and duration of training. This trend also originated from some *ab-initio* training providers, such as Oxford Aviation Training, who work with airlines for early selection of their pilots. The school synchronizes and adapts their training curriculums to better prepare the students for the training environment of their future employers. Both the MPL and the vertical integration of training service providers are closing the architecture of the flight training service product.

In summary, the trend of product architecture closure is a divergence from Christensen's disruptive innovation theory which would have anticipated architecture openness as a consequence of technological maturity. The key reasons studied in this research for this peculiar tendency of complex industries towards closed systems are:

i) Accumulated learning:

The inherent complexity in CoPS industries favors incumbents' accumulated learning of the product and its integration intricacies. With the costs of simulation software development making up nearly one third of the total cost of a simulator, accumulated experience allows manufacturers to leverage their existing libraries to make their new ones more competitively-priced. This is in addition to the learning cycle involved in the integration of the numerous components of the simulator and the extensive collaboration that needs to be orchestrated to qualify the simulators by regulatory authorities. These learning cycles make incumbents increasingly competitive and reduce the entrants' capability to operate more efficiently.

ii) The need for regulatory approval of innovations, therefore limiting the influence of the market selection forces on disruptive innovation waves:

Simulation products and services can only create value for the customers once they have been approved by regulatory authorities. This extensive regulation of all the elements of pilot training influences, almost dictates, customers' requirements and expectations from the products. The free market selection forces, assumed to play a role in disruptive innovation in appliance industries, are therefore too weak in CoPS industries to result in disrupting the incumbents' core competencies in favor of the entrants. The regulatory qualification process, in addition to adding to the accumulated learning advantage of incumbents, controls customers' requirements in-line with the regulation standards. This does not permit the clear disconnect in competitiveness criteria between the mainstream versus high-end markets, which is one of the underlying assumptions in the current disruptive innovation theory.

iii) The high expertise level of the industry customers and their direct involvement in the design and building of the simulation products, undermining the effects of market selection forces as per Christensen's model:

The clients of the aviation training industry are directly involved in the definition and even design of their products and services. Strong communication between buyers and suppliers does not allow the entrants to fly under the radar of the incumbents until they are technologically able to respond to the needs of the mainstream market. The entrants have rather catered to non-consumers at first but had to face the same challenges and offer similar proprietary architectures as the incumbents when they entered the competition for the mainstream clients.

iv) The public safety and legal liability considerations involved in aviation training that make an open architecture a potential security threat:

Open product architecture implies shifting the integration of the product from a particular enterprise to the market, using existing standards. The high public safety and legal liability risks involved with deficient product integration make this shift unacceptable for regulators and the industry in general. The complexity of the simulation products add to the possibility of catastrophic failures should the product integration be left for industry standards and customers. The material impact of one such catastrophic failure can seriously hurt the financial situation of an airline or a simulator component provider.

v) The high market concentration and the subsequent thinness of production volume for the development of a component supplier base to transfer the modularity from the product to the industry, thus opening the product architecture:

Open product architecture implies specialization and the development of a network of specialized component providers each focused on one or several subsystems that make the simulator. With a thin market ranging from 15 to 30 simulators per year, this is insufficient to sustain such a sub-component level of specialization and the formation of a network of specialized providers working off a standard product architecture.

The research conducted to test the hypothesis used case-based interviews. More than 40 interviews of senior management from 29 organizations in the aviation training industry were

conducted. A set of exploratory questions were developed for verifying the applicability of the constructs and the underlying assumptions of the disruptive innovation theory to complex product system industries. The interviews were analyzed and the results documented for discussion.

The research conducted demonstrated an exception to the prevailing disruptive innovation theory which has been developed through a single case study in an appliance industry. While the research is insufficient to propose an alternate global theory of disruptive innovation, it raises the flag that a more comprehensive study is needed taking into consideration industry cases from different innovation games. Until the means are available for such a wide-scoped research, disruptive innovation theories should not be generalized across industry games.

This research demonstrates for managers that the trend of architecture openness and modularity that has emerged as a result of the ICT industry's prominence in management literature is not necessarily applicable to their particular industries, especially for those in complex product industries. Players in these industries have a competitive advantage against potential entrants. Their accumulated learning and track-record permits them to create more value for their clients by closing the architecture of their products and services and thereby increasing the barriers to entry.

ABSTRACT

Disruptive innovation has become one of the most studied causes of industrial evolution in recent years. In the wake of the ICT (Information and Communications Technologies) bubble, many researchers have focused on explaining how successful companies with strong strategic positions have failed and were driven out of the market by entrants. One of the most prevalent results of such studies was the disruptive innovation theory by Christensen, Raynor and Chesbrough (Christensen, 1997; Raynor and Christensen, 2002; Chesbrough, 2004). The three studied the disk-drive industry; an industry that has demonstrated entire product lifecycles in relatively short time spans conducive to research.

The resulting disruptive innovation theory proposed that industries offer proprietary architecture products throughout their technological maturity path until the incumbent suppliers of the industry mature and start to exceed the clients' needs, catering to the specialized wishes of high-end clients. This opens the door for entrants into the industry catering to low-end and cost or flexibility-sensitive consumers. With technological advancement of the entrants, their products satisfy the needs of mainstream customers and hence start competing against those offered by incumbents. The new entrants' lower cost advantage is then further enhanced by the opening of the product architecture to enable specialization and parallel innovation on product components therefore shifting competition from technical merit to cost or flexibility. The entrants then drive the incumbents out of the industry until the standard product architecture they use becomes unable to support further development and innovation. Other entrants then offer closed proprietary product architectures of superior capabilities and with time displace their predecessors as the suppliers of the mainstream clients. This alternation between architecture openness and closure continues as product standards are defined, developed and eventually replaced by new standards when obsolete.

Disruptive innovation, as observed in Complex Product System (CoPS) industries, diverges significantly from this hypothesized pattern. A study of the aviation training industry, as an example of a CoPS industry, has revealed that in response to technological maturity, the product architecture has gone towards further closure instead of openness. The product architecture of the individual training product has remained closed despite its technological maturity and the ability of simulation providers to satisfy and exceed all the requirements stipulated by the regulatory standards. At the product suite level, the legacy open architecture based on acquiring different training devices from different suppliers has changed into closed proprietary training suites that offer seamless integration around a common core of simulation software. At the training services level, a similar closure trend was observed replacing the distinct phases of training, each conducted in a different market, with integrated training providers and a new integrated training license.

The evolution of the aviation training industry, as opposed to disruptive innovation theory, was shown to be influenced by the importance of accumulation of learning, the involvement and technical expertise of clients and the regulation requirements in the industry limiting the role of market selection of innovations. Furthermore, public safety and legal liability risks disfavored open architectures. Finally, the thinness of the market for simulation products also limited the industry's ability to develop a network of specialized component providers able to innovate in parallel based on a standard product architecture.

CONDENSÉ EN FRANÇAIS

Avant-Propos

J'ai toujours été intéressé par la théorie de l'innovation stratégique tant durant mes études universitaires que plus tard dans ma vie professionnelle. J'ai particulièrement été intéressé par la théorie de l'innovation disruptive et sa faculté de prédire les succès et échecs d'entreprises en fonction des indicateurs industriels tangibles. Cependant, tout au long de ma carrière dans l'industrie de formation aéronautique, je n'ai pas été en mesure de concilier les constats d'innovation disruptive au fonctionnement de cette industrie. La dite théorie prévoit une évolution rapide et le remplacement constant d'anciens joueurs par des nouveaux. Toutefois, c'est le contraire qui se passe dans l'industrie de formation aéronautique qui privilégie la stabilité et la longévité des entreprises, comme mon ancien employeur, qui était une des premières compagnies dans l'industrie et continue comme un des leaders mondiaux. Cette théorie prévoit une ouverture de l'architecture du produit, comme conséquence directe de la maturité technologique de l'industrie. Ceci une fois de plus, va en porte-à-faux avec les réalités observées dans l'industrie de formation aéronautique où l'architecture du produit est plus fermé que jamais malgré le fait que la maturité technologique est déjà atteint. C'est cette dichotomie entre la théorie et la pratique qui est à l'origine de cette étude. Son but étant de valider la pertinence de la théorie d'innovation disruptive, dans le contexte d'une industrie complexe telle que celle de la formation aéronautique.

Revue de littérature

Pour comprendre la dynamique des relations entre l'évolution de l'architecture du produit et la maturité technologique dans le cadre d'industries complexes, l'étude théorique de plusieurs disciplines a été effectués. Il s'agit plus particulièrement de la gestion stratégique, la gestion d'innovation, l'intégration des systèmes, la modularité et la complexité.

Gestion stratégique

En ce qui concerne la théorie de la gestion stratégique, les domaines suivants ont été amplement étudiés. Il s'agit de la stratégie concurrentielle de Porter, stratégies des configurations, théorie économiques évolutionnaires, le modèle axé sur les ressources (resource-based view), les paquets (bundling), ainsi que la théorie des jeux.

Gestion d'innovation

Dans le domaine de la gestion d'innovation les thèmes étudiés furent ceux de la destruction créative, la théorie d'innovation disruptive, la diffusion d'innovation et les joutes d'innovation.

Complexité, modularité et intégration des systèmes

Dans ce domaine les thèmes touchés furent ceux de la modularité, les systèmes de produits complexes, l'ouverture et la modularité d'architecture, ainsi que le modèle cyclique de l'ouverture et les solutions intégrées.

Réseaux et coordination.

Les domaines étudiés ici furent ceux de la classification des formes organisationnelles selon le degré d'intégration, les grappes, les réseaux de valeur ainsi que les plateformes.

L'industrie de formation aéronautique

L'industrie de formation aéronautique a émergé au début des années 1920. Malgré un départ assez lent elle a petit à petit gagné du terrain dans le domaine aéronautique. L'industrie de formation aéronautique est constitue de trois industries secondaires. Cette division s'est faite sur la base des produits fournis : l'industrie de simulation, l'industrie d'ensemble des produits de formation et l'industrie tertiaire des services de la formation.

L'industrie de simulation

Cette industrie fournit les simulateurs de vol pour la formation des pilotes ainsi que les équipes d'entretien qui eux permet de piloter, opérer et maintenir les appareils. Les produits de cet industrie sont classés en trois catégories : les simulateurs complets de vol (*Full Flight Simulators*, FFSs), les dispositifs d'entraînement au pilotage (*Flight Training Devices*, FTDs) (Rosenkopf *et al*, 1998) et plus récemment les dispositifs de formation de bureau (*Desktop Training Devices*, DTDs) (CAE, 2000).

L'industrie d'ensemble des produits de formation

Cette industrie est responsable de la production des ensembles des outils utilisés lors de la formation aéronautique.

L'industrie des services de formation

Cette industrie offre des services de formation des pilotes dans une des trois phases suivantes :

- *Ab-initio* : c'est la formation initiale qu'un individu reçoit pour obtenir une licence de pilotage.
- Formation spécifique (*type-rating*) : ou le pilote est formé sur un type d'avion spécifique avant de le piloter pour des buts commerciaux;
- Formation récurrent : c'est une procédure de formation annuelle que chaque pilote est dans l'obligation de passer pour conserver sa licence.

Hypothèse et méthodologie de recherche

La théorie d'innovation disruptive, se base sur le fait que lorsque les compagnies s'efforcent de satisfaire les exigences de performance des produits des clients, elles développent de nouvelles technologies avec une architecture du produit fermée. Cela leur permet de pousser la développement des technologies et de l'offrir à leurs clients. Cependant, une fois qu'ils atteignent la maturité technologique, des nouveaux concurrents entrent le marché et, dans le but de satisfaire les besoins de la clientèle bas-gamme, établissent une capacité concurrentielle basée sur la convenance, le coût et la flexibilité des services et produits. La conséquence d'une telle action est l'ouverture de l'architecture du produit par l'intermédiaire des normes et standards afin d'atteindre des niveaux de rendement plus élevés et être concurrentiels. Ce modèle a été formulé sur la base d'une étude sur l'industrie des disques durs en 1997 (Christensen 1997), et soutenu par des études de cas des industries des ordinateurs personnels et télécommunications (Christensen *et al*, 2001). Cette étude émet l'hypothèse que ce modèle n'est pas entièrement applicable aux industries des systèmes de produits complexes (*Complex Product Systems*, CoPS) définies dans la littérature des systèmes d'intégration (Johnson, 2004; Dosi *et al*, 2004; Davies, 2004; Prencipe, 2004).

Dans l'industrie de formation aéronautique, il a été observé que les compagnies existants ont déjà atteint, et même dépassés, la phase de maturité technologique du marché. Toutefois, au lieu d'être déplacés par des nouveaux concurrents offrant une architecture ouverte, ils ont commencé à offrir des solutions intégrées en fermant ainsi l'architecture du produit même plus loin aux trois niveaux de l'industrie définies au début.

L'hypothèse est donc la suivante :

En réponse à la maturité technologique, l'architecture de produit, dans les industries de systèmes de produits complexes, ne s'ouvre pas nécessairement comme le prévoit la théorie d'innovation disruptive.

Les questions suivantes constituent la base de l'instrument de recherche utilisée dans cette recherche pour la collecte des données :

1. *Quel sont les indicateurs de la maturité technologique de l'industrie?*
2. *L'industrie de formation aéronautique a-t-elle atteint la maturité technologique?*
3. *Observe t-on une tendance à l'émergence des fournisseurs de bas-gamme?*
4. *Quel est le rôle des régulateurs dans la détermination des besoins des clients de l'industrie?*
5. *Quelle est le niveau d'implication des clients dans la conception des appareils dans cette industrie?*
6. *Les responsabilités liées à la sécurité publique et aux risques représentent elles un souci pour les différents acteurs de cette industrie? Quelles sont leurs effets sur l'innovation de l'industrie?*
7. *L'apprentissage accumule joue t-il un facteur important dans l'industrie? Quel est son effet sur la compétitivité des différents acteurs?*
8. *Observe t-on des conceptions standards de l'industrie à l'un des trois niveaux?*
9. *Observe t-on une ouverture de l'architecture du produit à l'une des trois niveaux de l'industrie?*
10. *Quel est le volume du marché en terme de nombre des simulateurs de vol produits par année?*

La divergence de comportement observée entre la théorie d'innovation disruptive et l'industrie de formation aéronautique est due aux facteurs suivants :

1. Le valeur élevée de l'apprentissage accumulée dans l'industrie, qui a pour effet de favoriser les innovations soutenant au lieu des disruptives (Christensen et Raynor, 2003) ;
2. Le besoin d'approbation réglementaire d'innovations, limite l'influence des forces du marché sur les innovations et par conséquent celles des vagues disruptives;
3. Le haut niveau d'expertise des clients ainsi que leur participation directe dans la conception et la construction des produits de simulation, conduit aussi à réduire les effets de sélection des forces du marché qui jouent un rôle important dans le modèle de Christensen;
4. Les considérations de sécurité publique et de responsabilité légale impliquées dans la formation aéronautique qui rendent une architecture du produit ouverte une menace potentielle de sécurité;
5. La forte concentration du marché et l'insuffisance du volume de production pour l'émergence d'une base de fournisseurs pour transférer l'intégration du produit de l'entreprise vers l'industrie, ouvrant de ce fait l'architecture du produit (Chesbrough, 2003).

Collecte de données

Un instrument de recherche a été créé pour recueillir des données auprès des différents intervenants dans l'industrie aéronautique. Plus de 40 entrevues ont été menées auprès de cadres supérieurs représentant les différentes industries de ce secteur dont des fournisseurs de simulateurs de vol, des prestataires de formation aéronautique, des intégrateurs d'avions, des lignes aériennes, des fabricants de systèmes d'avioniques, des régulateurs ainsi que des fournisseurs de renseignements industriel. Ces entrevues ont été transcrites et analysées en vue de l'hypothèse soulevée, ainsi que dans le but d'apporter des éléments de réponse aux questions exploratoires mentionnées ci-dessus. En outre, des documents industriels ont été minutieusement examinés dont des communiqués de presse, des rapports rédigés par des magasins spécialisés, des associations ainsi que des cabinets de conseil. Pour une meilleure compréhension des résultats de ces recherches, un certain nombre de présentations ont été faites au fil du temps à des auditoires spécialisés des cadres et professionnels de l'industrie. Leurs réactions et commentaires ont contribué à affiner le champ de recherche, définissant les limites de cette dernière, et contribuant à une meilleure compréhension de son impact sur la théorie et la pratique.

Résultats de la recherche

La recherche entreprise a menée les conclusions suivantes :

- La maturité technologique de l'industrie est le résultat de plusieurs facteurs, notamment les dispositions réglementaires.
- L'industrie de formation aéronautique a en effet atteint la phase de maturité technologique. Dans certains cas, elle l'a même largement dépassé, car elle est parvenue à faire plus que simplement répondre aux exigences de ses clients. En ce qui concerne les produits de simulation, les simulateurs de niveau D démontrent un niveau de fidélité qui comble toutes les attentes pédagogiques et réglementaires des clients. Sur les ensembles des produits de simulation, le niveau de maturité atteint est encore une fois exceptionnel. Ceci se caractérise particulièrement par la maturité de différents appareils et leur intégration verticale avec du logiciel de simulation commun (George, 2003). Ces ensembles des produits de simulation ont introduit une standardisation de la technologie dans les phases diverses de la formation et donc résout en grande partie le problème, auxquels sont confrontés les fournisseurs de formation aéronautique, des différences majeurs entre les appareils ou la formation se faisait sur des appareils indépendants les uns des autres. Au niveau de fournisseurs de formation, la technologie est au niveau des appareils de formation et les outils d'enseignement associés avec eux. Les experts bien que n'étant pas tous d'accord sur la date à laquelle cette industrie a atteint la maturité technologique, reconnaissent cependant que cela s'est produit au cours des 5 à 10 dernières années.

- Le fait pour les acteurs principaux d'être parvenus à surpasser les besoins de leurs clients dans le courant principal de l'industrie, a ouvert la voie aux fournisseurs de produits de bas de gamme, leur permettant ainsi de pénétrer dans l'industrie de formation aéronautique. Les entreprises offrant des FTD de bas gamme, ont considérablement émergé. Aidés par les progrès rapides dans les technologies de l'ordinateur personnel, de nombreux employés ont lancé leurs propres entreprises qui offrent des simulateurs de base à faible coût.
- La recherche effectuée ont démontré que, l'architecture du produit dans l'industrie de la formation aéronautique, à ses 3 niveaux, a une grande tendance à la fermeture au cours de ces dernières années. Ces trois niveaux sont, cependant, restés modulaire grâce à la grande variété des produits et des services taillés. Au niveau des appareils de simulation de vol, les produits continueront d'adopter une architecture fermée. Plusieurs conceptions des appareils se concurrencent, chacun avec sa propre architecture fermée. Sur le niveau des ensembles de produits de simulation, l'architecture de produits a évoluée d'une architecture ouverte, composée des appareils indépendants de plusieurs fournisseurs, à une architecture fermée des solutions intégrées ou les fournisseurs des appareils offrent des modèles de simulation communs entre les appareils. Au niveau des services de formation, l'architecture du produit a démontré encore une fois une tendance à la fermeture. C'était un marché qui était divisé en deux segments, chacun d'eux comportant des fournisseurs différents. Cette division tend cependant à disparaître. La formation *ab-initio* et celui offert par les lignes aériennes (composé du type-rating et de la formation périodique) étaient des segments traditionnellement distincts sur le marché. Des centres de formation aérienne ont commencé à offrir de formation intégrée débutant par *ab-initio* utilisant les mêmes simulateurs de vol qui sont utilisés par les phases suivantes de la formation.
- Dans les trois niveaux de l'industrie de formation aéronautique les clients sont généralement très bien informés au sujet des produits et, par conséquent, ont une influence significative sur sa

conception. La recherche a démontré la boucle de rétroaction positive accumulée de l'apprentissage auxquelles les entreprises sont soumises. Chaque nouveau simulateur construit rend la société plus efficace car lui permet d'amortir les lourds coûts de développement sur un plus grand nombre de produits. Cela constitue à créer des barrières à l'entrée pour les novices et limiter leur accès au marché des produits plus complexes tels que des simulateurs de vol complets.

- La sécurité publique ne semblait pas être une préoccupation majeure ni pour les fournisseurs des simulateurs de vol, ni pour les fournisseurs de la formation. Les régulateurs l'ont identifié comme un facteur clé dans l'industrie mais les gérants l'ont pris pour acquis. Cependant, le risque de la formation négative est très claire pour ces gérants. Tous ont conviennent qu'en cas d'accident, les répercussions entraînés sur l'industrie sont très souvent assez radicales, car elles touchent plusieurs secteurs y compris les dispositions réglementaires.

Discussion

La recherche présentée ci-dessus a examiné la validité du modèle cyclique des industries, alternant entre des architectures ouvertes et fermées, dans le contexte d'une industrie des systèmes de produits complexes en prenant pour exemple l'industrie de formation aéronautique.

Les dix questions posées lors de la formulation de l'hypothèse trouvent donc leurs réponses ci-dessous :

1. Quels sont les indicateurs de la maturité technologique de l'industrie?

Il a été démontré que les dispositions réglementaires sont l'une des déterminants les plus importantes des besoins de la clientèle à tous les niveaux de l'industrie. Les règlements déterminent la durée, l'équipement de simulation utilisé et les qualifications acquises à chaque phase de la formation du pilote de la phase préliminaire *ab-initio* au « type-rating » jusqu'à la formation récurrente.

2. L'industrie de formation aéronautique a-t-elle atteint la maturité technologique ?

Il a été constaté que l'industrie de formation aéronautique a en effet atteint la maturité technologique dans les trois niveaux de produits définis dans cette recherche. Objectivement, l'industrie est depuis longtemps en mesure de satisfaire aux plus strictes exigences réglementaires avec les simulateurs de niveau D qui sont jugées équivalentes à des performances d'un avion dans l'enveloppe normale de vol.

3. Observe t-on une tendance à l'émergence des fournisseurs de bas-gamme?

Au cours des 10 dernières années, l'industrie a connu une augmentation des fournisseurs de bas de gamme offrant des FTD et des simulateurs de bureau à faible coût pour les compagnies aériennes et certains non-consommateurs de simulation synthétique telles que les écoles de pilotage *ab-initio*. De 30 a 50 entreprises dans le monde, sont impliquées dans la fabrication d'un ou plusieurs produits de simulation ou services de formation avec environ 5 d'entre eux qui sont en mesure d'offrir des simulateurs complet de vol.

4. Quel est le rôle des régulateurs dans les besoins des clients de l'industrie?

Les clients et fournisseurs de l'industrie de formation aéronautiques sont restreints par les dispositifs réglementaires. La création de valeur d'un produit ou un service est atteignable seulement s'il est certifié par les régulateurs. Cet effet ralentisse l'introduction des innovations au marché ainsi que filtre ces innovations selon les dispositifs établis. Ces deux facteurs réduisent la pouvoir de sélection du marché des innovations et ont pour effet que la plupart des innovations introduites au marché sont soutenants est non pas disruptives.

5. Quelle est le niveau d'implication des clients dans la conception du produit ?

Les compagnies aériennes ont traditionnellement été des experts en matière de technologies de simulation. La participation des clients tels que Swissair, Lufthansa, ou KLM dans la conception des produits d'appareils de simulation, a atteint une ampleur telle que leurs ingénieurs participaient à la correction des codes sources de simulation. Cette intime participation permet une communication étroite entre les fournisseurs et les clients, ce qui aide les entreprises à mieux répondre aux attentes de leurs clients.

6. Les responsabilités liées à la sécurité publique et aux risques représentent elles un souci pour les différents acteurs de cette industrie? Quelle est leur effet sur l'innovation de l'industrie?

La sécurité publique est l'une des raisons principales de l'existence de l'industrie de simulation. Les considérations de sûreté et de responsabilité de public continuent à d'être à l'avant garde des préoccupations des régulateurs et des autorités gouvernementales en charge de l'aviation. Pour les constructeurs, les fournisseurs de simulation et les responsables de formation, la crainte de l'échec est grande et va au-delà des considérations des potentielles conséquences catastrophiques. Cette crainte renforce la position concurrentielle des joueurs actuels et ralentisse l'acceptation des nouvelles technologies présentées par des débutants, qui manquent la crédibilité.

7. L'expérience accumulée joue t-il un facteur important dans l'industrie? Quel est son effet sur la compétitivité des différents acteurs?

L'expérience accumulée sur le produit et des prestataires de service dans l'industrie ont un effet principal sur leur compétitivité. Dans un environnement où la construction d'un simulateur est un projet complexe qui s'étend sur 12 à 24 mois et coûte de dizaines de millions de dollars, l'expérience professionnelle de la compagnie est essentielle pour gagner la confiance des clients. En outre, la possession par une compagnie du logiciel de simulation, peut réduire le coût de fabrication de son simulateur de 20 à 50 %. Par conséquent, l'expérience accumulée augmente la compétitivité des sociétés et aide à renforcer leur position stratégique face aux novices proposant des produits.

8. Observe t-on des conceptions standards de l'industrie à l'un des trois niveaux?

Aucun des experts interviewés tout au long de cette recherche ne reconnaît l'existence des normes qui régleraient l'architecture du produit dans cette industrie. Ceci malgré les fréquentes transactions portant sur l'intégration de technologies provenant de multiples fournisseurs tels que l'intégration des systèmes visuels d'Evans & Sutherland sur les simulateurs de CAE et Thales. Une collaboration étroite existe entre les entreprises et est indispensable à tout projet d'intégration de systèmes ainsi que leurs fonctionnalités.

9. Observe t-on une ouverture de l'architecture du produit à l'une des trois niveaux de l'industrie?

Comme indiqué ci-dessus l'architecture des produits dans les différents niveaux de l'industrie, continue à faire preuve de fermeture. Sur la gamme des produits et des services de formation, l'architecture affiche une tendance très rapide à la fermeture. C'est la réaction prévisible des grands opérateurs en place, en réponse aux menaces concurrentielles des produits et technologies peu coûteux des débutants.

10. Quel est le volume du marché de simulateurs de vol?

Le marché de simulateurs de vol complets est trop mince pour soutenir l'émergence des fournisseurs spécialisés des composantes des simulateurs de vol. Avec un moyen de 30 simulateurs par année et un prix entre 10 $M et 15 $M, le chiffre d'affaires du marché ne justifie pas l'existence profitables des fournisseurs des composantes qui ne font pas d'intégration des systèmes.

La théorie d'innovation disruptive s'engage à démontrer que les industries passent à une architecture ouverte des produits, une fois que ces derniers ont atteint leur maturité technologique (Christensen, 1998). Cette transformation d'une architecture fermée à une architecture ouverte est cyclique tout le long du cycle de vie de l'industrie (Chesbrough, 2004). L'hypothèse implicite qui sous-tend cette théorie est que la fermeture de l'architecture technologique, n'est pas une caractéristique inhérente de l'industrie, mais plutôt une fonction de sa maturité technologique qui est liée aux exigences de la clientèle. Lorsque les industries sont encore sur la voie de la maturité, leurs architectures technologiques sont fermées et répondent au besoin d'intégration du niveau de l'entreprise. En mûrissant, leur architecture de fermeture diminue à un niveau qui peut être géré au niveau de l'industrie. Cette relativité de l'interdépendance de l'architecture technologique a fait la base de l'hypothèse de base des études de Christensen, Chesbrough et d'autres qui ont étudié l'industrie des 'électroniques et des autres industries pareils (Christensen, 1997; Chesbrough, 2004).

L'industrie de formation aéronautique s'est écartée de ce schéma. Son architecture fermée persiste tout au long de son évolution technologique de maturité. Le seul changement que l'industrie a démontré était vers plus de fermeture, comme clairement démontré ci-dessus. Les facteurs favorisant cette fermeture souligne la besoin inhérente d'une société d'assumer activement un rôle intégrateur afin de gérer un grand nombre de composants et disciplines nécessaires à la construction d'un produit complexe.

Conclusion

La recherche présentée ci-dessus a démontré que les industries de système de produits complexes (CoPS) n'adhèrent pas nécessairement à la théorie d'innovation disruptive proposée par

Christensen et Chesbrough (Christensen, 1997; Chesbrough, 2004). Grâce à une étude sur l'industrie de formation aéronautique s'étendant sur 4 années, cette dernière a démontré qu'elle avait atteinte et même dépassé la maturité technologique requise par ses clients. Cependant, ceci n'a pas eu pour conséquence, la remplacement des joueurs actuels par des débutants de bas de gamme, comme le suggère la théorie. En outre, on n'a, à aucun des niveaux, observé l'ouverture de l'architecture du produit. En fait, l'industrie va dans le sens contraire, à savoir la fermeture de la dite architecture. La théorie d'innovation disruptive n'est pas, donc, suffisante pour prédire la structure et les conséquences des technologies disruptives sur les acteurs dans les industries de produits complexes.

Limites

La limite principale de cette recherche est qu'une seule industrie a été étudiée et s'est avérée être une exception à la théorie d'innovation disruptive. Ce n'est pas suffisant pour établir une théorie alternative et décrire le comportement des industries CoPS en réponse à la maturité technologique. Une recherche plus approfondie regroupant un plus grand nombre d'industries de secteurs différents est nécessaire pour se faire une idée plus juste de la situation dans le domaine des innovations.

Opportunités de recherche approfondie

Une recherche approfondie de cas est nécessaire pour établir une solide théorie d'innovation disruptive dont les constructions, les propositions et les arguments logiques de base s'appliquent plus largement et permettent une plus large exploration des questions de recherche. Cette recherche établie sur la base de cas concrets devrait se produire plus à l'étape de formulation de la théorie tout en employant des cas additionnels pour amplifier la puissance analytique (Eisenhardt et Graebner, 2007). La recherche présentée ci-dessus a indiqué que les joutes d'innovation pourraient former une base intéressante dans le choix des cas qui couvriraient les différents types de comportement, en réponse à la maturité technologique des industries.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

BOT:	Build-Operate-Transfer
CBT:	Computer Based Training
COTS:	Commercial Off-The-Shelf
CMOT:	Canadian Ministry of Transport
DTD:	Desktop Training Device
EASA:	European Aviation Safety Agency
FAA:	Federal Aviation Administration
FAR:	Federal Aviation Regulations
FFS:	Full Flight Simulator
FNPT:	Flight Navigation and Procedures Trainer
FTD:	Flight Training Device
IATA:	International Air Transport Association
ICAO:	International Civil Aviation Organization
ICD:	Interface Control Document
IFR:	Instrument Flight Rules
IPT:	Integrated Procedures Trainer
JAA:	Joint Aviation Administration
JAR:	Joint Aviation Regulations
LCoS:	Liquid Crystal on Silicon
MPL:	Multiple-crew Pilot License
PCB:	Printed Circuit Board
RAeS:	Royal Aeronautical Society
SBC:	Simulation-Based Courseware

SOP:	Standard Operating Procedures
VFR:	Visual Flight Rules
VSim:	Virtual Simulator
WBT:	Web Based Training
ZFT:	Zero Flight Time

LIST OF APPENDICES

AVANT-PROPOS

Strategic innovation literature was very interesting for me throughout my academic and professional career. I was especially fascinated by disruptive innovation and its capacity to foretell the rise and failure of companies based on tangible industry and product indicators. However, with more than 7 years of diversified work experience in the aviation training industry, I was not able to reconcile the constructs of disruptive innovation theory. While the literature predicted rapid change and constant displacement of old players by new ones, the aviation training industry enjoyed long-lasting stability with the life of some companies, such as my previous employer, spanning the entire life of the industry. This dichotomy between literature and practice was most pronounced during my work as a proposals engineer when I was mandated with architecting a low-level FTD to compete with WICAT, the most ferocious competitor of the company in the FTD markets back then. This mandate gave me first-hand experience with the heavy cost and procedural structures of the industry incumbents contrasted with the agile workshops of simulation engineers producing simulation devices. This expertise was further enriched when I became one of the few project managers in the newly formed division of Integrated Training Solutions, a division operating semi-autonomously for architecting and selling integrated training suites including low-level FTDs. I was involved in key projects such as Airbus's acquisition of more than 30 of these low-level FTDs (called M/FTDs) for using them in their global network of training centers as the only complement to the full flight simulators. I was also the project manager of a training suite for the FAA which has opened the door for collaboration between the company and the regulatory body on defining the advanced training curriculum that integrates the new training devices. I also managed the first fully integrated suite delivered to Air Canada Jazz airline and succeeded to challenge and stretch the interpretation of Transport Canada regulations to qualify these low-level FTDs. I therefore witnessed the disruptive threats from WICAT and other competitors but was also part of the response of an incumbent in offering closed architecture suites that gained back the lost market shares and eventually drove WICAT out of business. Therefore I wanted to study the disruptive innovation theory and validate its constructs and predictions in the context of a complex industry such as the aviation training industry where I worked.

The research presented in this thesis was carried-out as a part of the MINE (Management of Innovation in the New Economy) research program. This program was lead by Professor Roger Miller, Jarislowsky Chair on Innovation and Competitiveness at l'École Polytechnique de Montreal.

CHAPTER 1 INTRODUCTION

Strategic management of technology is a relatively new discipline that has evolved rapidly in the past 30 years. In the 1980's Porter's work on strategic positioning and competitive strategies dominated the field (Porter, 1980, Porter 1985 and Porter 1990). Following the realization that competitive positions are built and sustained through a firm's unique assets and attributes, the focus of literature was gradually including internal parameters such as core competencies (Hamel and Prahalad, 1990; Collis, 1994), resource based-view (Barney, 1986) and dynamic capabilities (Teece, 1987; Zollo and Winter, 2002). However, with the information technologies boom and the rapid development brought about by advanced telecommunications and the internet, systems integration and product architecture have become the focus of a significant portion of strategic management literature (Miller and Olleros, 2008; Bargigli, 2005). Theories such as disruptive innovation and open innovation are focused on a firm's ability to architect its product in alignment with its market and industry architecture (Raynor and Christensen, 2002). Many revisited existing research through the perspective of product architecture and innovation. For example, Christensen's disruptive innovation dilemma (Christensen, 1997) is rooted in Schumpeter's description of innovation in capital economies with an additional emphasis on product and market architecture following product maturity (Schumpeter, 1934).

Influenced by the rapid growth and market boom, most of the modern systems integration and product architecture research in the late 1990's and 2000's was based on information technology, consumer electronic industries or the internet (see for example Christensen, 1997; Chesbrough 2004; Gawer and Cusumano, 2002; Olleros, 2007). The resulting literature, as hypothesized in this dissertation, may therefore have had an inherent bias towards consumer appliance industries offering limited applicability to other industry types. A revisit of this literature in light of the context of other industries may therefore be necessary before a global systems integration theory is formulated.

One such category of non-consumer appliance industries that has gained increased attention in recent years is Complex Product System (CoPS) industries (Johnson, 2004), defined as capital-intensive industries comprising multiple technologies, individuals and scientific disciplines that are too complex for any one individual to comprehend, hence requiring the orchestrated collaboration of multiple entities (Johnson, 2004; Simon, 2004 and Prencipe, 2004). The University of Sussex Science Policy Research Unit (SPRU) is one of the specialized research centers in the domain with a number of scholars interested in innovation and product architecture in complex industries.

The research presented in this dissertation builds on this existing literature and aims at investigating the evolution of product architecture in complex industries as they attain technological maturity; a phase in an industry's lifecycle that has received increased attention from scholars such as Christensen, Raynor and Chesbrough (Christensen, 1997; Christensen and Raynor, 2003; Chesbrough, 2004; Raynor and Christensen, 2002). The industry selected for this investigation is the aviation training industry, one that has been previously identified in CoPS literature (Prencipe, 2004). The industrial boundaries defined for this research span the flight simulation equipment industry, the training product suite industry and the training services industry.

Chapter 2 presents a summary of this literature review with comments on the relevance of these theories to the research objectives. For this investigation, innovation theory was first reviewed to understand disruptive technologies and their diffusion mechanisms. Systems integration and product architecture literature were also reviewed to gain an understanding of the different architectural states of products, their triggers and evolution mechanisms. Networks and coordination theories were reviewed as they form an integral part of the organization of complex industries as defined above. Finally other management literature was reviewed to provide an understanding of the different schools of thought and offer the right tools to analyze the product architecture and technological maturity variables within an industrial evolution context.

This is followed, in Chapter 3, by an introduction to the aviation training industry, its organization, regulation and the different industries it interfaces with. Chapter 4 then formulates the research hypothesis, the main questions associated with it and the research methodology selected for answering these questions. The detailed list of interviewees, their affiliations and positions is provided in Appendix A. Chapter 5 describes the research findings of the research while chapters 6, 7 and 8 are dedicated to describe the 3 sub-industries mentioned above presenting the product of the industry, the state of its technological maturity and the subsequent effects, if any, on its architectural evolution. The findings presented in these three chapters are the result of the case-based research interviews conducted throughout this research project.

Chapter 9 then discusses the theoretical implications of the research findings answering the initial research questions posed. The conclusions and limitations of the research are then presented in chapter 10 followed by a description of future research opportunities in the domain. The

Bibliography of academic, industrial and management literature resources used throughout the research is then presented.

CHAPTER 2 THE EVOLUTION OF INDUSTRIES - LITERATURE REVIEW

To understand the dynamics of the relationship between product architecture evolution and technological maturity in complex industries, the existing literature in several domains was reviewed. Literature from innovation management was reviewed followed by literature from systems integration, modularity and complexity to gain an in-depth understanding of the specifics of complex systems and how these may affect their adherence to innovation models developed in other industries, such as the disk drive industry (used to develop the disruptive innovation theory). Literature from networks and coordination theory was also reviewed to complement the understanding of complex product systems where coordination is often a key competency of industry players. Finally literature from other theories of strategic management was reviewed to ensure completeness.

These domains in the literature therefore provide a deeper understanding of the various components of the research hypothesis, namely complex industries, the dynamics of product architecture, innovation and its relationship to product maturity.

2.1 Innovation Management

Innovation research has seen a surge since the 1970's (Rogers, 1986) after years of lack of attention to it in early economics literature (Rogers, 1962; Freeman, 2003). A review of this innovation management literature was necessary in this research to understand technological maturity in the industry. The domains of literature reviewed are presented below.

2.1.1 Creative Destruction

In the 1930's Joseph Schumpeter published "Theory of Economic Development" which contained a model of innovation in capitalist economies (Schumpeter, 1934). Creative Destruction, Schumpeter argued, is the continual emergence of innovations that destroy the core competencies of the key incumbent players in an industry, thus possibly giving rise to a new set of players, a new industrial structure and even new industries altogether (Schumpeter, 1934). Schumpeter's model depicted technological evolution of products from their inception, to their battle against existing technologies, to their maturity into dominant designs and finally to obsolescence by a radical innovation that requires new core competencies that existing players do not possess. A graphical representation of Schumpeter's model of industrial evolution is shown in Figure 2.

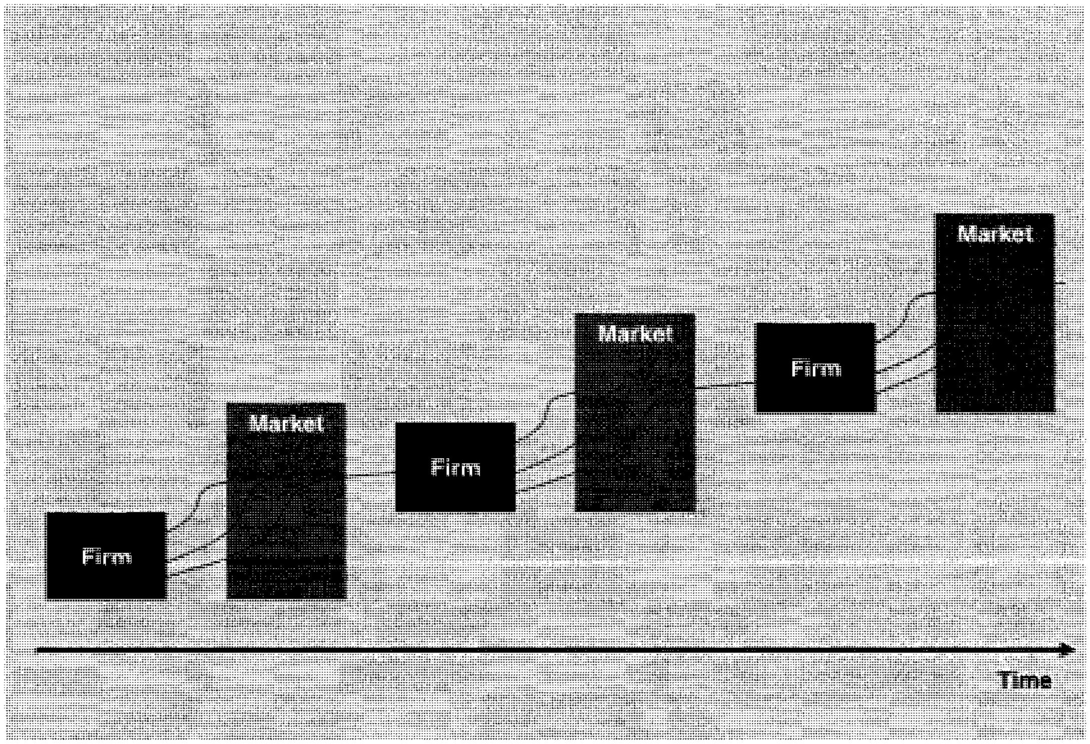


Figure 2.1: Schumpeter's Creative Destruction Force in Industrial Evolution

Studies on the effects of Schumpeter's cycle on industries raised the concern that creative destruction may be a disincentive for companies to invest in new technologies and thus leading to underinvestment in innovation (for example Nordhaus, 1969). On the other hand, Aghion and Howitt argued that because the creators of disruptive technologies are often not the incumbents, they have a tendency to over-invest (Aghion and Howitt, 1998). Still, Baumol argues that even the externalities leading to the underinvestment fear prevalent in some studies are beneficial to the society (Baumol, 2001).

The interest in Schumpeter's concept has been revived in the recent literature studying radical innovations in various industries especially those related to the ICT (Information and Communications Technology) sector (Freemand, 2003). These industries, such as the disk drive industry, have exhibited the evolution pattern of successive industrial revolutions proposed by Schumpeter (Schmidt and Druehl, 2005; Christensen 1997; Christensen, 1998).

Schumpeter's work was the foundation of Christensen's model predicting a continuous cycle of products entering the market and maturing only to be eventually overturned by new disruptive innovations (Freeman, 2003). This research will therefore heavily use the models of Schumpeter and Christensen to understand and validate the behavior of complex product industries, represented by the aviation training industry, consequent to their technological maturity.

2.1.2 Disruptive Innovations

The innovator's dilemma, argues Christensen (1997), is that suppliers in mature industries who listen to their clients and respond to them most usually end up catering to the high-end specialty customers and continue offering them a proprietary architecture product with increasing technical features and capabilities. Meanwhile, low-end entrants to the market start to offer lower-cost products, initially to non-customers, competing on other features such as cost or flexibility. With continued technological maturity, the incumbents overshoot the needs of the mainstream customers in the industry while entrants start to meet them. This results in the entrants displacing the incumbents shifting the competitiveness focus from technological merit to cost or flexibility. Consequently, the entrants open the industry architecture to enhance the productivity and permit further cost efficiencies. This open architecture becomes the new standard in the industry replacing the proprietary architecture products already existing.

The entrants manage to fly under the incumbents' radar due to the following reasons that Christensen presents (Christensen, 1997):

1. Companies depend on customers and investors for resources:

Customers and investors often fail to recognize the added value of new disruptive technologies at their onset. Consequently, firms that are mostly customer-driven ignore these technologies. By the time the added value of these technologies is recognized later, it is often too late for the incumbents to enter the newly created markets. To overcome this dilemma, Christensen suggests that large companies need to create new units or organizations for addressing promising disruptive technologies. These organizations will only operate in the emerging markets and will hence have the necessary scale to justify their investments in the new technologies.

2. Small markets don't solve the growth needs of large companies:

Large companies often allocate resources to their various projects based on their prospective contribution to their overall growth and profitability. This may deprive disruptive technology projects of resources due to their lower margin prospects and higher risks. Therefore to mitigate this risk, the organizations that large companies need to create, for addressing the emerging customers, need to be small for the small low-margin emerging markets to be adequate for their operations and growth.

3. Markets that don't exist can't be analyzed:

Large companies, that are used to sound decision-making methodologies relying on collecting market data before investing, find it difficult to invest in disruptive technology markets that have no available market information (Porter and Rivkin, 2000). Christensen, therefore, suggests that companies need to prudently invest in new technologies with the failure prospects in mind. The investments need to be considered as the price of learning and need to be flexible enough for iterative learning.

4. Technology supply may not equal market demand:

Continuous improvements on existing products often render them too good for what the market demands or can absorb. Competing lower end products, that may have been popular in smaller markets, could then become viable choices for the mainstream markets, especially that they usually offer superior price, reliability and convenience than existing mainstream ones. To ensure that this does not drive out producers of disruptive technologies, they need to move early and find markets for new attributes of their products. When mainstream markets reject certain attributes, companies need to find smaller markets where they are accepted. These latter markets are likely to become the mainstream markets of the future.

The disruptive cycle is depicted in figure 3 below with an additional line showing the slow-to-evolve regulatory requirements (Christensen, 1997).

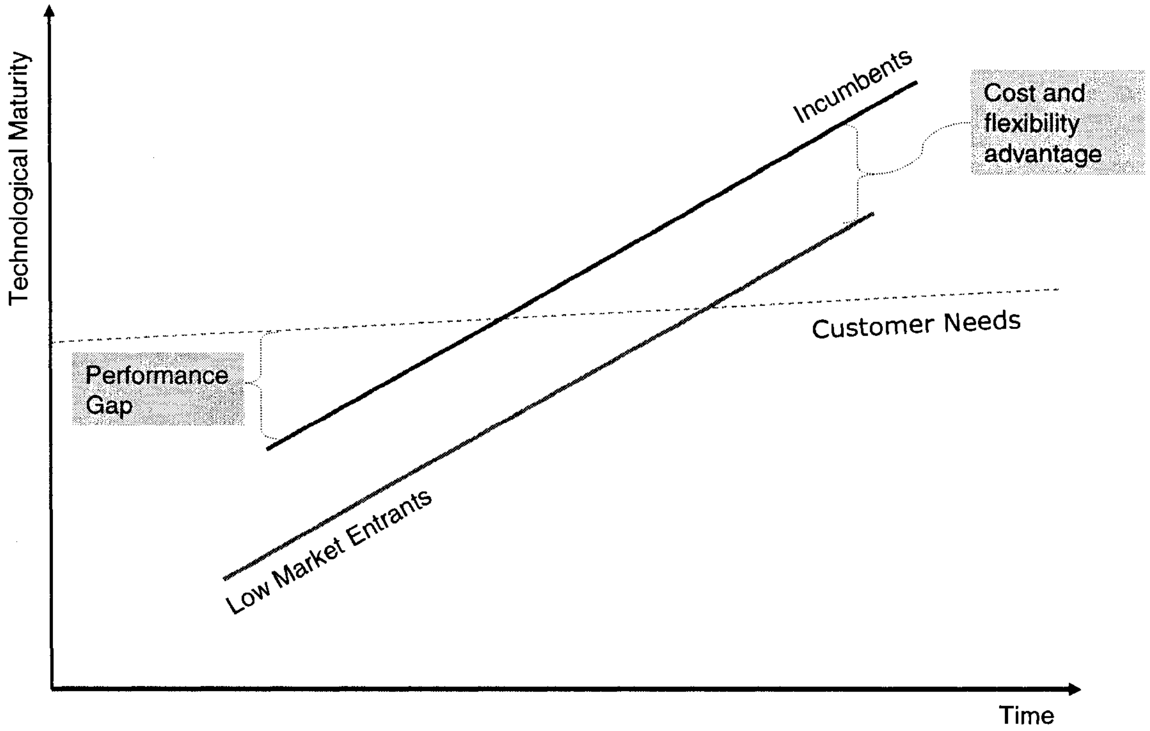


Figure 2.2: Disruptive innovation cycle (Christensen, 1997) with the slow-to evolve regulations

The constructs of disruptive innovation theory, presented by Christensen, and its implicit assumptions are the following:

1. Suppliers are customer-driven

Disruptive innovation theory assumes a market-driven industry where consumer needs evolve and alternates between technical features, at the early stages of a developing platform, and cost or flexibility later on as it matures.

2. The incumbents miss the evolution of customer needs as they continue to focus on high-end clients

The theory also assumes that as incumbents focus on the needs and specifications of their upper-end customers, they miss the needs of the majority of customers in the market and hence overshoot with their product offering the needs of the mainstream industry.

3. An open architecture permits better efficiency and cost savings than a closed one.

The theory states that entrants will offer an open product architecture to enable better efficiencies and compete on the cost and flexibility parameters demanded by the mainstream clients. It hence makes an implicit assumption that an open product architecture is more efficient than a proprietary architecture.

Following "The Innovator's Dilemma", Christensen and Raynor published "The Innovator's Solution" (Christensen and Raynor, 2003) about managing technological discontinuities, highlighting the following points:

1. Technological disruptions belong to one of the following 2 categories:

New Market Disruptions: these involve finding solutions that enable customers to do jobs not doable before and therefore create new markets. As the new products improve, customers from incumbent value chains are often attracted to the new one. An example is the affordable office photocopier technology that created a new value chain around customers doing their own photocopying instead of sending them to specialized companies. Once the technology proved to be reliable, many customers acquired it for the improved convenience and pricing over the old value chain.

Low End Disruptions: these provide innovative solutions that resemble those in mainstream markets but that are less costly, more flexible or more affordable for that market segment.

2. Companies may be able to anticipate the next disruptive technology by considering the "circumstances" of using their product rather than who their customers are. This will give them an understanding of whether "nonconsumers" present a market opportunity or if they have no use for the new product in their lives. A nonconsumption that may create a market opportunity is one where potential consumers have a need to use the product but have no access to convenient solutions because they do not exist, are too expensive, or are too complex to use.

3. When products are still struggling to satisfy customer requirements, companies should offer proprietary and interdependent designs. This helps them to maintain a competitive advantage when value is captured in the market. When products exceed customer expectations, new emerging markets are eminent to emerge and it is better for companies to outsource and resort to an open modular architecture to attain efficiency and speed in bringing innovations to market.

4. Whenever commoditization and architecture openness is happening at the product level and is eroding the profitability of suppliers, de-commoditization and architecture closure is happening at the sub-system level in the value chain and is providing opportunities of value capture. The high competitive forces on the product suppliers push for proprietary designs at the sub-component level to increase efficiency.

5. The resources, processes and values of a company determine its potential for pursuing disruptive technology markets.

6. Disruptive technologies should be treated as opportunities not threats by preparing the company for harnessing them. This can be done by:

   a. Starting to look for disruption growth opportunities when the company is experiencing growth and creating a specialized group for that purpose;
   b. Placing a senior manager, capable of autonomous execution, in charge of the group;
   c. Accumulating expertise in the group for moving and shaping new ideas in the right technological channels, sustaining and disruptive;
   d. Training the sales, marketing and engineering employees to recognize disruptive opportunities and channel them through the right venues in the corporation.

In summary, the first volume of Christensen's work warns against disruptive technologies that start small, grow unnoticed by large firms until they become the mainstream products thereby pushing incumbent firms out of competition. He points-out that large companies may be reluctant to venture into these markets due to their small volumes and thin margins, their little information available or because they are too focused on mainstream markets that they overshoot the clients' requirements in them.

In the second volume, Christensen and Raynor present some solutions of how organizations can be redesigned for harnessing the opportunities presented by disruptive innovations: companies should pay attention to the patterns of using their products instead of the consumers themselves, align their product architecture strategy with the product maturity level, search for de-commoditization opportunities in their value chains and create special units capable of recognizing and channeling these opportunities in time to capture value from them (Christensen and Raynor, 2003).

As mentioned above, Christensen's model of disruptive innovation, and implicitly Schumpeter's model of creative destruction, will be the main focus of this research. The implications of the model on product architecture will be verified for complex systemic product industries, following the same sequence of steps proposed by Christensen. This will help to verify the applicability of the model to complex industries as well as elaborate on the differences, in the case that they diverge from it.

2.1.3 Innovation Diffusion

The literature on innovation diffusion is typically focused on either the factors approach, investigating the factors that influence the rate of diffusion and adoption, or the stages approach where the different stages of the diffusion and adoption processes are studied (Xu and Quaddus, 2005, Utterback, 2007). The bulk of the models in the stages approach demonstrate that diffusion follows a sigmoid pattern as shown in figure 4 below (Geroski, 2000; Geroski, 2003; Abernathy and Clark, 1985; Stoneman and Karshenas, 1995, Utterback, 2007). The convexity and concavity of this curve, representing the rate of the diffusion process, differ significantly across industries, technologies and countries (Stoneman and Karshenas, 1995). The stages of this diffusion process also differ significantly between industries and have therefore given rise to several staged models in the literature (Xu and Quaddus, 2005; Kwon and Zmud, 1987). Some of the models accounting for the delay, demonstrated in the s-curve, between the introduction of the technology and its rapid adoption are: the epidemic model of information diffusion, the probit model, legitimation and competition, and information cascades (Geroski, 2000). The innovation curve can be decomposed into 2 superimposed curves, one for the product and another for the process. There is a time offset between the two curves as process innovation is often at its peak once the product innovation has tapered off and the market is in the process of selecting the dominant designs (Abernathy and Utterback, 1978; Utterback, 2007).

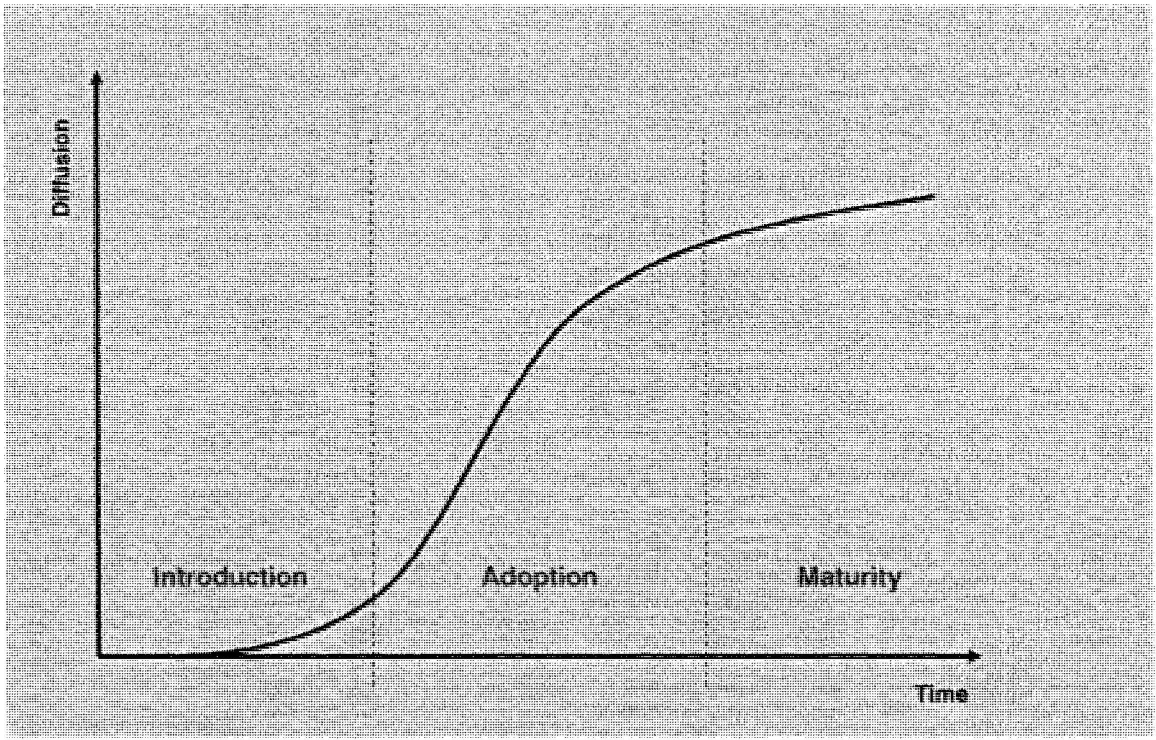


Figure 2.3: S-curve of Technological Diffusion

Epidemic model

The epidemic model is the starting point for most literature on technological diffusion (Stoneman and Karshenas, 1995). The news about a new technology typically starts from a single common source (Geroski, 2000). This source transmits the information about the actual technology, i.e. the hardware, as well as how it can be used and its advantages over alternatives, i.e. the software (Rogers, 2003). While the hardware demonstrates the technical superiority of the innovative technology, it is the software that moves people to embrace it. Word of mouth becomes the second process of spreading information about the product after manufacturer's initial introduction. The convexity of the information flow S-curve depends on the summation of the two information flow processes (Geroski, 2000).

Other factors that may not be reflected in the 2 drivers presented above can affect the rate of information flow. Population density, communication between the users and potential-user communities, and the ease of describing the new technology may all affect the rate of flow of information about it (Geroski, 2000). The degree of homophily or heterophily of the population may also affect the information flow. While homophilic populations have lower communication barriers between their members, they risk keeping the innovations confined to their boundaries hindering its vertical communication to other homophilic communities (Rogers, 2003).

However, the rate of information flow about the new technology may not necessarily correspond to the rate of its adoption by potential users. In fact, Rogers proposes two phases within the information flow phase, namely information flow from mass media to opinion leaders followed by interpersonal influence of opinion leaders on less informed adopters (Rogers, 2003). Factors such as the complexity of the new product, the costs associated with switching to it and its superiority over the existing alternatives come into effect between the spread of information about the innovation and its adoption by new users (Geroski, 2000).

Despite its usefulness, the epidemic model can not be taken as an accurate depiction of the innovation diffusion mechanism model due to the changes in the information flow rates, the technology features and the potential users profile throughout the diffusion process, which may last for years (Geroski, 2000). Its main weakness remains to be its tight correlation between the adoption of technologies and the flow of information about them.

An extension of the epidemic model was proposed by Mansfield based on the objection that information flow is not the main obstacle to innovation diffusion but rather the uncertainty about the performance characteristics of the new products. Mansfield's model demonstrates that the uncertainty is reduced over time as a result of the growth of the installed product base and the consequent learning accumulation (Mansfield, 1968). The resulting model, therefore, depicts the diffusion as a function of the profitability of installing the new technology and the capital requirements for doing so (Stoneman and Karshenas, 1995). Mansfield's model has its own inaccuracies in its assumption of static adopters' population, technology versions, and adoption profitability throughout the whole diffusion process (Stoneman and Karshenas, 1995).

Probit Model

While the epidemics model takes into account the flow of the innovation software, it does not account for the individual choices of the potential technology users. The probit model, on the other hand, represents the adoption rate by a function of variable x, where x is a feature that affects the user's profitability of adopting the new technology. The number of the technology adopters is, therefore, determined by the value of this feature, its threshold level for adoption and the shape of the mathematical function representing the population. The rate of adoption varies with the change in the rate of change of the threshold value of x, the feature variable (Geroski, 2000). Davies argues that x is the return on investment of the innovation (Davies, 1979). Alternately, x can be viewed as the net benefit of adopting the new technology. It can therefore account for both: factors in favor of the new technology, such as technological superiority, and factors hindering its diffusion, such as higher switching or learning costs.

The pattern of change of the threshold of x determines whether it is a type A or type B innovation. Type "A" innovations are transparent for users and have, therefore, easy software diffusion. They therefore get adopted rapidly at the beginning but then their adoption rate slows down and decreases shortly afterwards. Type B innovation, on the other hand, are less transparent for users and therefore take a longer time to start diffusion. Once started, though, type B innovations reach their plateaus faster than type A innovations (Geroski, 2000).

Legitimation & Competition

Based on the density-dependent population growth model, presented in ecology literature, the legitimation and competition model justifies the S-curve of technology diffusion by the intensity of industrial competition around the innovation hindering its acceptance and institutionalization (Geroski, 2000). Two of the competitive forces that affect the diffusion rate are the “pre-emption effect” and the “rent displacement”. Pre-emption effect occurs when adoption of the new technology is more favorable to some firms than others, therefore making the former adopt the technology faster than their rivals. Rent displacement arises when the adoption of the new technology is particularly costly for some firms primarily because the new technology cannibalizes some activities that they do (Geroski, 2000). This can be the reason for the different adoption rates between incumbents and new entrants.

Competition however may change, in rate and form, during the process of diffusion. At the early stages of the introduction of the new technology, competition is often between the new and the old technologies. Later on in the adoption cycle, competition shifts to become primarily amongst the new technology adopters. A study has also shown that competition between incumbents only is not a sufficient motivation for firms to adopt new technologies. However competing entrants often do stimulate incumbents to adopt new technologies (Geroski, 2000).

Information Cascades

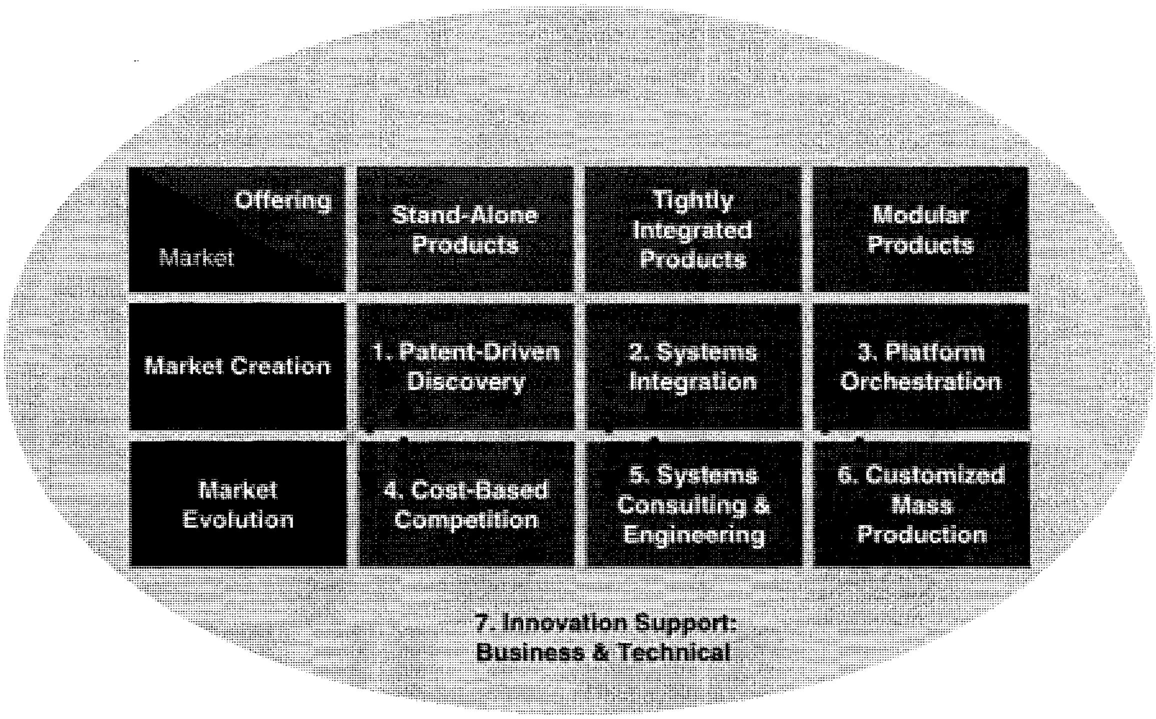
To account for the initial conditions of the innovation diffusion function, Stoneman and Karshenas recommend considering generic technologies rather than the particular generations of the innovative product (Stoneman and Karshenas, 1995). Geroski, however, proposes an information cascades model based on the different competing product variants (Geroski, 2000). For 2 new versions of a new product, A and B, early adopters will invest in selecting the more favorable one between them. Later adopters, however, are less likely to make similar investments and more likely to chose the product of wider popularity and larger installed base. This information cascade effect starts with an initial choice between the products, followed by a lock-in phase where the product initially more popular is increasingly favored and finally a bandwagon effect where later adopters mostly imitate early ones (Geroski, 2000).

The possible outcomes of this information cascades model are more generally applicable than the others described above. If the initial choice between A and B is made quickly, then the information cascade will accelerate the lock-in effect and the diffusion of A. On the other hand, if the initial choice phase is slow and indeterminate, the adoption rate may be slower and both products may share the market or both die-out and never diffuse. Factors such as performance differential between products A and B can affect the speed of the initial choice phase and the subsequent phases driven by the information cascades (Geroski, 2000).

Most models of diffusion are based on free selection of innovation by mass markets. In this study of complex industries, innovation diffusion is governed by regulatory forces and a specialized market where information cascades, legitimation & competition and the probit model all influence the rate of technology adoption by clients.

2.1.4 Games of Innovation

A game of innovation is "a distinct logic of innovative activities that is largely contingent on product architectures and market lifecycle stage" (Miller and Olleros, 2008). Games are categorized into a number of natural trajectories (Nelson and Winter, 1982) that are classified based on the 2 axes: product architecture category and market phase. Miller and Olleros (2007) define the seven games of innovation depicted below in Figure 5.



Offering / Market	Stand-Alone Products	Tightly Integrated Products	Modular Products
Market Creation	1. Patent-Driven Discovery	2. Systems Integration	3. Platform Orchestration
Market Evolution	4. Cost-Based Competition	5. Systems Consulting & Engineering	6. Customized Mass Production

7. Innovation Support: Business & Technical

Figure 2.4: Games of Innovation (Miller and Olleros, 2008)

A description of the games of innovation is presented below.

Patent-Driven Discovery

This game of innovation is common in appliance industries where the market's well-defined needs drive in-sourced research and development leading to patenting for value capture. The high R&D and capabilities-building expenditures necessitated often result in a few large competitors surrounded by their smaller complementary suppliers.

Cost-Based Competition

After patents expire, manufacturers of commodities lose their appropriation protection the competition metrics shift to cost. Innovation shifts towards cost-cutting process innovation and differentiation to target customers in niche markets. Economies of scale become more important for competitiveness favoring players with more financial resources.

Systems Integration

This game is common in industries with demanding large buyers of complex engineering products. Collaboration with the customers is required before offering them proprietary systems to solve their problems. Reputation and product quality are very important assets of suppliers in this game as they compete for a share of the market.

Systems Consulting & Engineering

As suppliers in systems integration games mature, many forward integrate into offering integrated solutions and consulting expertise to their clients, hence entering the Systems Engineering and Consulting game. In this game of innovation where customer needs go beyond the technical system requirements, knowledge accumulation transcends the boundaries of the organization towards networks of expertise including universities, consultants and other experts.

Platform Orchestration

In this game of innovation, leaders promote open platforms where players can independently innovate based on an established standard. Promoting open standards and collaboration are the key innovation levers in this game allowing the technological advancement of the entire platform and its growth.

Customized Mass Production

Consequent to the selection of a particular platform, players often start mass producing components switching the competition battle to the brand level instead of the technology platform one. Lean supply chain networks and flexible assembly permit suppliers to differentiate away from each other and towards non-consumers of their products. Barriers to entry at the periphery of the established platform become lower while they rise at the core facilitating its growth and extension.

Supporting Innovating Firms

Firms in this game innovate for selling their innovations to other industries. Market research firms and R&D contractors are examples of firms in this game that compete for low-margin services of providing technical or specialized expertise to their clients.

2.2 Complexity, Modularity and Systems Integration

To better understand the specifics of complex product industries and their divergence from other industries, the literature on complexity, modularity and complex product systems was reviewed.

2.2.1 Modularity

Herbert Simon observed and recorded how complexity in natural systems, such as social, biological and physical systems, results in their decomposability into hierarchic layers of compound systems with diminishing complexity (Simon, 2004). While absolute decomposability is mostly theoretical, near decomposability is the most common organizational form in complex industries (Simon, 2004). Near decomposability allows the whole complex system to create value while minimizing the need and costs of coordination (Simon, 2004).

Baldwin and Clark define three requirements for systems modularity, namely an architecture that specifies the component modules and their functions, an interface dictating how they fit together and communicate and standards that verify the conformity of each of the modules to the design rules (Baldwin and Clark, 2000). Parnas recommends information hiding in systems modularity, by encapsulating the knowledge within the different modules, for minimizing the complexity of the required interface and standards (Parnas, 1972). Bargigli argues that modularity is needed for support high product variety as it permits interoperability of components and the linear association between components and functions (Bargigli, 2005).

Amongst the three modularity elements, standards have been the most developed and have given rise to a significant portion of recent economic literature (Garud *et al*, 2003). While many firms attempt to establish their proprietary product architectures as standards, this increases their competition hence destabilizing the existing ones. This inherent instability in standards influences the strategic outcome of first-mover advantages (Garud *et al*, 2003). Network effects have also been observed when the value to an individual of adopting a standard is dependent on the others who also adopt it (Garud *et al*, 2003). The role of standards extends beyond verification of conformance. They act as accumulators of knowledge and experience, codifying tacit knowledge (Garud *et al*, 2003). They also reduce the transaction costs of coordination and create economies of scale (Kindleberger, 1983). In fact, it is standards that act as the vanishing hand and permit the decentralization of design and the production of modular systems (Langlois, 2003).

Modularity is quite commonly exhibited in complex industries thereby necessitating an interrogation of the literature on complexity and complex products.

2.2.2 Complex Products

Complex product systems (CoPS) may be defined as "a set of humans and technologies united to perform a specific function, which are collectively incomprehensible to any single person" (Johnson, 2004). Simon defines them as "made up of a large number of parts that interact in a non-simple way" (Simon, 2004). Dosi *et al*, characterize complex products by having an increased number of functionalities requiring multiple components, and an increasing number of distinct scientific disciplines and technologies (Dosi *et al*, 2004). Yet Prencipe provides another definition for CoPS as capital-, engineering and IT-intensive business-to-business products that are often produced by multi-firm alliances as a one-off or in small batches for specific customers (Prencipe, 2004). All these definitions converge to identify the following feature of CoPS industries:

1. They are made of integrated multiple components
2. They require special integration skills
3. They are unique products
4. They require the emergence of alliances and networks of suppliers to make them
5. They have specific and involved customers

The military industries in the US have played a significant role in driving innovation and systems integration since World War II (Sapolsky, 2004). Pavitt attributes increased product complexity, since the industrial revolution, to the trend of increased specialization, bolstered by mass production, and the appearance of periodic waves of major innovations in specific technologies (Pavitt, 2004).

Modular complex products may develop open product architectures where the integration of the product modules is done by the market. Such a product architecture requires a re-organization of the industry to support it while protecting the intellectual property rights of the various players.

To better understand the effects of product architecture on industry organization, the definitions of open and closed product architectures were sought in the literature.

2.2.3 Architecture Modularity & Openness

Ulrich defines product architecture as "the scheme by which the function of a product is allocated to physical components and by which the components interact" (Ulrich, 1995). He elaborates further that product architecture is the arrangement of functional elements; the mapping from functional elements to physical components; and the specification of the interfaces among interacting physical components (Ulrich, 1995). In these terms, he defines a modular architecture as one where there is a one-to-one mapping between functional elements and physical components (i.e. every function is performed by one distinct component). This enables standardized and simple interfaces between the product components (Shibata *et al*, 2005). An integral architecture, on the other hand, is where there is no such linear relationship between functions and physical components, i.e. multiple components may do the same function or one component may perform multiple functions (Ulrich, 1995). This lack of linearity between components and functions hinders the development of standardized interfaces and thus modularity (Shibata *et al*, 2005).

Along different axes from those of modularity or integrality, architecture openness is the degree of sharing standard component interfaces amongst the companies in an industry (Shibata *et al*, 2005). This openness directly affects the capability of these companies to create value independently from one another and sometimes in the absence of arm's length contracts. While hypothetically modular and integral products may have open or closed architectures, creating four possible product configurations, it is quite uncommon to find integral products with an open architecture (Shibata *et al*, 2005). The inadequacy of standardized interfaces in the integral product will hinder value creation from companies that are not directly involved in defining the proprietary architecture. This leaves three configurations of products: closed integral, closed modular and open modular. Closed integral products are composed of a single module and produced by one firm and its network of certified subcontractors (Miller and Olleros, 2008). Closed modular products are composed of multiple modules but still produced by one firm. Open modular is when a modular product is produced collectively by several companies in the industry governed by product standards rather than formal contractual agreements. Figure 6 depicts these 2 axes and their resulting configurations.

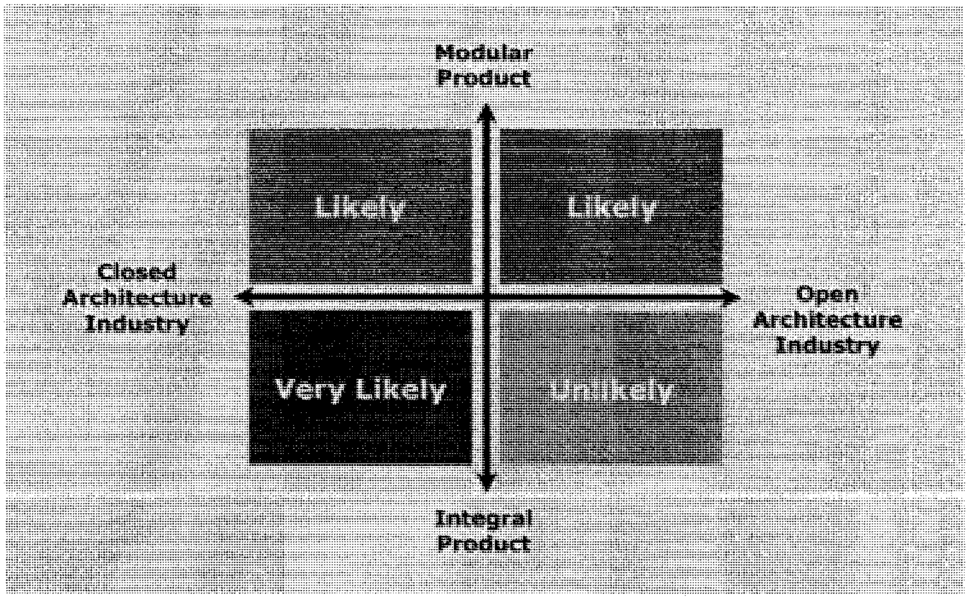


Figure 2.5: The configurations resulting from product modularity and industry architecture openness

It is important to make the distinction between architecture modularity and architecture openness as the former refers to the product integration scheme while the latter pertains to the industry organization structure (Shibata *et al*, 2005). Some literature seemed to invariably correlate architecture openness with product modularity. Christensen, for example, hypothesizes that when modular products reach technological maturity, competitive pressures result in pushing their coordination to the market level and hence opening the architecture (Christensen and Raynor, 2003). Gawer and Cusumano presented a similar view in their study of platform industries where core component suppliers who invested in defining a global product architecture where successful in opening the architecture of their modular products (Gawer and Cusumano, 2002). Simon, on the other hand, finds that the costs of coordinating the member organizations and maintaining their motivation towards the organizational goal may hinder architecture openness even in conditions of product modularity (Simon, 2004).

2.2.4 Hierarchical vs. Heterarchical Architectures

The literature describing open architectures often refers to cases of hierarchical architectures where a deterministic strategy of defining an interface then opening the architecture is pursued by the provider of a distinguishable core component (Chesbrough, 2003; Chesbrough et al, 2006, Gawer and Cusumano, 2002). This is true in many cases such as Intel, Microsoft and Cisco as described by Gawer and Cusumano (Gawer and Cusumano, 2002). For other industries though, a heterarchical open architecture may be created through a series of uncorrelated industry moves carried out by different players. Olleros uses such a non-normative approach to non-contractual innovation to interpret the failure of Sony's Betamax standard in front of its VHS competitor (Olleros, 2007). The adoption of the VHS standard by video-rental stores created the necessary network externalities for establishing it as a monopoly in the US market and later internationally. Neither Sony nor JVC had much influence on this grassroots movement by individual video rental stores that shaped the industry despite Hollywood's opposition and Sony and JVC's surprise. Olleros also highlights the literature's oversimplification of the core and periphery roles citing Apple's desktop publishing platform where it is quite hard to identify the core and periphery amongst the McIntosh computer, laser printer, PostScript printer interface and PageMaker application (Olleros, 2007). The literature therefore makes a distinction between normative hierarchical open platforms centrally created and maintained, and decentralized heterarchical platforms where architectural openness is driven by the peripheral component markets.

2.2.5 The Cyclical Model of Openness

Chesbrough and Christensen predict a cyclical model of modularity in industries where product architectures constantly alternate between modular open architectures, at times of technological maturity, and proprietary closed architectures at times of technological development (Chesbrough, 2004; Christensen and Raynor, 2003). They predict that administrative coordination of subcomponents integration, i.e. within the firm, is needed at the earlier phases of a new product lifecycle. As the product matures, its component attributes better understood and its supplier base expands, this administrative coordination may be replaced by a market coordination, which is the creation of an open product architecture. Chesbrough, similar to Christensen, further argues that while organizations will focus on competing within the boundaries of the new architecture, they may be losing the necessary system-level knowledge necessary to define a new architecture when the limits of the current one are reached (Chesbrough, 2004). Even for those who avoid this pitfall, transforming the architecture while it is open and modular may be very difficult due to the complexity of collaborating the transformation with all the players and reforming the appropriate system of connections. Chesbrough therefore suggests that the product shifts back to an interdependent proprietary stage, where it can be reviewed, a new architecture made and then modularized again for the market (Chesbrough, 2004). The result, predicts Chesbrough, is a technology path that alternates between modular (open) and interdependent (closed) architectures with the transition happening as firms and markets outperform each other in each mode (Chesbrough, 2004).

2.2.6 Integrated Solutions

Integrated solutions have become one of the popular themes of recent systems integration literature (Brady *et al*, 2005; Wise and Baumgartner, 1999; Davies, 2001; Galbraith, 2002; Oliva and Kallenberg, 2003) and an important trend in many industries. Rooted in the infrastructure construction industry BOT (Build-Operate-Transfer) projects, integrated solutions are unique combinations of products and systems with services in order to produce and support a system throughout its lifecycle (Brady *et al*, 2005; Davies, 2001). Integrated solutions, unlike their constituent products, are often customized requiring the supplier's full understanding of the client's needs (Kandampully, 2002). Several key drivers of integrated solutions are identified in the literature. First, the increased complexity of clients and their needs has created a "market pull" effect that favors customized and comprehensive product offering (Shepherd and Ahmed, 2000; Brady *et al*, 2005). Second, the rapidly changing markets, and consequently client needs, necessitate that suppliers remain in close contact with their clients and hence favoring post-sales support and involvement with the product lifecycle (Shepherd and Ahmed, 2000). Third, integrated solutions provide continuous revenue streams to suppliers unlike the occasional demand surges and long sales cycles, characteristic of most complex products (Brady *et al*, 2005).

To make the transition from a traditional products organization to one offering integrated solutions requires overcoming an enormous inertia and acquiring new skills and competences (Brady *et al*, 2005). Brady, Davies and Gann conducted research on suppliers of complex industries transitioning to integrated solutions and concluded that they need to acquire: systems integration capabilities, operational service capabilities, business consulting capabilities and financing capabilities (Brady *et al*, 2005). These capabilities often require a change of corporate culture and this adds to the complexity of their acquisition.

2.3 Networks and Coordination

Networks, alliances, joint ventures and partnerships are formal mechanisms of cooperation between companies. They occur for various objectives such as developing new products, penetrating new markets or acquiring competitive advantages (Kamel, 2006). On the other hand, forms of informal network formation and collaboration have also emerged in industries. Researchers such as Langlois, Porter, Nalebuff and Cusumano studied various forms of collaboration modes that shape industries today. The dominant theories of clusters, bundling, value nets and platforms are reviewed below.

2.3.1 Integration-Based Classification of Organizational Forms

Robertson and Langlois presented a 2-axes classification of the different organizational forms that industries may assume based on ownership integration and coordination integration extents (Robertson and Langlois, 1995). Figure 7 below depicts this classification followed by a description of the various forms and their links with more recent research ((Robertson and Langlois, 1995).

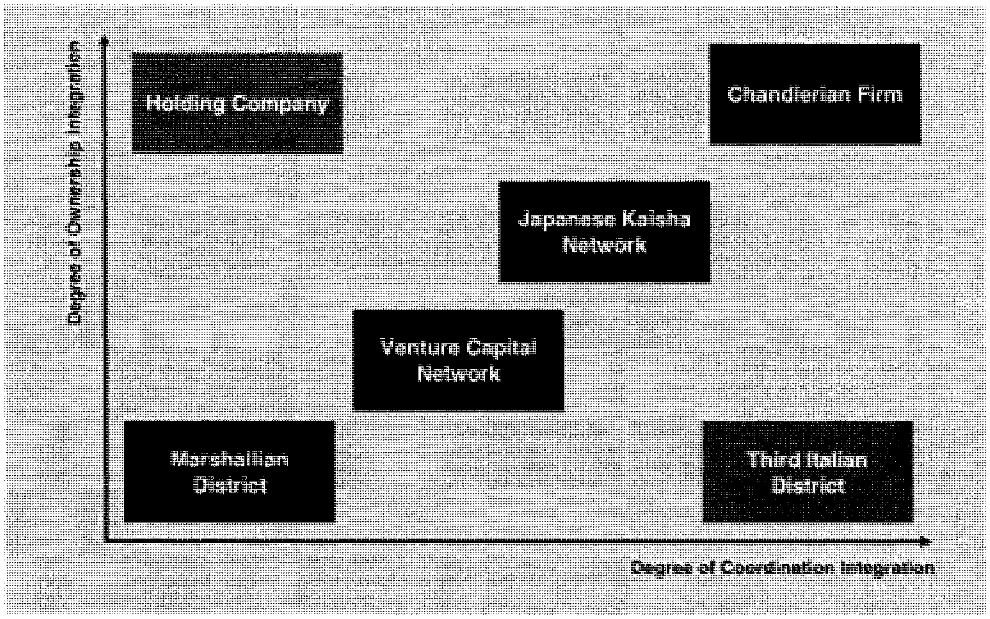


Figure 2.6: Classification of organizational forms based on degrees of ownership and coordination integration

The ownership integration axis refers to the firm boundaries surrounding the various entities networked. The coordination integration refers to the degree of formal collaboration between them.

Marshallian districts refer to clusters of small producers of a particular product with little legislation and market interactions between them. They exhibit the least coordination and ownership integration as they are often distinct firms relying on market mechanisms. Venture capital networks are relatively independent networks with some synergies and coordination imposed by a layer of venture capitalists superimposed over the management layer. Japanese Kaisha networks are coordination mechanisms prevalent in the Japanese automobile industries where tier-1 suppliers are given autonomy over the design and provision of complete sub-assemblies according to arms-length contractual specifications. Chandlerian firms are vertically integrated exhibiting a high degree of ownership integration as well as coordination integration. "Third Italy" firms are those modeled after the region in Northeast Italy where much of the industry is located in smaller towns in the form of small independent producers with intense cooperation between them (Brusco, 1982 and Robertson & Langlois, 1995). Finally, a holding company model, one that is becoming increasingly popular since the legacies of General Electric and Mitsubishi, networks companies through integrated ownership but distinct and independent operations.

2.3.2 Clusters

Porter defines clusters to be "geographic concentrations of interconnected companies and institutions in a particular field" (Porter, 1998). As shown in the few examples that Porter cited, clusters may go beyond geographical limitations to establish a network of suppliers and clients of a particular product sharing the same logistical, informational and marketing support mechanisms.

Clusters permit and encourage cooperation and competition relationships to coexist along different axes and among different players (Porter, 1998). Bell argues that this involvement in the cluster enhances the innovativeness of the individual players (Bell, 2005). In establishing an informal cooperation bond between competitors, clusters address the difficulties of contractual relationships without imposing the onerous need for vertical integration or for establishing expensive alliances and cooperation agreements. They also drive the pace of innovation in an industry while encouraging new businesses to emerge, motivated by the benefits of operating within the cluster (Porter, 1998).

Clusters literature addresses the geographical or logistical proximity of similar and complementary products and is therefore suitable to analyze a higher level of coordination than that required to produce a single systemic product. Clusters literature is therefore expected to be of limited use in this research.

2.3.3 Value Nets

Another major milestone in modern strategic management science was Brandenburger and Nalebuff's introduction of the concept of co-opetition, meaning simultaneous competition and cooperation (Brandenburger and Nalebuff, 1995). Contrary to Porter's model of antagonism between firms, Nalebuff introduced the need to collaborate even with competing firms in some circumstances. While competitors, customers and suppliers are crucial, Nalebuff added Complementors to a firm's external interactions to group all other firms, competitors or not, whose products add value to the firm's own product. The relationship between the firm and its complementary organizations are not necessarily formal contractual ones but are often circumstantial. Nalebuff's value net, describing the above-mentioned interactions, is shown in Figure 8 below.

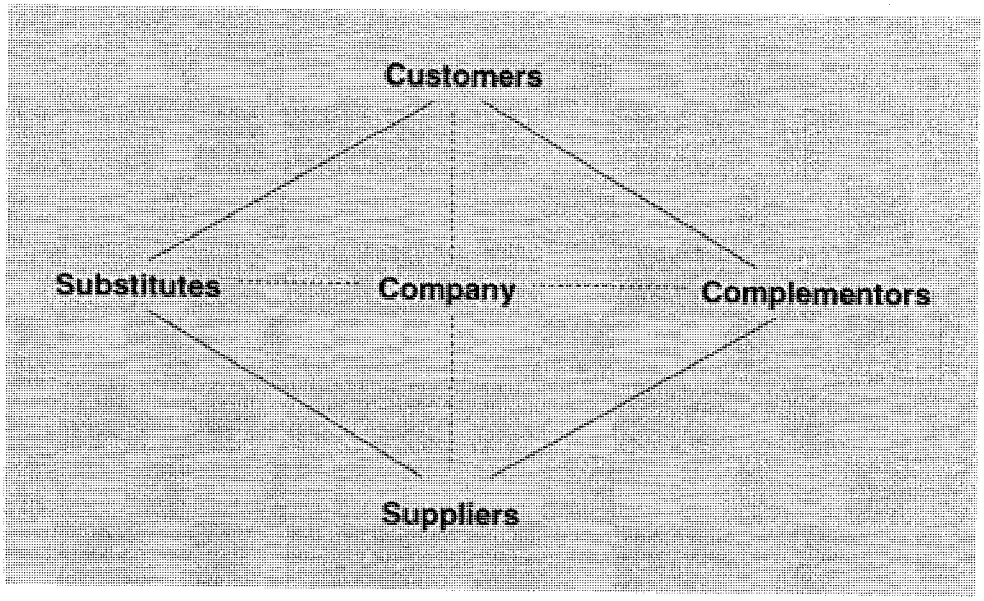


Figure 2.7: Nalebuff's Value Net Framework

Value nets provide a tool for understanding some interactions within an industry. However, they are quite limited in their applicability towards understanding and analyzing concepts like product maturity, product architecture and disruptive innovations.

2.3.4 Platforms

A platform is a locus of new business opportunity that offers option value to its members through its flexible and scalable architecture (Miller and Olleros, 2008). In 2002, Gawer and Cusumano published "Platform Leadership, how Intel, Microsoft and Cisco drive Industry Innovation". In this work, the authors used the cases of Intel, Microsoft and Cisco to elaborate the creation, maintenance and leadership of platform industries. A platform industry is one where a central product component is defined as the core and other components are defined to be peripherals interfacing with it (Gawer and Cusumano 2002; Cusumano and Gawer, 2003). The core provider defines and makes the interface standards to the core available, thereby reducing the risks of innovation for peripheral suppliers and enabling the emergence of new ones. The defined interface standards enable suppliers of peripheral components to focus their design and innovation efforts on the functionality of their own peripheral without having to coordinate their moves with those of other suppliers or the core. The onus of developing the whole platform, therefore, lies on the core supplier and its development of the core and its interface.

The examples cited in the platform industry literature are from the ICT (Information and Communications Technology) sector (Gawer & Cusumano, 2002). Intel, building the processor chips, realized that for its business volume to continue to grow it would have to develop the PC industry and create demand for its component. The PCI Bus Interface was created as the standard for connecting the various components and peripherals of the PC in a standard way. The PCI Bus permitted component developers to focus on developing their input/output peripherals pushing their CPU performance needs further and hence growing the processor's market. The established standards also permitted the emergence of many entrepreneurial firms supplying peripherals, increasing the competition on the established players and hence accelerating the demand for the core processors (Gawer & Cusumano, 2002).

The mechanisms of platform creation and leadership are expected to be quite useful for this research. Complex products may evolve to a platform configuration with the definition of a core and an architecture that maintains the independence of peripheral components from each other.

2.4 Management Literature

2.4.1 Porter's Competitive Strategy Framework

Porter's perspective on strategy is that coping with competition is its essence (Porter, 2007). His theoretical framework, discussed below, was based on an economic view of the firm and its interactions with the main entities surrounding it (Porter, 1980). Porter's five force industry structure is graphically represented in Figure 1 below.

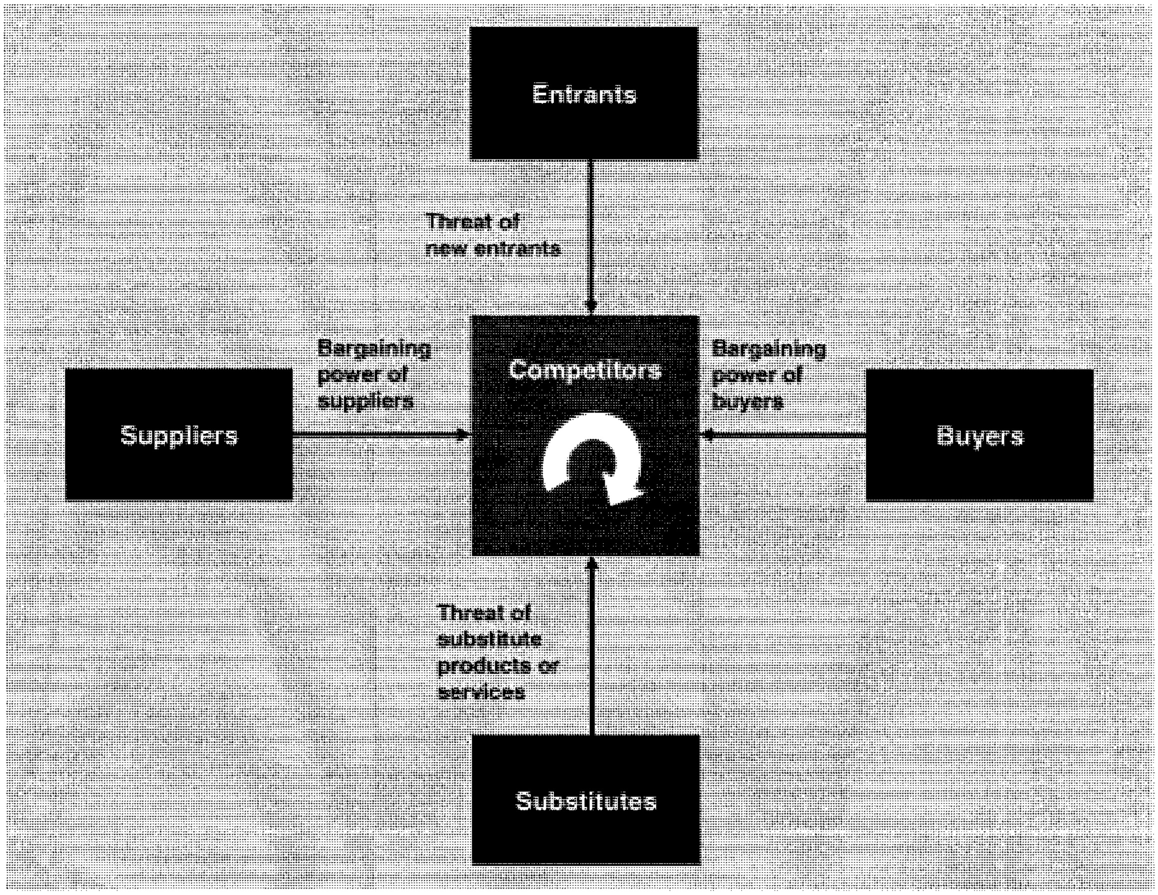


Figure 2.8: Porter's Five Force model (Porter, 1980)

In this model, Porter argues that a firm interacts with the following 5 entities:

1. Suppliers
2. Buyers
3. Possible Entrants to the industry
4. Substitutes
5. Competitors

A firm's optimal strategy is one that enables it to leverage its relationship with these five entities, protect itself against them and influence them in its favor. This allows the firm to secure a competitive advantage position in its market. Increasing the negotiation power over customers, decreasing the negotiation power of suppliers, building high entry barriers to entrants and sustaining comparative superiority over substitutes enables a firm to build a competitive position in its market. The industry's long-term profitability, as a whole, is also influenced by these 5 competitive forces (Porter, 2007). Porter went further to suggest three distinct strategies that firms ought to choose from to ensure their competitive success, namely:

1. Cost Advantage;
2. Quality Advantage;
3. Market Segment Specialization.

Porter warned against hybrid strategies combining these three strategies as they may expose the organization to their combined risks.

In approaching the question of disruptive innovation in complex industries, Porter's model is insufficient to account for the complex interactions among the firms that collaborate to make the product. The primary unit of analysis in Porter's model is the production organization. It will therefore be insufficient for investigating relationships between different competitors and complementors inside that primary unit. Porter's model also represents clients as an external entity, independent of the product organization. This latter assumption may not be true in complex industries where expert clients are heavily involved in the product design and manufacturing processes.

2.4.2 Industry Transformation

Porter's view of industry structure, composed of 5 competitive forces, usually evolves slowly as relationships reinforce one another into one of a few internally consistent configurations (Porter and Rivkin, 2000). Shifts in industry dynamics, however, do occur and can be triggered by changes in cost or buyer value in the same industry or in another upstream or downstream to it. These shifts may result in industrial transformation and shakeout of incumbent players. Such shifts may be triggered by changes in technology, in customer needs or in regulations. The triggers alter relative positions of the 5 competitive forces forming the industry structure, favoring some positions over others and forming management to make tradeoffs to adapt to the transformation.

The transformation triggers often first result in a period of experimentation where different companies initiate trial-and-error attempts to find the new winning formula (Porter and Rivkin, 2000). This period usually coincides with flooding the industry with numerous entrants seeking their opportunity to find the next optimal configuration of relative positions. Alliances usually abound during experimentation periods as entrants seek to hedge their risks and acquire knowledge from others. Management's decisions during such experimentation periods may influence, not only their respective companies' market positioning during and after the transformation, but also the array of possible industry structures. Experimentation periods are usually followed by convergence where 50% or more of the players in the industry are driven out of the market by the emerging dominant designs (Porter and Rivkin, 2000).

The pace of industrial transformations has dramatically increased over the last few decades. Agarwal and Gort reported a 10 fold decrease in the average duration of first-mover monopoly between the turn of the 20th century and the period of the 1960's – 1980's (Agarwal and Gort, 2001). This should result in an increased emphasis on strategic planning with an increased awareness of the inherent uncertainties and increased attention to anticipating industry structure in the future (Porter and Rivkin, 2000).

Industrial transformation literature will be an important tool in the understanding of the evolution of product and industry architecture in response to technological maturity in complex industries. Its unit of analysis, however, remains the individual company thereby limiting its applicability for the research subject at hand where inter-firm collaboration is key.

2.4.3 Configuration Strategy School

In contrast to Porter's deterministic strategy style, Mintzberg and other academics in strategic management have developed the configuration school (Mintzberg *et al*, 1998). While the strategic positioning school sets the optimum strategy based on external factors, the configuration school, on the other hand, considers corporate strategy to be a description of a company's state as a function of time (Mintzberg *et al*, 1998). In other words, the configuration school adapts the strategy to the company's status quo rather than seeking to change the company's present state to adhere to the strategy.

It is difficult to understand disruptive innovations in complex industries through the configuration school's perspective. The somewhat reactive strategic management approach, that the school promotes, does not provide an adequate framework for understanding the deterministic coordination relationships engineered by players in complex product industries.

2.4.4 Evolutionary Theory

"In contrast to economic approaches that assume perfect rationality, evolutionary theory implies uncertainty, learning, and a permanent 'race' for competitive advantage" (Barron, 2003). Different evolutionary schools have been introduced in the literature: Institutionalists, post-Keynesians, neo-Austrians, neo-Schumpeterians and neo-classical economists (Foster, 1997). Perhaps the most influential of these is evolutionary economics developed by Nelson and Winter (Nelson and Winter, 1982). Other important evolutionary approaches are McPherson's niche overlap model (McPherson, 1983) and Hannan and Freeman's organizational ecology theory (Hannan and Freeman, 1977).

With the exception of post-Keynesian school, all the modern evolutionary schools use biological analogies, and particularly competition, to analyze evolutionary change in economic systems (Foster, 1997). The general guidelines common to all evolutionary approaches is that they involve 3 distinct mechanisms: variation, selection and retention (Barron, 2003). Blind variation is the presence of alternative technologies, organizational forms or products, the results of implementing which are unknown (Barron, 2003). Selection is the process that favors the more beneficial amongst the different alternatives available. For the effect of selection in an industry to be well understood, it is important to specify the product characteristic that is being selected for and the expected output of that selection (Barron, 2003). Selection from the variations does not necessarily result in optimality. This is because of the limitation of the human ingenuity capacities, the constant changes in the environment thereby constantly re-defining optimality and the entrenching of some technological variants due to non meritocratic technical factors (Barron, 2003).

Evolutionary Economics

In Nelson and Winter's evolutionary economics model, organizations possess bundles of routines that constitute their memory and knowledge of how to carry-out their core operations (Nelson and Winter, 1982; Nelson and Winter, 1997; Barron, 2003). These routines are contained in the explicit processes and procedures but more importantly in the tacit knowledge that each member of the organization possesses about his role. Coordination to produce the organization's product lies at the core of these routines (Nelson and Winter, 1997). Evolution takes place when routines are updated and improved by the organization management following their performance evaluation. These organizational routines are often self-sustaining and are difficult to depart from. Quality and competitiveness therefore become functions of the organization's ability to control its routines and ensure their smooth operation.

One way to achieve this smooth operation is by controlling the various inputs to the routine as well as the components and equipment that it utilizes (Nelson and Winter, 1997). Some of this control would be exercised using other routines while some will be *ad-hoc*. In either case, this control affects the organizational routines and hence the competitiveness of the organization (Nelson and Winter, 1997). Teece has further developed this concept by introducing dynamic capabilities, which permit firms to integrate, build and reconfigure these routines (Teece, 1987). Zollo and Winter further explored this area investigating the mechanisms of creating and developing these dynamic capabilities (Zollo and Winter, 2002).

Another feature of evolutionary routines is their additivity, which is their modularity and ability to be replicated for similar operations but of different scales (Nelson and Winter, 1997). The existing routines can serve as templates for new ones to be formed. Obstacles such as poor communication, poor codification and reluctance to share information may hinder the replication process though (Nelson and Winter, 1997).

Unlike replication, which happens within organizations, imitation attempts to copy routines, or their final outputs, from one organization to another. Imitations are likely to be most successful when copying a novel combination of standardized components and is likely to be least successful if the routine contains a lot of idiosyncratic and tacit knowledge (Nelson and Winter, 1997).

Niche-Overlap Model

Sociologist Miller McPherson's niche overlap model relies on ecological principles to explain the evolution of organizations and their markets. The space of potential clients available to an organization is termed its niche (McPherson, 1983). The areas of intersection of niches of different organizations represent the customers that they compete on. Large overlap areas, representing fierce competition, can be thought of as exploitation hills where the market is overexploited. Organizations on these hills will often try to find niche markets by differentiating into under-exploited areas, represented by valleys. This 'down-hill' movement results in increased differentiation either towards other resource niches or towards specific subgroups of the existing niche (Barron, 2003). Similar to Nelson and Winter's model, McPherson's model focuses on an internal characteristic as the driver of adaptive evolutionary change in an organization. Both models would predict reaching equilibrium if the environment is stable (Barron, 2003). McPherson's model does not rely on managerial action for evolution. While awareness of the model dynamics may help managers accelerate it, the model will still work autonomously (Barron, 2003).

Organizational / Population Ecology

Hannan and Freeman developed yet another evolutionary theory, namely organizational ecology, or population ecology (Hannan and Freeman, 1977). In their theory, the selection is for organizational survival and the variation is caused by industry entrants rather than the adaptation of the incumbents (Barron, 2003). Their Darwinian approach emphasizes the inertia that firms have and their resistance to change and hence the selection level at the industry level (Barron, 2003).

Some evolutionary theories, such as that of Hannan and Freeman, emphasize the 'Darwinian' natural selection of the fittest as being the driver behind industrial evolution rather than the evolution of individual organizations (Hannan and Freeman, 1995; Barron, 2003). This is attributed mostly to the fact that managers can not predict environmental changes early enough to adapt their organizations to them and the assumption that organizations need some level of inertia to survive (Barron, 2003). However, Hannan and Freeman have shown that most changes in organizations happen at the peripheral level with little changes to their core features, namely the mission, form of authority, basic technology and general marketing strategy (Hannan and Freeman, 1995). Barron sees that this resolves the apparent contradiction between the Lamarckian approaches, emphasizing individual organization's evolution, and the observation that inertia is essential for organizations (Barron, 2003).

Foster argues that the use of biological analogies has weakened the evolutionary approaches and hindered their embracement in mainstream economics (Foster, 1997). He argues that a self-organization approach, based on thermodynamic systems theory, is a more appropriate foundation given that an economic system can be modeled as an open system with semi-closed boundary conditions (Foster, 1997). Irrespective of the foundations of its modeling, evolutionary theories need significant further development in their consideration of demand, knowledge, networks and co-evolution before they can be comprehensive enough to tackle disruptive technologies (Malerba, 2006).

Evolutionary theory may be a useful tool for analyzing complex industries due to its emphasis on path dependence and learning accumulation within the organization. However, the picture provided by evolutionary theory is limited inside the organization and does not account for the coordination with external entities, which are an integral part of complex product industries.

2.4.5 Bundling

In their work, Adams and Yellen define bundling as "the practice of package selling" (Adams and Yellen, 1976). Stremersch and Tellis define it as "the sale of two or more separate products in one package" (Stremersch and Tellis, 2002). The latter authors emphasize the word 'separate' and define it as products that have distinct markets, from an end-user perspective, to distinguish between bundled product packages and complex products made of numerous sub-products (as defined by Salinger, 1995 and Telser, 1979). By limiting their study to pure bundling, Fang and Norman were able to develop a model for the optimality of bundling in various industries (Fang and Norman, 2003). Their model suggests that products of "thin markets" (i.e. those with high marginal production costs or dispersion in valuations) should not be bundled while those in "thick markets" are better bundling candidates (Fang and Norman, 2003).

Marketing and economics literature distinguish between 3 categories of bundling strategies: pure and mixed bundling (Adams and Yellen, 1976), product and price bundling (Stremersch and Tellis, 2002) and mixed-leader bundling and tie-in sales (Simon *et al*, 1995).

Mixed bundling refers to a pricing strategy where the products included in a bundle may also be purchased separately while pure bundling occurs when the products in the package are not offered for sale individually (Adams and Yellen, 1976; Fang and Norman, 2003).

Product bundling refers to "the integration of two or more separate products at any price" entailing the introduction of an integral architecture encompassing the subcomponents. The integrated product bundle should provide more value to the end-user than its individual components. This value may be in the form of compactness, seamless integration, reduced risk or convenience (Stremersch and Tellis, 2002). Product bundling, therefore, raises the consumers' reservation prices higher than the sum of the conditional reservation prices of its individual components (Stremersch and Tellis, 2002). An example of a product bundle is a PC system composed of different parts, each with its own separate market, packaged into an integrated product. Price bundling on the other hand involves "the selling of two or more separate products in a package at a discount" (Stremersch and Tellis, 2002). While price bundling is an easier quick-to-implement promotional tool, product bundling is a more strategic approach involving the creation of an integrated product architecture (Stremersch and Tellis, 2002). The reservation price for the price bundle is equal to the sum of the conditional reservation prices of its components, which indicates that the price bundle does not offer any added value to the end user and hence has to be offered at a discounted price (Stremersch and Tellis, 2002).

Related to Stremersch's work on product bundling is the relatively recent work on integrated solutions involving both products and services (Davies 2001; Brady *et al*, 2005; Wise and Baumgartner, 1999). The trend towards integrated solutions has appeared in complex capital sectors such as the large construction projects industry (Brady *et al*, 2005) or the flight simulation industry (Miller *et al*, 1995; Kamel and Miller, 2004).

In mixed-leader pricing strategies, a mature low-priced product is bundled with an innovative high-end product. This permits raising the profit margins on the innovative leader products. In tie-in sale bundling, the tying product, a durable product, is bundled with tied complementors which are often its accessories. This helps the tying product supplier to extend its market penetration and control to the tied products (Simon *et al*, 1995). The example studied in the literature of tie-in sales is IBM's strategy in the 1930's of bundling its tabulating machines, enjoying a semi-monopoly market position, with punched cards for enlarging its market share in the punched cards market (Simon *et al*, 1995).

Product bundling, and integrated solutions more specifically, will be a useful concept in the research analysis as it has been a growing trend in the aviation training industry in recent years.

2.4.6 Resource-Based Theory

The resource-based view is a key component of the theory of the firm, focusing on the costly-to-copy attributes of the firm as sources of rents and drivers of performance and competitive advantage (Conner, 1991; Barney, 1986). Rooted in evolutionary economics (Spanos and Lioukas, 2001), the resource-based theory links companies' performance with their acquisition of their resources (Wernerfelt, 1984) and their development of distinctive competences (Selznick, 1957; Collis, 1994) and dynamic capabilities (Teece, 1987; Zollo and Winter, 2002). In contrast to classical and neo-classical economic theories, the resource-based view of the firm does not assume competitors' equal access to similar production resources but rather justifies their discrepant competitiveness by their ability to find and utilize superior hard-to-copy resources (Peteraf and Barney, 2003). Unlike Porter's competitive strategy framework, the resource based theory takes an inside-out approach to understanding the competitive advantage of firms (Spanos and Lioukas, 2001). While the debate concerning the relative effects of the industry vs. specific firm effects on performance continues (Spanos and Lioukas, 2001), the two theories, may be seen as two sides of the same coin as the examination of the strategy implementation skills can not be understood outside the context of the competitive environment (Barney, 1986). While the resource-based view recognizes the role of revolutionary innovation to shift markets, it supports the view that incremental innovations, protected by resource barriers, are also sufficient for above-average profitability (Conner, 1991). In either type of innovation, the resource-based view is insufficient for considering both the internal and external sources of competitive advantage simultaneously.

Similar to evolutionary theory, the resource based view emphasizes the firm's internal capabilities and thus highlights the value of learning and knowledge accumulation which are critical for complex product industry players. Both theories are lacking in their treatment of inter-firm collaboration relationships, industrial organization and product architecture.

2.4.7 Game Theory

Game Theory is an interdisciplinary strategic approach to studying behavior. The theory appeared in 1944 when John von Neumann and Oskar Morgenstern published their book 'Theory of Games and Economic Behavior' (von Neuman and Morgenstern, 1944). A game, as defined by the theory, is composed of players, strategies and payoffs. The players are the two or more decision-making entities whose utilities are interdependent. The strategies are the set of possible moves available to the players while the payoffs are the resulting outcomes of the decisions made by each of the players (Wilkinson, 2005).

Von Neumann and Morgenstern presented two main types of games. In the first 'rule-based games' the rules of engagement are known to the players through contractual, regulatory or legislative guidelines (Bradenburger and Nalebuff, 1995). In these games, players' actions are met with predictable reactions from the other players. Winning strategies are therefore those that take into consideration the series of response strategies that will be adopted in response to the initial move. In free-wheeling games, the second type of games identified by von Neumann and Morgenstern, players interact freely without any particular structure (Bradenburger and Nalebuff, 1995). This results in players not being able to take more out of the game than the added value that they bring to it (Bradenburger and Nalebuff, 1995).

Wilkinson summarizes at least seven categories of games distinguished in the literature (Wilkinson, 2005):

1. Cooperative and non-cooperative games: cooperative games are ones where the different players may communicate with each other and collude. Most business games in developed economies are non-cooperative due to the legal restrictions on collusion.
2. Two-player and multi-player games: two player games are the simplest form of games. In multi-player games 'the tragedy of the commons' is more likely as it is easier for players to defect than to collude. Risks of coalitions between some players against others are also possible in multi-player games.
3. Zero-sum and non zero-sum games: zero-sum games are those involving a fixed pool of payoffs such that the gain of one player is the loss of the other. In non-zero games, on the other hand, the combined profits of the players vary according to their respective strategies. Most business games in reality are non zero sum games.
4. Perfect and imperfect information games: in perfect information games, the payoffs resulting from adopting the various strategies are well known to all the players involved. Imperfect information games are more common in business.
5. Static and dynamic games: static games involve the players making their moves simultaneously and therefore eliminating reactive moves made by one player in response to the moves made by the others. Dynamic moves, on the other hand, involve sequential moves involving reactions amongst players.
6. Discrete and continuous strategies: in discrete strategies, a player has to choose from a defined list of available strategies. However, in business reality, continuous strategies are

more common where the number of possible choices available to each player is virtually unlimited.

7. One-off and repetitive strategies: one-off strategies are those made only once. Business games, in reality, are mostly repetitive involving several moves and responses made by the different players throughout their market lifetimes.

Game theory assumes rational economic behavior from all the players, seeking to maximize their profits or utility value at all times (Wilkinson, 2005). The theory therefore assumes that the game will come to an equilibrium situation and defines three such situations (Wilkinson, 2005):

1. Dominant strategy equilibrium: this involves the availability of a strictly dominant strategy for one of the players that will always give a payoff at least as high as any other strategy, irrespective of the strategies adopted by the other players.
2. Iterated strategy equilibrium: this involves one player adopting strategies that will iteratively lead to having a dominant strategy.
3. Nash equilibrium: is when each player will pursue their best strategy in response to the best strategy of the other players. This is the most general type of equilibrium encompassing the first two.

Kretschmer presents an example of a game theoretic strategy that Boeing pursued in response to Airbus's plans to build the A380 airplane (Kretschmer, 1998). The payoffs to Boeing were optimal had neither Airbus nor Boeing pursued the project to completion. A positive response from Boeing launching a comparable aircraft program would have jeopardized the sales of their B747 jumbo jet, the next largest aircraft in the industry. Boeing would have, therefore, had a dominant strategy had their attempts to deter Airbus from pursuing this program been successful (Kretschmer, 1998).

The primary insight that game theory brings to strategy literature is the allocentric view of strategy that encompasses not only the firm's strategy but that of other firms involved in its game (Brandenburger and Nalebuff, 1995). This renders game theory a suitable tool for understanding and analyzing complex industries where extensive interactions exist between competitors and collaborators. However, game theory does not provide a model for technological evolution in an industry but rather a model of coordination of the players involved in it. Therefore, while some principles from it may be used for this analysis, it is not the main tool in this research.

To study the effects of technological maturity on the product architecture of complex industries, the disruptive innovation theory of Christensen and Chesbrough is at the core of the analysis with its underlying constructs used to formulate the research hypothesis. The literature about complex products, complexity, modularity and product architecture were also used to help formulate the hypothesis and analyze the results of the validation. These theories and definitions given in the literature have guided the research throughout its phases from hypothesis formulation to the research instrument creation, to data collection and finally data analysis. Tables 2.1, 2.2, 2.3, and 2.4 summarize the key theories from innovation literature, complexity literature and management literature discussed above and their relevance to the evolution of industries.

Familiarity with the aviation training industry and its numerous peculiarities is also critical for understanding the various observations made in the industry and linking them to the reviewed literature. Chapter 3, therefore, presents an overview of the aviation training industry.

Table 1.1: Innovation Strategies

	Innovation Strategies			
	Creative Destruction	**Disruptive Innovation**	**Innovation Diffusion**	**Games of Innovation**
Key Concepts	1. A model, proposed by J. A. Schumpeter, of industrial organization in capitalist economies.	1. As products mature to exceed customer needs, lower end products emerge competing on flexibility and cost, initially for lower end customers in the market.	1. Generally follows a sigmoid curve with a slow initial acceptance, accelerated market penetration and normalization followed by approaching saturation and a plateau rate of diffusion.	1. Industries can be classified based on their natural trajectories into 7 games of innovation.
	2. Incumbent products in the market are replaced by new innovative ones that destroy the incumbents' competencies and hence competitive advantage.	2. With the emergence of the lower end products, the product architecture opens and modularity increases to decrease product costs.	2. Dominant models are the epidemic model, probit model, legitimation and competition model and information cascades.	2, The games depend on the product architecture category and the market phase.

Table 1.1: Innovation Strategies (continued)

	3. Innovation in the economy progresses through successive waves of creative destruction.	3. With the increase in product modularity, the architecture of sub-products closes to enhance their technological superiority.		3. The seven games are: Patent-driven discovery, systems integration, platform orchestration, cost-based competition, systems-consulting & engineering, customized mass production and innovation support
Relevance to Complex Product Industries Research	1. Forms the basis of Christensen's theory of disruptive innovations.	1. Makes little distinction between systemic and non-systemic products.	1. Makes little distinction between systemic and non-systemic products.	1. Distinguishes between innovation practices in different industries based on the type of their product architecture
	2. Does not distinguish between systemic and non-systemic products in predicting the successive ways of creative destruction.	2. Forms the basis for the hypothesis in this research as complex products are hypothesized to diverge from the model.	2. Of little relevance to complex products as they are often specialized and involve the clients from an early phase.	2. Can help the analysis of the results accounting for differences between the industries used to construct the literature theories and the one studied.

Table 2.2: Complexity, Modularity and Systems Integration

	Complexity, Modularity & Systems Integration **Complexity, Modularity & Systems Integration**
Key Concepts	1. Complex systems have 2 main dimensions multi-component and multiple disciplines involved with it. 2. Complexity often leads to decomposability which may lead to modularity (i.e. the presence of a one-to-one relationship between product functions and components). 3. Modular products may have an open architecture where the standards of how the components interface are available to a group of companies in an industry. Integral products are very unlikely to have an open architecture.
Relevance to Complex Product Industries Research	1. Complex products often exhibit a modular configuration. Christensen hypothesizes that this modularity results in an open architecture under competitive pressures at times of technological maturity. 2. The research will analyze the degree of openness of the product architecture in complex product industries during times of product maturity.

Table 2.3: Networks and Coordination

	Networks and Coordination		
	Clusters	**Value Nets**	**Platforms**
Key Concepts	1. Geographic concentrations of interconnected companies and institutions in a particular field.	1. Networks of firms highlighting their relationships with their suppliers, clients, complementors and competitors.	1. Composed of a core component and peripheral components independently attached to it via standard interfaces.
	2. Encourage competition and cooperation relationships simultaneously between member organizations.	2. Emphasize non-contractual relationships between firms and the complementors relations.	2. Depict a particular case of open architecture products where the standard interface defines the interaction between the peripheral components and the core only, maximizing their autonomy and hence facilitating their independent evolution and innovation.

Table 2.3: Networks and Coordination (continued)

	3. Facilitate coordination and sharing of logistical infrastructure between complementors and competitors.		
Relevance to Complex Product Industries Research	1. Analyses collaboration between complementors and competitors rather than collaboration between producers of components of systemic products.	1. Can help understand competitive and collaborative relationships between producers of systemic complex products 2. Are too limited to analyze disruptive innovation and product architecture openness.	1. Present an interesting particular case for an open product architecture, which is a common configuration of complex products. 2. May not be applicable to all complex products as it requires leadership to define and lead a core-peripherals platform configuration.

Table 2.4: Strategy

	Strategy					
	Porter	Configuration School	Evolutionary Theory	Bundling	Resource-Based Theory	Game Theory
Key Concepts	1. Competitive positioning	1. Adaptive Strategy	1. Bundles of routines constitute organizational learning	1. Selling separate products together as a single product or as a discounted bundle	1. Assumes the unequal access of different firms to resources.	1. Analyzes behaviour in game situations with players, strategies and payoffs.
	2. External view of the firm	2. Non-deterministic view	2. Routines improve following their failure and review	2. Product or Price based	2. Attributes competitive advantage to the firm's capability to build and sustain the superiority of inputs.	2. Games are either rule-based, where players adhere to specific rules, or free-wheeling where players are free to decide on their strategies

Table 2.4: Strategy (continued)

	3. Assumes antagonism between the firm and its surroundings	3. Little literature	3. These routines are at the core of the organizational evolution	3. Creates value either through an integrated architecture or price discounts.	3. Emphasises the role of learning and accumulated knowledge in competitive advantage	3. Assumes rationality and therefore that each game will come to an equilibrium (either dominant strategy, iterated strategy or Nash equilibrium).
Relevance to Complex Product Industries Research	1. Unable to account for coordination 2. Does not recognize firm's competencies & accumulated learning	1. Unable to account for coordination (which is highly deterministic) 2. Under-developed in the literature 3. More related to corporate strategy than technology strategy	1. Emphasizes the role of accumulated learning which is important for complex product industries. 2. Limited to firm level analyiss and can not accoomdate industry-level analysis. 3. Limited to internal firm routines and unable to account for industry routines or inter-firm development of	1. Limited pertinence to complex products as it addresses independent products with separate markets	1. Emphasizes the role of accumulated learning which is important for complex product industries. 2. Limited to firm level analyiss and can not accoomdate industry-level analysis. 3. Limited to internal firm routines and unable to account for industry routines or inter-firm developme	1. Allows an allocentric view encompassing several players other than the main firm in question. 2. Does not provide a model for technological evolution but focuses more on competitive strategic moves.

[redacted]			routines.		nt of routines.	

CHAPTER 3 THE AVIATION SIMULATION & TRAINING INDUSTRY

The aviation training industry emerged in the early 1920's and following a slow start, it has gradually gained importance since in the aviation sector. A brief synopsis of the history of the industry's emergence is given below.

3.1 Historical Emergence of the Industry

3.1.1 Early Attempts

The history of flight simulation is almost as old as the history of flight itself. With the increased importance of flight, the process of learning to fly was becoming more indispensable. The costs and, above all, safety risks of airborne training favored the emergence of simulation tools to familiarize pilots with the cockpit environment on the ground.

One of the widely used early simulation techniques was referred to as the "*Penguin System*" (IMECHE, 2007). This learning approach used the aircraft itself as the flight simulation tool. The flight student was allowed to sit behind the controls of a reduced wingspan aircraft and was towed on the ground, while moving the aerodynamic controls of the aircraft. This introduced the student to the feel of the controls and partially replicated his flight manoeuvres to be conducted in the air. This system was used in the French Ecole de Combat during the World War I.

Another similar system was the *Sanders Teacher* which consisted of a full aircraft cockpit mounted on a universal joint and placed in the direction of the prevailing wind (Rolfe and Staples, 1986). This allowed the flight student to move the aircraft controls and feel the resulting forces on the aircraft. Another version of the Sanders Teacher included a bar that the student had to align with the horizon and hence learned to maintain a stable aircraft attitude[1]. These early attempts were precursors to the new aviation simulation and training industry soon to emerge when Edwin Link introduced his revolutionary flight simulator.

3.1.2 Link's Simulator

In 1920, Edwin Link started to learn to fly. Frustrated with the lack of hands-on training opportunities in the field, he abandoned the flying lessons to work with his father in his piano factory (Rolfe and Staples, 1986). In 1927, a group of barnstormers taught Edwin how to fly and he got his pilot license in the same year. In the same year, he also acquired the first Cessna aircraft built and started investigating ways of making a living using his newly acquired expertise and equipment. Constantly concerned about the costs and convenience of flight training, Link started a design project of an aircraft cockpit replica for training pilots. He later called his machine the "Pilot Maker" and launched it in 1929, out of his father's factory basement, as the first synthetic flight training device.

As in the case with most new technologies, the aviation industry did not comprehend the implications of the new training tool and hence did not show any interest in acquiring it. Training for the airlines industry was, and continues to be, an overhead cost of operation and hence convincing airlines management to invest in new technologies of training is an uphill battle. Perhaps another reason for the failure to see Link's achievement was the dominance of VFR[2]

---

[1] Aircraft attitude is a term commonly used in the aviation industry and it refers to the position, configuration and motion vector of the aircraft in question. A 'banking attitude' for example would mean that the aircraft is tilted along its longitudinal axis and is moving in that position.

[2] VFR = Visual Flight Rules: flying using the pilot's visual cues to locate his aircraft in space and identify his aircraft's attitude and relative positions from nearby terrain.

flying which relies on the pilot's understanding of the flight dynamics vs. IFR[3] flying which also relies on the pilot's understanding of the aircraft navigational instruments. Flights were few and far between and risky enough that adverse weather conditions were considered a sufficient reason for flight cancellation. In the absence of any replication of the out-of-window environment in Link's technology, the added value of simulating the flight instruments was not clear to the potential end users. The commercial value of Link's new technology was not high in light of the prevailing flying techniques. Amusement Parks were the principal customers of the newly formed *Link Aeronautical Corporation.*

In an attempt to demonstrate the added value of his new invention, Link opened *Link Flying School* where the curriculum was heavily based on the new simulation technology that he developed. The market timing of the new technology-based service was not in its favor as it coincided with the great depression of 1930.

In 1934, the US Air Force was mandated to deliver the mail by Air around the US (US Centennial of Flight Commission, 2007). The military pilots were not trained to fly in the dark and in adverse weather conditions. Unlike the commercial flights, still considered a luxury at the time, mail delivery was a more pressing need that reshaped the demand on the flying industry. New techniques had to be devised to minimize the risk of night and adverse-weather flying, especially after 5 pilots and their planes were lost in the first few days of the new mail-delivery service. Openness to the new notion of instrument-dependent flying was increasing and hence Link's invented technology was now seen as a value-adding tool. Link was invited by the Air Force to Newark airport to demonstrate his new technology. Flying in, Link's approach of instrument

---

[3] IFR = Instrument Flight Rules: flying using the aircraft navigational instruments and displays for identifying the aircraft location in space and its proximity to nearby terrain.

flying proved its success by his own safe and smooth flight despite the stormy weather. This started the negotiations that ended by Link receiving an order of six pilot trainers for the US Air Force (Borden, 1968).

The launch order of Link's training devices was timely with the increasing importance of the flying industry and the increasing dependence on its timely and consistent performance. This emphasized the instrument flying technique and increased the demand for new instrument flight training equipment. It was not until the second world war though that the simulation training equipment industry boomed and Link Aviation grew significantly to employ 1500 people, producing more than 80 simulators per year (Rolfe and Staples, 1986).

The period between 1934 and 1945 was the time of technology transfer from the applied research stage of Edwin Link (Rodgers, 1996) to a commercially profitable product. Using Abernathy's transilience map (Abernathy and Clark, 1985), Link's innovation resulted in an architectural innovation as his product gave birth to a new industry that soon developed a stable architecture and grew to be an $800 Million industry over the following 5 decades.

The aviation training industry can be divided into three sub-industries based on the type of products provided: the simulation product industry, the training product suite industry and the training services industry. These three sub-industries will be treated differently throughout the research and the dissertation.

3.2 The Simulation Product Industry

This sub-industry provides synthetic flight simulation equipment for training aircraft pilots and maintenance crews to operate, and maintain aircraft systems. Products of this industry may be divided into three categories: Full Flight Simulators (FFSs); Flight Training Devices (FTDs) (Rosenkopf *et al*, 1998) and the more recent Desktop Training Devices (DTDs) (CAE, 2000). As their name implies, FFSs provide a faithful replication of the flight cues and aircraft experience including the motion and visual aspects. FTDs, on the other hand, have more limited simulation fidelity and focus on particular systems or specific maneuvers training (Rosenkopf *et al*, 1998). DTDs appeared mostly in the 1990's following the PC revolution providing theoretical and limited operational knowledge about systems and procedures (CAE, 2000).

FFSs became the norm in flight training in 1980 following their adoption by the FAA as a substitute to aircraft training (FAA, 2007). The widespread use of FTDs, however, was not until the mid 1980's when the regulators were convinced of their added value (Rosenkopf *et al*, 1998). DTDs have gained increasing popularity since the late 1990's due to their cost advantages especially during the times of economic difficulties in the industry as well as rapid technological advancement resulting from strides in computing power and graphic realism in the PC industry (Kamel and Miller, 2002).

3.3 The Training Products Suite Industry

With the evolution of the industry and its increased specialization, different levels of training products emerged and airlines were combining them in different permutations for accommodating their specific training needs. Training product suites have emerged with time and technological advancement as airlines seek to optimize their training fleets. In the 1970's, full flight simulators were the norm combined with rudimentary classroom "chalk-and-talk" instruction. In the 80's, FTDs started to occupy a more prominent position in the composition of the training product suite as level 6 and 7 FTDs were demonstrating significant training value for their lower costs. In the 90's, levels 6 and 7 started to disappear and get replaced with level 4 and 5 FTDs as these latter were proving more efficient in training particular flight maneuvers and operator checklists. In the past few years, level 4 FTDs and LCD-based IPTs (Integrated Procedure Trainers) are becoming increasingly popular as the non-FFS components of the training products suite. The suite has evolved from relying on high-fidelity simulation for both the informational and the tactile part of the training to offloading the informational part to increasingly lower levels of training fidelity capable of reproducing the basic system performance. Enhances in computing technologies also helped this trend by allowing high-fidelity simulation models to be available on lower level devices.

The other aspect of training product suites that has evolved is the market dynamics of their creation. The onus of selecting compatible training devices and bridging any incompatibilities was traditionally on the training centers. In recent years, training device suppliers have assumed an increasing role of packaging their devices into integrated suites (Christensen *et* al, 2001, Pavitt, 2004) emphasizing seamless integration and inter-operability within the suite.

3.4 The Training Services Industry

Hardly any academic research has been conducted on the aviation training services industry. In the mid 1990's when most of the research about the aviation training industry was being conducted (Miller and Olleros, 1993; Miller *et al*, 1995; Rosenkopf *et al*, 1998), most airlines conducted their own training and the services industry was limited to the business jets and private pilots market. Following the financial difficulties that faced the airlines industry in the late 1990's independent aviation training providers became more prominent, especially when some simulator manufacturers decided to vertically integrate into offering training services (Kamel and Miller, 2002).

Training services are sold in one of two main distribution channels: dry leasing or wet leasing (Kamel and Miller, 2002). Dry leasing is the leasing of the training equipment, the facilities hosting them and the technical support required for the maintenance of the equipment, but without any involvement in the training itself. This form of entrepreneurial exploitation of the simulation equipment is still the most common in independent training centers providing simulation equipment for commercial aircraft. Wet leasing, on the other hand, consists of providing a turn-key service including the training equipment, instructors, curriculums, publications and even logistics (such as travel and accommodation of students) in some cases. This form of selling training is more common in the business and executive jets training markets where clients are often independent jet owners or private pilots whose use of the equipment does not justify the investment in developing their own curricula or hiring their own instructors (Kamel and Miller, 2002). Wet leasing is becoming increasingly popular in commercial aviation following the efficiency pressures that the airlines industry has undergone rendering the outsourcing option of training more attractive to many (Kamel and Miller, 2002).

The main categories of training that a pilot needs throughout his career are:

3.4.1 Ab-Initio

Ab-Initio training is the initial training that an individual receives to become a licensed commercial pilot. *Ab-initio* training traditionally comprises a theoretical component, introducing the student to the theory and basic aerodynamics of flight, followed by a number of flying hours with an instructor in different weather and lighting conditions. *Ab-initio* training has traditionally been conducted at the student's own expense at a flying school and ends either in a commercial pilot license and a few hundred hours of logged flying time or a private license for leisure flying. To become candidates for airlines positions, pilots typically then seek to accumulate more flying hours by flying for small regional airlines, flying schools or air taxi companies.

It is noteworthy to mention that *Ab-Initio* training has been traditionally done in a single-crew cockpit such as that provided by a Cessna 132 or similar light piston-engine aircraft. Pilots often started experiencing multi-crew cockpits only at later stages in their training and careers. MCC (Multi-Crew Coordination) courses were used to bridge the knowledge gap and get the pilots used to interacting with their cockpit colleagues. This involves the pilots letting go of some tasks that they were trained on performing, but also doing more communications tasks that they were not trained to do before. This setup lengthens the overall duration of training and is seen by many experts in the industry as an undue risk to the quality of pilot training (Fiorino, 2005(1)).

In response to forecasted pilot shortage airlines have been putting pressure on the training industry to reduce training cycle duration. Some *Ab-Initio* training providers are currently providing the entire training in a multi-crew cockpit environment to avoid the learn-unlearn cycle involved in the current approach. Oxford Aviation Training in the UK is one of the pioneering schools in that domain working closely with several European airlines for maximizing pilots' readiness for their line operation environments. The school reduces the overall training duration and reduces the number of learn/un-learn cycles by training its students on multi-crew coordination since the very beginning of their flying careers. The consequences of this trend on the aviation training industry will be discussed further in Chapter 8.

3.4.2 Type-Rating

Before flying with commercial passengers, a licensed pilot needs to be type-rated for the particular aircraft he is flying. Type-rating training is often conducted after pilots are hired by airlines and is often paid for by the airlines. In new aircraft deals, a portion of type-rating called entitlement training is usually carried out by the aircraft manufacturer for the client pilots. Some parts of type-rating training needs to be conducted on the aircraft itself or on a Zero-Flight-Time (ZFT) simulator.

3.4.3 Recurrent Training

Aviation regulatory authorities demand some periodic training for refreshing pilots' skills and bringing them up-to-date with the airlines operating procedures and emergency checklists. Recurrent training typically requires a ZFT simulator for some components of it.

3.5 Industry Organization

The training equipment, training product suite and services industries interact heavily with each other as well as with several other industries such as aircraft manufacturers, avionics system controllers and aircraft engines industries. Kamel and Miller proposed the organizational structure in figure 9, below, based on their study of the industry (Kamel and Miller, 2002).

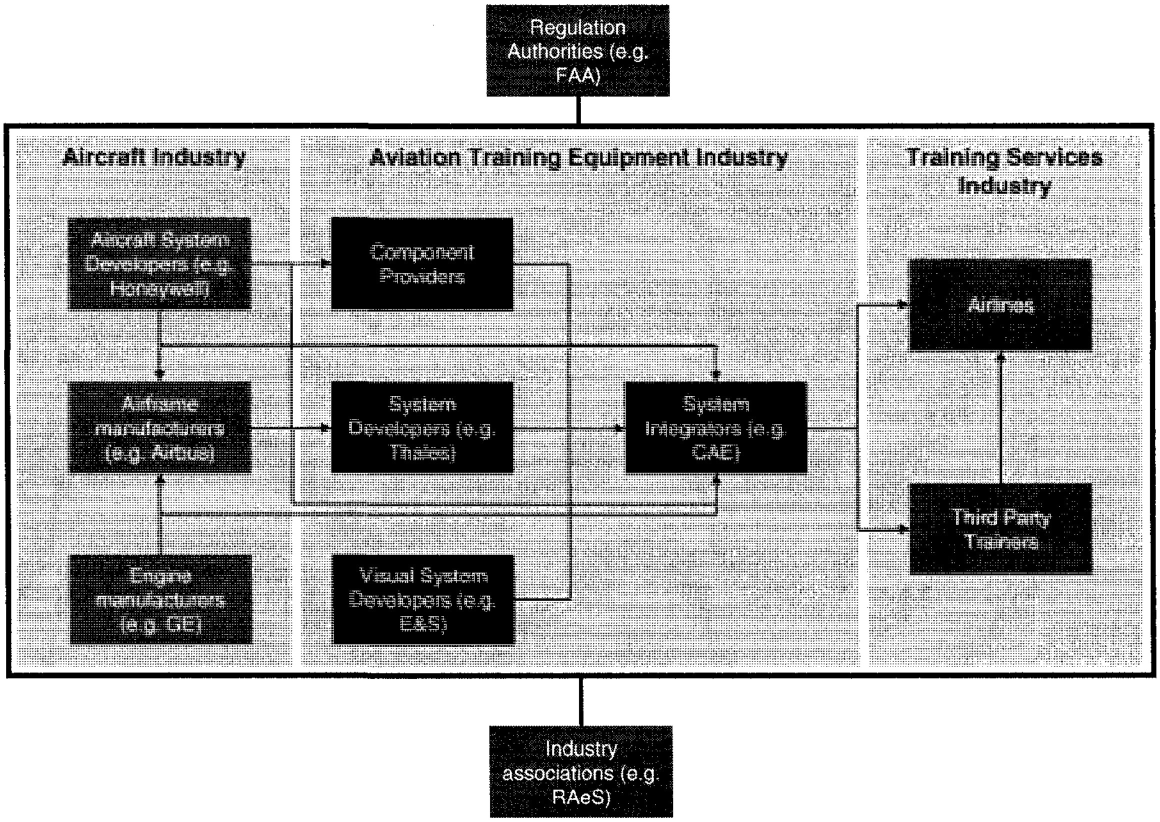


Figure 3.1: Organizational design of the aviation industry

The aircraft industry is at the upstream-most position of the value chain providing the aviation training industry with components and data for replicating aircraft. Airframe manufacturers play an integrator role putting together numerous specialized systems (e.g. landing gear, wings, control surfaces, avionics, etc.) with the most technologically complex component, namely engines. A similar organization is found at the aviation training equipment industry where systems integrators combine components from specialized system providers with systems simulations and visual systems into a portfolio of different training products geared at different applications of their clients. The airframe manufacturers, as well as their engines and component suppliers, all provide simulation data and components both directly to simulation systems integrators as well as to their component and systems suppliers. Finally the simulation equipment integrators provide their simulation products either to airlines or third party trainers for offering training services to pilots. Third party trainers offer services to business and small airlines pilots or to airlines during peak periods that require more training capacity than what their facilities can provide.

3.6 Industry Characteristics

The aviation training industry has certain unique features that have to be considered when attempting to analyze its product architecture:

- Aviation safety is the key factor that gave birth to this industry and continues to be the driving factor at the core of its existence. This puts significant emphasis on the quality of the industry products and allows very little tolerance to errors or failures.

- Customers of this industry are well-informed and highly specialized operations and management teams who are directly involved in the design of their training products and services. This is further accentuated by the hefty investments they have to make for acquiring their training products and services.

- Training simulation devices and curriculums have an intrinsic regulatory necessity of being customized to the customer's aircraft fleet and training requirements. This challenges the traditional definition of a "dominant design paradigm" from Abernathy's mass-produced design model (Abernathy & Utterback, 1978).

- Airlines are legally mandated to regularly train to maintain their flying license. For them, therefore, it is a regulatory overhead cost that does not generate any rents. This puts significant price reduction pressures on the suppliers therefore increasing emphasis on process innovation.

- Due to the aforementioned high cost, safety and regulatory pressures, reputation is an indispensable asset of a supplier firm in this industry. This imposes a high barrier to entry but also generates a positive feedback loop for incumbent players as their reputations and proven-track records improve over time. Earlier studies in this industry have revealed that few entrants were able to penetrate the high entry barriers since the establishment of the industry in the 60's (Miller *et al*, 1995).

- Synthetic flight simulation products are quite advanced technologically as they not only replicate the aircraft systems but also the ambient whether and environment effects. This introduces an accumulated knowledge positive feedback loop whereby incumbents become more competitive with every additional simulation they build. Adding to the company's library of simulation models significantly cuts the development and buildinig costs of simulation equipment. One key player in the industry for example, boasts that it has the simulation models of almost every configuration of the Boeing 737-NG, an aircraft that is highly customizable and has numerous configurations worldwide.

- The limited number of key players in the industry on the global level makes connections with regulators, presence in industry forums and participation in industry standards almost essential for firm survival in this industry.

3.7 The Traditional Industrial Organization

Individual training products have traditionally had a closed product architecture, with a few oligopolic firms competing with their proprietary designs. Training product suites, on the other hand, have traditionally had an open product architecture due to the regulators definition of the specifications of individual devices and the interfaces between them (Kamel and Miller, 2002). Figure 10, below, depicts the typical architecture of a training suite composed of different levels of training devices manufactured by different industry suppliers (Kamel and Miller, 2002).

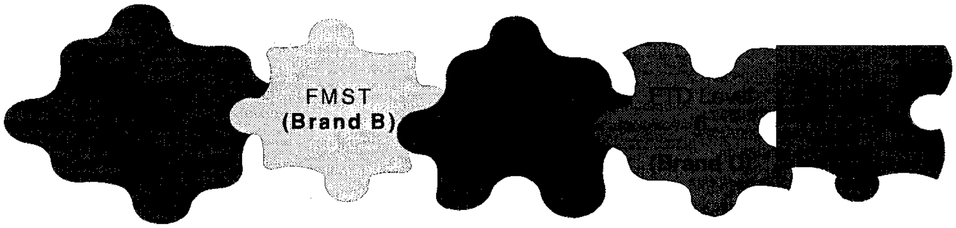


Figure 3.2: A graphical depiction of a regulation-driven training curriculum

The training services industry has traditionally had an open architecture as well due to its high level of regulation and the segmentation between the generic *ab-initio* training and the more aircraft-specific type-rating and recurrent training at later stages (FAA, 2006).

3.8 Regulation

The regulatory authorities have identified various levels of fidelity of flight training products for the various stages of pilot training. Adherence to the minimum requirements of each of these training devices is what gives any training device its commercial training usability and hence commercial value. Regulatory guidelines define the structure of negotiations between buyers and sellers (Brandenburger and Nalebuff, 1995). The FAA or JAA certification level achievable by any aircraft simulation device is what determines the training credits that can be obtained from it and hence the returns on the investment made. The authorities' qualification decisions also take into consideration the end user's perception of the product quality as well as its planned utilization in the user's training program. This is an important feature of the flight simulation equipment industry since innovation is not solely dependent on the technology transfer capabilities of the innovative firm but also on customer acceptance (Miller and Olleros, 1993).

Due to the high safety implications involved, the regulation guidelines were slow to evolve in reaction to technological evolution (Kamel and Miller, 2002). Few and far between revisions of the guidelines were made, and these were mostly related to training methodologies rather than being technology-driven. In other words, these changes reflected the evolution of the aviation industry rather than that of the aviation training industry. The only changes made to simulators' qualification guidelines were reactive to accidents revealing their deficiencies (Kamel and Miller, 2002).

CHAPTER 4 HYPOTHESIS & RESEARCH METHODOLOGY

In the theory of disruptive innovation, Christensen presents a model linking the change in the architecture of a product, and subsequently that of its industry, with the level of technological maturity of the product (Christensen, 1997; Christensen *et al*, 2001). When technologies are still striving to meet the performance requirements of clients, companies offer proprietary closed architectures that permit them to develop state-of-the-art functionality and performance. However, once the technology matures to surpass clients' needs, entrants at the lower end of the market establish a competitive position based on convenience, cost and flexibility catering to non-users of the technology or to specialized market sectors with lower technical requirements. As the entrants improve technologically and approach satisfying the needs of the mainstream market, competition shifts from technological capabilities to price. Entrants, now mainstream players, therefore open the product architecture to attain higher efficiency levels and be competitive. Product standards are often developed to help in shifting the market from proprietary designs to modular ones. Chesbrough builds on this further and describes the conditions for the product modularity to result in a similar shift towards industry modularity (Chesbrough, 2003). With the increase in competition in the open architecture market, product integrators impose performance and cost pressures on their suppliers, the component providers. The latter, in turn, close the architectures of their products to attain the required higher levels of performance and market differentiation. This model, conforms to earlier literature (Baldwin and Clark, 2000) predicting a constant increase in modularity and architecture openness.

4.1 Research Question

Christensen's model was formulated based on the disk drive industry (Christensen 1997), and supported by case studies from the PC and telecommunications industries (Christensen et al, 2001). The present research hypothesizes that this model is not fully applicable to Complex Product System (CoPS) industries defined in systems integration literature (Johnson, 2004; Dosi et al, 2004; Davies, 2004; Prencipe, 2004). In the aviation training industry regulatory standards define the performance specifications of the various components of the training product suite, namely the different types of simulation-based training devices, and the training credits that can be earned on them. Therefore, the regulatory standards define, in essence, the product performance expectations of the market. Since the late 1990's the industry's technological capabilities have been observed to attain, and gradually surpass, the regulatory requirements. This should signal the start of Christensen's disruptive innovation cycle. Entrants at the lower end of the market, started to offer training devices at higher flexibility and lower-costs at the expense of some performance features that surpassed the regulatory requirements. Low-cost and no-frills airlines were the most receptive to the new products that were aligned with their cost-minimization business models. The changes in the industry were, thus far, in line with Christensen's model. However the result of the emergence of the lower end of the market was observed to diverge from the model. Instead of the new entrants opening the product architecture, and the incumbents driven out or losing market share, the incumbents were prompted to close the product architecture further thus earning back their market shares and driving out the entrants. Instead of the regulation-centered open-architecture training product suite, what happened is that the incumbents offered a closed-architecture suite of training products focused on the pedagogical value. This aspect has traditionally been too far downstream for the simulation equipment providers to be concerned about. However, as Wise and Baumgartner predict, it forms the basis of the services end of the industry which promises more value-capturing potential for the simulator producers (Wise and Baumgartner, 1999). The incumbents have, therefore, been observed to extend downstream to the services industry while closing the products architecture further. The hypothesis of this research is:

In response to product maturity in Complex Product System (CoPS) industries, the product architecture does not necessarily open as predicted by the disruptive innovation theory.

To hypothesize the reasons for the divergence between CoPS industries and disruptive innovation theory, the constructs and implicit assumptions of the theory were examined to verify their anticipated applicability to complex product system industries. The sequence of steps leading to the opening of the product architecture presented by the disruptive theory were all verified in the case interviews to verify the point at which CoPS industries diverge from the behavior predicted by the theory. At these points of behavioral divergence, the implicit assumptions of the disruptive innovation theory were examined to verify if they are applicable to CoPS industries. Table 1 summarizes the list of steps observed in the disruptive innovation theory as well as the implicit assumptions made for some of them. The table also presents the questions used in the research instrument to verify the validity of these steps and assumptions in the context of CoPS industries. Where divergence was expected between the theory and CoPS industries, the table presents the reasons hypothesized.

Table 4.1: Constructs of disruptive innovation theory and questions used to validate them

Disruptive Innovation Theory Steps & Constructs	**The Underlying Assumptions**	**Exploratory Questions to verify the validity in CoPS industries**	**Hypothesized Reasons for Divergence from theory**
With continuous technological advancement, industries attain and start to overshoot the needs of their clients	*Customer needs are specific, at least over the short and medium terms*	What are the indicators of technological maturity in the industry?	No divergence hypothesized
		Has the industry attained technological maturity?	

Disruptive Innovation Theory Steps & Constructs	**The Underlying Assumptions**	**Exploratory Questions to verify the validity in CoPS industries**	**Hypothesized Reasons for Divergence from theory**
Entrants enter the market and cater to non-consumers or low-end customers	• *Surmountable barriers to entry* • *Adequate market size to attract entrants*	Has there been an influx of low-end entrants?	No divergence hypothesized
With continuous technological advancement, entrants gradually displace incumbents by attracting mainstream customers and gaining market share	*Entrants fly under the radar of incumbents who continue to listen too closely to their top-tier clients who, in turn, are constantly pushing the envelope on technical features*	What is the role of regulators in influencing customers needs in the industry?	The need for regulatory approval of innovations, therefore limiting the influence of the market selection forces on disruptive innovation waves
		What is level of involvement of the clients in the design and characteristics of the product?	The direct involvement of clients in the design and characteristics of their products prevents incumbents from ignoring the needs of mainstream clients.
Competition between entrants shifts to non-technological parameters such as cost or flexibility and hence they work on opening the product architecture to increase efficiency.	*Competition can shift from technological features to cost or flexibility*	Is public safety and risk liabilities a key concern for industry players?	The public safety and legal liability considerations involved make an open architecture a potential security threat.
	Open product architecture is more efficient	Is accumulated learning an important factor in the industry? What is its effect on the competitiveness?	The high value of accumulated learning favors sustaining to disruptive innovations
	Market volume does permit the emergence of specialized component suppliers	What is the market volume (measured in terms of number of simulators produced per year)?	The market thinness and subsequent inability to support the emergence of a network of specialized component providers
Standard designs emerge to support the open architecture and the product architecture opens.		Have any standard designs emerged?	
		Has any opening of the architecture been observed at any of the three product levels?	

The relationships between the theory constructs and the research questions are explained below:

- *Attaining and overshooting the needs of the clients:*

To be able to establish whether the industry has indeed attained its technological needs of its clients, it is first important to establish a metric for measuring these needs. In Christensen's theory, the market indicator of incumbents' survival was used to highlight the cases where the incumbents failed to cater to the needs of the mainstream market efficiently and were therefore pushed out of the market. Given that the hypothesis expects the incumbents to survive the entrants, it would be inconclusive to use market survival as an indicator of client needs satisfaction. The research needed to probe what would be an alternative metric of technological maturity followed by a validation that the industry is indeed on the path of disruptive innovation predicted by Christensen's theory.

- *Entrants enter the low-end of the market and start catering to low-end customers*

Industry experts were asked to validate whether a trend of low-end entrants, as would be predicted by Christensen's theory, was observed.

- *Entrants gradually displace incumbents by catering to mainstream clients*

Christensen's disruptive innovation theory attributes the rise of the low-end entrants to the level of satisfying mainstream clients to their flight under the radar of the incumbents who are mostly focused on their top-tier clients. One implicit assumption in this construct is that the relationship between suppliers and customers is direct and does not include any third party that governs it. This would permit the entrants to increase the sales of their products while the uninformed incumbents undermine the threat that they pose. This free "push" market mechanism can be hindered by one of two factors: regulation or a pull market effect.

In a regulated industry where regulators have to approve every individual product and where customers needs are heavily influenced by a rare-to-evolve set of regulatory guidelines, incumbents are always aware of their competitors' sales, thus preventing the flight under the radar, as well the needs of the mainstream markets, which are dictated by the regulations. The effect of regulation on the ability of the entrants to fly under the incumbents' radar was therefore validated by the fourth question about the role of regulators.

In a pull market, customers are too involved with their clients in the design and specifications of the products to allow an incumbent supplier to get disconnected from the mainstream market. The clients' level of expertise and direct involvement communicates their needs clearly to the suppliers. This effect is further amplified by the market thinness and the fact that all clients are significant, in terms of their revenue contributions, for the incumbents.

- *Competition shifts to non-technical parameters such as cost and flexibility*

For the competition between the suppliers to shift away from technological merits to cost and flexibility, three implicit assumptions have to be satisfied:

1. Customers of the industry make their acquisition decisions based on optimizing the technological features, the cost and the flexibility of use of the products. In a consumer product, these decision criteria are indeed valid. In an industrial product that will be used for revenue generation, these criteria change introducing others such as revenue generation potential or public liability considerations. These factors may influence decisions in favor of technological features against any cost or flexibility factors. The effect of public liability on

the customers' decision making, and hence the market's likelihood of switching competition towards these factors, was validated by the fifth question.

2. The other implicit assumption in the disruptive innovation theory is that an open product architecture is more efficient for suppliers and would therefore be preferable when the market switches to cost competition. This assumption may be valid in mass production products where parallel innovation, permitted by an open architecture, allows increased production efficiencies. In a CoPS industry where products are unique large systems, the research wanted to validate if such efficiencies can offset the cost efficiency value of accumulated learning. This was validated in the sixth question.
3. The last implicit assumption in disruptive innovation theory's model of the product architecture opening is that the market volume does present sufficient business opportunities for the emergence of an open platform with parallel innovation. A thin market with a few number of products annually may not justify the existence of specialized system components producing to a standard product architecture.

The three questions address the three implicit assumptions underlying the theory's construct that once entrants reach critical mass in the mainstream market, they find it more favorable for competition to introduce an open product architecture based on a standard product architecture.

- *Standard designs emerge and the product architecture opens*

The two questions that followed from this construct were simply for validating the emergence of standards and the eventual openness of the product architecture.

The exploratory questions listed above are explained further below:

1. *What are the indicators of technological maturity in the industry?*

   In the consumer electronics industry studied by Christensen, technological maturity depends on, among others, client needs and expectations from the product. Technological maturity can therefore be indicated by the industry's attainment of the features and functionalities that users expect and communicate in market studies and surveys as well as from their patterns of purchasing particular products and not others. In regulated CoPS industries, however, clients select products using more complex criteria such as regulatory compliance, returns on investments and operational efficiency. It is therefore essential to identify the indicators of technological maturity in the aviation training industry.

2. *Has the aviation training industry attained technological maturity?*

   Disruptive innovation is hypothesized to start when the industry attains technological maturity hence allowing product selection criteria to shift from technological advancement and features to price and convenience. For the research to validate the applicability of disruptive innovation theory in CoPS industries, the first observation of the theory, namely that the industry has attained technological maturity, has to be supported by the analysis of the data collected in the case interviews.

3. *Has there been an influx of low-end entrants in the industry?*

   Disruptive innovation theory hypothesizes that in response to technological maturity, a low-end segment of the market emerges to cater to less sophisticated clientele requiring less expensive and less performance products. With the continuous advancement of the incumbents and the emerging entrants, this eventually becomes the mainstream market. The research therefore verifies the validity of this mechanism in the disruptive innovation for complex product industries.

4. *What is the role of regulators in influencing customer needs in the industry?*

   To confirm the validity of the assumption that the entrants replaced the incumbents in satisfying the mainstream market, the role of regulatory constraints on the needs of customer should be validated. Unlike the consumer electronics industry, the airline customers of the aviation training industry are bounded by regulations about their use of training products and services.

5. *What is level of involvement of the clients in the design and characteristics of the product?*

   If the hypothesis is valid and the product architecture of complex products does not necessarily open consequent to technological maturity, then an explanation of the alternate behavior is needed. The hypothesized differences between complex product industries and the disk drive industry, which is at the base of disruptive innovation theory, were verified with the interviewees to establish their significance in maintaining a closed architecture despite technological maturity. The first such difference is the degree of involvement of clients in dictating the features of their suppliers' products. Experienced clients may change the market forces significantly. Their significant influence on the design may not allow its feasible standardization. Their tight collaboration with the suppliers may also limit the incumbents' technological overshooting and the subsequent loss of competitive advantage to the entrants.

6. *Is public safety and risk liabilities a key concern for industry players?*

   To verify the industry's likelihood of favoring cost and flexibility factors over technological features, the risks and public safety liability associated with the product. High risks or costs of failures may continuously favor technological features and suppliers with proven track records over less-known but lower cost entrants. They may also result in an open architecture being less favorable because of the dilution of responsibility of quality control of the various components of the product.

7. *Is accumulated learning an important factor in the industry? What is its effect on the competitiveness of industry players?*

   Another factor to be validated to verify if an open architecture is indeed more efficient in CoPS industries is the value of the accumulated learning that the incumbents possess and its impact on their market competitiveness. If a positive feedback loop is increasing the incumbents' competitiveness with every new project they deliver, then entrants have a much harder task to penetrate the market, let alone topple existing players.

8. *Have any standard design emerged in the industry?*

   Baldwin and Clark noted that standardization is a pre-requisite to architecture openness (Baldwin & Clark, 2000). Detecting standardized product forms in the industry may, therefore, help identify a precursor to architecture openness.

9. *Has any opening of the architecture been observed at any of the three product levels?*

   If a standard architecture has been observed, then an open architecture may have been evolving as predicted by disruptive innovation theory. Following the explanation of the meaning of an open architecture, the interviewees were asked if this does exist at any level in the industry: training device, training product suite or training service.

10. *What is the market volume (measured in terms of number of simulators produced per year)?*

    The average number of simulators produced per year by the market can help confirm if it is too thin to support the emergence of specialized component providers.

The literature about CoPS industries and the preliminary observations from the aviation training industry have given rise to five hypothesized divergences of the aviation training industry from the constructs and underlying assumptions of the disruptive innovation theory. These five reasons of divergence, listed in table 2, are described below:

1. The high value of accumulated learning in the industry, favoring sustaining to disruptive innovations (Christensen and Raynor, 2003);
2. The need for regulatory approval of innovations, therefore limiting the influence of the market selection forces on disruptive innovation waves;
3. The high expertise level of the industry customers and their direct involvement in the design and building of the simulation products, also undermining the effects of market selection forces in Christensen's model;

4. The public safety and legal liability considerations involved in aviation training that make an open architecture a potential security threat;
5. The market thinness and subsequent inability to support the emergence of a network of specialized component providers.

These factors were validated throughout the research and will be revisited later in the findings and discussion.

4.2 Data Collection

The field study leading to this dissertation was conducted by interviews over a period of 2 years between June 2005 and December 2007 as part of the broader MINE research program. At the time the data collection started, the industry's response to disruptive threats from emerging FTD manufacturers was in progress. By the end of the period, the response was well under way and the incumbents have outlived the entrants as explained in detail in Chapter 5 of the thesis. Data for building these case studies came from diverse sources as explained below.

4.2.1 Interviews

Eisenhardt and Graebnert state that "...interviews are a highly efficient way to gather rich, empirical data, especially when the phenomenon of interest is highly episodic and infrequent" (Eisenhardt and Graebner, 2007). Since the research about technological maturity in a high-inertia industry, such as the aviation training industry, is certainly episodic and infrequent, interviews were selected as the key mode of data collection in the research. A research instrument was created and used to collect data from different stakeholders in the aviation industry. To avoid impression management and retrospective sense-making biases in the results of the interviews, Eisenhardt's recommendations of using numerous interviews with highly knowledgeable informants who view the subject from diverse perspectives was followed (Eisenhardt and Graebner, 2007). More than 40 interviews were conducted, mostly in person, with executive managers in a variety of sub-industries including flight simulator providers, aviation training providers, airframe manufacturers, airlines, avionic systems manufacturers, regulators and industry intelligence agencies. These interviews were transcribed for analysis against the hypothesis and the aforementioned exploratory questions. With the number of interviews conducted and the cultural diversity of the interviewees, it was decided to use a manual analysis technique instead of any particular text treatment software packages. The research instrument developed to guide the interviews is shown in Appendix B.

4.2.2 Industry Intelligence

In addition to the scientific literature reviewed prior and throughout this research, industry intelligence documents describing the industry were identified and reviewed. These ranged from press releases to reports made by specialized magazines, industry associations and consulting firms.

4.2.3 Validation with Experts

For further validation of the research findings, a number of presentations were made over time to specialized audiences of industry executives and specialists. Their feedback and comments have contributed to refining the research scope, identify the limitations and identify the research's contribution to theory and practice.

A presentation was made to a team of senior management at CAE, a leading company in the simulation production and training services industries. Another presentation, describing the research findings, was made at the Flight Simulation Conference at the Royal Aeronautical Society in London (Kamel, 2005). This conference is one of the most prestigious industry events where the majority of leaders and managers of the aviation training industry gather to discuss their common challenges and advances. Interviewees were also presented with the preliminary findings of the research, *after their interviews*, to further validate the observations and analysis.

A list of the interviews conducted can be found in Appendix A while the industry reports consulted can be found in the Bibliography section of this thesis.

4.3 Industry Organizations Studied

The companies and institutions selected for interviews throughout this research represented most of the different categories and types of companies in the industry including both incumbent and entrant companies. A list of these companies, with a brief introduction about each, is provided in Appendix A.

CHAPTER 5 SUMMARY OF RESEARCH FINDINGS

The literature review, interviews and other means of data collection used in this research have answered the 10 exploratory questions identified in Chapter 3. The responses to the questions pertaining to the industry's adherence to the pattern predicted by the disruptive innovation theory were all focused on the lower-cost FTDs disruption, which erupted in the late 1990's and came to an end around 2003. In fact, it is worth mentioning, that WICAT systems, a major low-cost FTDs provider that was considered a major competitive threat for the incumbents in the late 1990's, went bankrupt in the early 2000's. The summary of these historical findings is as follows:

5.1 Indicators of Technological Maturity of the Industry

Technological maturity of the industry is determined by several factors, most notably the regulatory requirements. Concerning business and general aviation customers, Tracy Brannon, Vice President/Managing Director of SimCom says (Bangs, 2004-1): "...most of our customers if not required by insurance of the FAA would simply not train." The standards established by the regulatory authorities define the bulk of customer requirements and needs from aviation training. It is the regulators that create value for the simulator customers when they certify their machines as capable of giving accredited training hours to student pilots. The satisfaction of customer needs can therefore be gauged by the satisfaction of regulatory requirements. Throughout the relatively short history of aviation training regulation, new requirements are defined every 10 – 15 years, often in response to technology surpassing the previously set requirements and therefore opening new possibilities and capabilities of synthetic training. Between these few and far-between evolutions, however, the industry strives to attain the technological requirements of the standards. Examples of such evolutions in the regulation include the 1970's regulation of flight simulators by the FAA and the 1980s' regulation of flight training devices. In both cases, the regulators prescribed a level of simulation that represents a stretch for existing capabilities yet one that is made possible through some recent advances. Therefore, in summary, the key indicators of technological maturity of the industry are its attainment of the regulatory requirements and the subsequent pedagogic needs of training service providers.

This indicator of technological maturity constitutes the first divergence from disruptive innovation theory where a market indicator, i.e. the disappearance of the incumbents after the entrants' penetration of the mainstream market, was used to establish maturity. However, this indicator could not have been used to demonstrate an exception to the theory since the survival of the incumbents is inconclusive as an indicator of maturity as it could have been caused by numerous other factors.

5.2 Attaining Technological Maturity

The aviation training industry has indeed reached the technological maturity phase where it has met, and in some cases exceeded, the requirements and expectations of the mainstream clients in the industry. These requirements are determined by the pedagogical needs of the airlines to maintain safe operations, satisfy regulatory frameworks (Bangs, 2004-1) and, in the case of business and general aviation, reduce insurance underwriting costs (Bangs, 2004-1).

At the simulator device level, Level D full flight simulators, being the highest fidelity devices, have met the regulatory, pedagogical and insurance requirements of clients. Especially for cockpit equipment simulation, the industry has attained the expectations of its various stakeholders. Jean-Claude Siew, VP of Systems Engineering at CAE notes that: "Quality and fidelity are not issues anymore; it's simply what we do...the cockpit has become a non-issue" (Larson, 2006). Marj DeLong, Marketing Director of CAE Simuflite, also attests to the quality standard attained and notes that the level of realism attained has "brought the people out of the airplane into the simulator for check rides[4]", (Esler, 2002). The head of flight training at TUIfly, a division of the transport giant Hapag Lloyd, said in an interview that

> "*...with the beginning of 1990 vintage simulators, the needs from a flight simulator were already met. They (flight simulator providers) added some enhancements later on, such as touch screens for example, but for the real simulation quality that you need for doing flight training, the 1989 simulator was sufficient*".

He went further to say that "*...the needs have in fact been met with the level C simulator*". The Dean of the flight training school at London Metropolitan University, echoes the same opinion affirming that simulators resemble the aircraft fully except that they "*...only lack the fear factor.*" An engineering team leader at Lufthansa flight training affirms that compared to the needs and requirements of regulators and airlines, flight simulator providers have "*...even surpassed them*". The general manager of Lufthansa Aviation Training concurred that the industry has reached the technological plateau: "*I think right now we are at a stage where you can get all the training credits, the highest training credits with these (existing) devices. Even if you put more technology into it, it is not possible to get the value from the training credits out of it.*" Furthermore Bangs states that following the availability of the Level D simulators, even insurance underwriters have reached the level of confidence and satisfaction in simulation technology to put financial pressures on their clients to utilize them for training (Bangs, 2004-2).

---

[4] Checkrides are the operational examinations of the training that allow a passing student to fly passengers in a commercial capacity.

At the training product suite level, the technology has also attained a maturity level indicated by the maturity of the individual devices and their seamless vertical integration into a suite with common simulation software (George, 2003). Training experts acknowledge the integral value of the entire product suite for the quality of the training offered and the pilot's preparation for the valuable ZFT simulator time (George, 2003). This acknowledgment was also paralleled with an increased emphasis from device providers on integrated suites. FlightSafety International has introduced its vertically integrated devices suite MatriX, CAE introduced its Simfinity line of integrated training solutions and Thales Training & Simulation introduced its comparable suite focused on the FFS together with low-end devices ranging from desktop simulations to an LCD screen-based trainer (George, 2003). These integrated training suites introduced technology commonality throughout the different phases of training and hence resolved a significant part of the training providers' problem of designing around the learn-unlearn cycles of traditional independent devices. Jean-Claude Kuoyo, FSI's EMEA marketing manager, comments on his clients' consistent feedback about FSI's vertically integrated software suite: "Customers say it's much easier to learn using the MatriX simulations" (Bangs, 2004).

At the training services level, technology is composed of the individual training devices, their integrated suite, as well as learning management tools and pedagogical aids. Some aviation training centers enable students to login to their prescribed training courses and simulator courses via an online LMS (Learning Management System) (CAE, 2007). PC-based courseware, FTD sessions and FFS sessions are all scheduled into this system that stores a profile file for every student containing everything from contact information to the results of evaluation tests conducted at the end of PC-based courseware modules. The LMS is integrated with the scheduling software used to manage the center, the various computerized training devices, as well online training tools that the pilot can access anywhere in the world. The system also produces the necessary reports for the pilots to provide to the regulatory authorities as proof of their fulfillment of their annual training requirements.

Despite the maturity level attained, technology continues to develop incrementally for simulation systems tied with the computing industry (Larson, 2006) and at a more rapid pace for visual systems introducing innovative technologies such as LCoS[5] and Laser Projection (Larson, 2006). These developments however are targeted, at least in the short term, towards the elite clientele seeking continuous technology and fidelity improvements. Mainstream clients, on the other hand, have reached the technological satisfaction level that allows them to seek higher efficiencies and lower costs of training. The industry has been assessing a proposal by Mechtronix, a recent entrant into the FFS market, to utilize lower level B FFSs for the majority of their recurrent training hence significantly reducing their FFS investments into the more expensive level D simulators (Anselmo, 2006; Potomac, 2006; Hughes, 2005).

The industry experts, articles and intelligence sources consulted in this research do not agree on a particular point in time at which the 3 sub-industries have attained technological maturity. However, they all agree that this has happened within the last 5 to 10 years.

5.3 Low-end Entrants

As described by disruptive innovation theory, as the incumbents matured and started surpassing the needs of the mainstream clients in the industry, low-end simulation providers entered the aviation training industry. Companies offering low level FTDs and different levels of desktop

---

[5] LCoS: Liquid Crystal on Silicon is a novel visual projection technology similar to LCD screens technology commonly used for computer screens and home entertainment systems (Larson, 2004).

trainers emerged to grab a share in the lucrative market. Helped by the rapid advances in the personal computer technologies, many employees of simulation providers started their own companies offering desktop trainers and low-cost FTDs. Some of these companies later developed into larger providers that expanded the depth and breadth of their expertise and started offering more advanced simulation devices. Examples of such companies include Opinicus, a simulation company started by an ex-CAE employee that has developed into a low-level FTD provider and eventually a full-flight simulator provider (Opinicus, 2007).

The appearance of these low-level entrants in the industry occurred in parallel to that of low-cost airlines that have "*...increased significantly over the past few years*" as noted by the General Manager of Lufthansa Flight Training. This has created sufficient demand to allow the efficient low-end device providers to gain momentum and build the necessary expertise to grow their product offering in an attempt to cater to the needs of mainstream clients. This influx of entrants was a relatively rare incident in the industry's history which traditionally had a relatively stable number of producers organized in an oligopoly (Miller and Olleros, 1993). Therefore, similar to the prediction of disruptive innovation theory, entrants did emerge in the industry to cater to the low end of the market.

5.4 Role of Regulators

Regulators, such as the Federal Aviation Administration in the USA or the Ministry of Transport in Canada, have a significant influence on all stakeholders in the aviation training industry. Pilots, training providers, simulation device producers and airlines all have to abide with certification requirements from their local regulation authorities. Training service providers, both independent and airline centers, need to qualify their training curriculums indicating the details of their plans to train their pilots on a list of maneuvers and skills prescribed by the regulators. These plans also include the number and qualification levels of the simulation devices that will be used to achieve the training.

At another level, flight simulation devices have to satisfy a detailed set of requirements and performance tolerances to attain specific qualification levels. These requirements define the customer expectations as well as the suppliers' overall product design. They also limit innovation to their prescribed boundaries. New products or technologies need to comply with the regulatory guidelines before they can create value for their customers. Customers needs, therefore, become primarily the prescribed requirements in the regulations. Suppliers, on the other hand, can not offer new or innovative technologies before getting them approved by the regulatory bodies. This process can be a long one lasting from a few months to a year during which competitors usually have enough time to react. For example, introducing touch-sensitive LCDs to replace tactile cockpit panels in low-level FTDs was first introduced by Thales Training & Simulation. CAE soon followed suit and pushed the concept further and even announced its intention to attempt to qualify it to a level 4 FTD. By the time the actual first qualification on an LCD-based FTD was obtained, Mechtronix and FlightSafety (the other 2 remaining key players in that market) had already introduced their versions of the innovative product and were working on its qualification. The lengthy regulatory process not only hinders the innovative company from introducing its innovation to the market rapidly but it even penalizes it as it facilitates the process for subsequent imitators who introduce their products only after the regulators have become more familiar to them.

Therefore, while the entrants did cater to the low end of the market, they were unable to advance and penetrate the full flight simulation niche or the services market while the incumbents were too close to their top-tier clients. In fact, the lobbying required with the regulatory authorities to advance their innovative attempts put them at a disadvantage compared with the incumbents who have proven track records and higher credibility.

5.5 Level of Involvement of Clients

Another factor that prevents the entrants' introduction of low-cost or high-flexibility products while the incumbents are not listening to the mainstream market is the tight relationship that the suppliers of this industry have with every one of their clients. While some airlines may indeed be more important clients in terms of their business volume, every client of the industry is a significantly large organization with specialized engineering crews that study the technologies offered on the market and play an important role in defining the suppliers' products and services. Unlike the consumer industry model where suppliers innovate and push their innovations to the market, the aviation training market is characterized by the pull of the clients' specialized crews. This direct intervention and pull from the market has resulted in the incumbents always being able to hear the needs of the mainstream market and adjust their product offering accordingly.

5.6 Public Safety

While none of the interviewees attributed a conscious influence of public risk and safety concerns on decision-making, they all, especially regulators, expressed concerns with negative training risks. All have agreed that should an accident happen, the effects in the industry are often quite drastic and regulatory frameworks are often changed as a result. Therefore public safety concerns do play a key role in the industry favoring the proven track records of the incumbents and raising the barriers to entry for the entrants, especially to the more critical technologies and training phases (such as the full flight simulators and the type-rating training respectively).

5.7 Accumulated Learning

Customers of the three levels of the aviation training industry are typically quite knowledgeable about their products and hence have a significant influence on its design. For example one incumbent made several attempts to standardize its full flight simulation products hence reducing their costs. In one such attempt in the late 1990's, two directors were named and the company was re-organized around the standard product concept. Heavy investments were made in researching and developing the most common configurations of different aircraft types to create the standard products. Customers, on the other hand, continued to get heavily involved in the design and customization of products to suit their specific needs and the standard products were eventually abandoned demonstrating the strong role of the customer in the design and configuration of the simulation devices.

On the simulation providers' end, the research has demonstrated the positive-feedback loop of accumulated learning that companies are subject to. With every new simulator made, the company becomes more efficient in the specific aircraft type as it becomes able to amortize the heavy development costs over a bigger number of products. This continues to raise the barriers to entry for industry entrants and limits their access to the more complex products such as full flight simulators. Accumulated learning therefore was found to have a strong role in the industry favoring the incumbents' track record perception, economies of scale and technical skills and knowledge.

5.8 Standard Designs

Despite the high modularity of the products of the aviation training industry and the frequent integration of some products made by different vendors, such as E&S visual systems for example on CAE simulators, no standard designs or integration protocols have emerged in the industry. The complexity and specificity of every single product has resulted in the failure of most standardization attempts. In the early 2000's, CAE tried to introduce the concept of a standard product based on a common aircraft configuration and which may be offered at a lower price than highly customized products. After 3 years of investing in acquiring the expertise and working on the technical designs, the company dropped the idea and both directors of standard products lost their positions. Every device brought about its own technical complexities and integration challenges. While the accumulation of tacit knowledge about these integrations was taking place, they were never codified into product standards or interface control documents (ICDs) that were published or shared in the industry.

5.9 Opening of Product Architecture

The research and literature review conducted have demonstrated that the product architecture of the aviation training industry, at its 3 different levels, have exhibited a trend towards further closure over the past few years. All three product levels, however, remained modular to support the high variety of products and services tailor-made to satisfy the diverse client needs. At the flight simulation device level, products continue to adopt a closed product architecture with a few competing proprietary designs offered by competing providers. Industry respondents have all confirmed that there has never been any noticeable degree of non-contractual interfacing between simulation components. Even visual systems, which are the most portable components of full flight simulators, require contractual collaboration between the simulator provider and the visual system provider to integrate. This closed architecture has not exhibited any changes in the last 10 years when the simulation technology, at the different levels explained above, have attained maturity.

At the device suite level, the product architecture has exhibited a shift from an open architecture of independent devices, assembled by the client, into an integrated training suite that offers software commonality across its different components. Simulator providers started to architect complete solutions of multiple-level training devices offering consistent training at the same high fidelity level. CAE's Simfinity and FSI's MatriX product lines were amongst the earlier integrated solutions offered (Bangs, 2004).

At the training services level, the architecture has exhibited a similar closing trend from a market segmented into 2 main segments, each with its different suppliers, to an integrated one. *Ab-initio* and air carrier (consisting of type-rating and recurring training) segments were traditionally separate market segments where small aircraft-equipped flight schools catered for the former while large, capital-intensive and simulator-equipped training companies catered for the latter. Two parallel initiatives are changing this open service architecture into an integrated offering spanning the entire training lifecycle of a pilot.

The first initiative is industry-driven and consists of partnerships and backward vertical integration of some air carrier training providers. In 2005 CAE, the second largest player in the training industry, created the CAE Global Academy, a network of A*b-initio* flight schools that collaborate with CAE for providing a similar standard of training to laymen seeking pilot careers. The services of the members of the Global Academy are integrated with those of CAE enabling a complete pilot outsourcing solution for companies where CAE finds, recruits and trains pilots all the way from the initial ground school classroom component to the type-rating and specific operating procedures of the client airline (CAE, 2007). CAE's main competitor, FSI, shortly followed in its footsteps announcing partnership with a flight school for providing integrated ground school for its clients. These partnerships are not mere business partnership agreements as they involve synchronization and harmonization of the training curriculum to bridge gaps and reduce redundancies.

The second initiative that is resulting in closure of the training industry architecture is a collaborative one proposed by an ICAO (International Civil Aviation Organization) panel in 2005. MPL (Multiple-crew Pilot License) is the name given to the new training program currently being formulated by industry forums consisting of experts from regulators, simulator manufacturers, airlines and training providers. Bud Oaster, member of the ICAO panel, says that the MPL "takes a zero-time pilot candidate to airline first-officer in less time and at less cost than traditional methods" (Fiorino, 2005 (2)). To meet the surge in demand for pilots expected over the next few years, the MPL is expected to reduce the pilot training cycle from 45 weeks down to 18 – 26 and from $90,000 - $180,000 down to $75,000 (Fiorino, 2005 (2)). The MPL relies on increasing the pilot's training time spent in the simulator and thus increasing its effectiveness and efficiency, all while providing a seamless integrated service solution to airlines.

5.10 Market Thinness

A review of the annual reports of all the key players in the flight simulation industry between 1991 and 2007 was conducted as a part of this research. This revealed that the number of full-flight simulators, which are the best documented products, ranged between 17 and 47 with an average of 30 simulators per year. Figure 14 shows the number of simulators per year in this period. Priced at between $10M and $15M, the total market size is too thin to justify the existence of specialized component suppliers independently innovating on an open product architecture. This is especially true given the complexity of the components and the R&D investments that are required to satisfy their technical requirements.

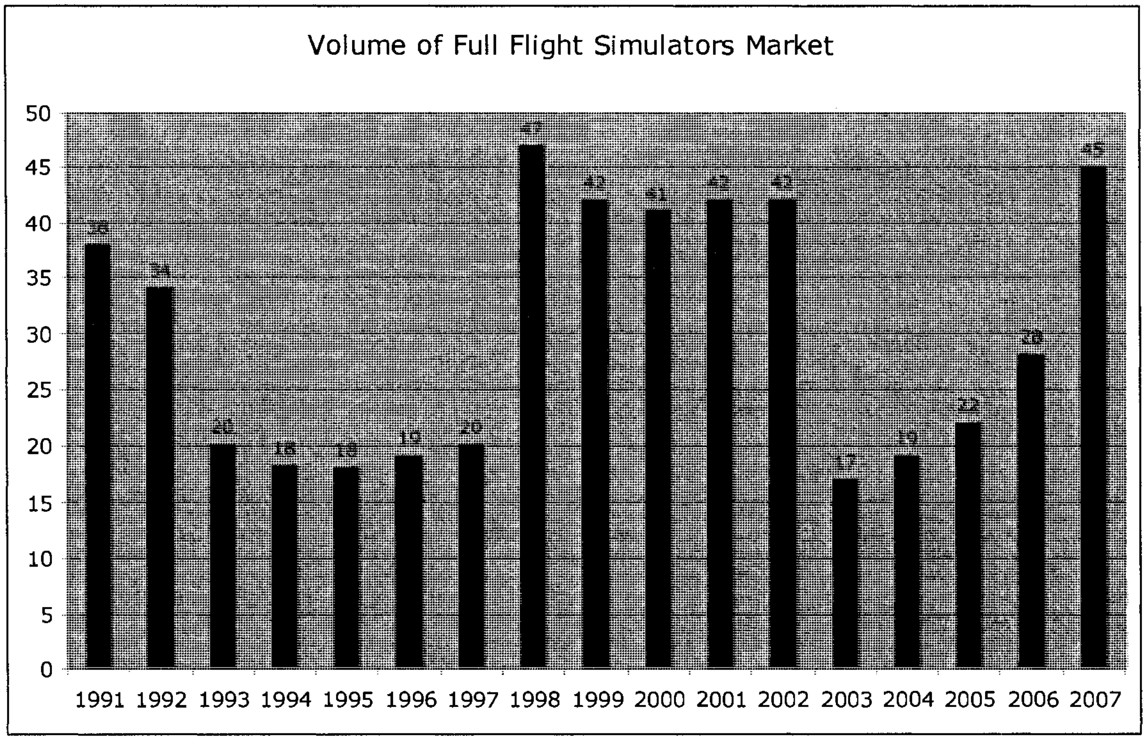


Figure 5.1: The number of full flight simulators produced between 1991 and 2007

The interviews conducted and the industry literature reviewed yielded the answers to the 10 exploratory questions of this research explained above. The following 3 chapters explain in further details the findings of the research with special emphasis on each of the 3 sub-industries identified and their specific trends and changes.

CHAPTER 6 RESEARCH FINDINGS - SIMULATION DEVICES

Following the presentation of the answers to the 10 questions formulated in the research, chapters 6, 7 and 8 present the details of these answers and the findings for each of the 3 sub-industries studied. Each chapter starts with a description of the product of the sub-industry, followed by a description of its architecture. The key trends and changes following technological maturity in the sub-industry were presented next followed by a conclusion about the effects of these trends on the product architecture evolution.

6.1 The Product

The flight simulation device is the primary product of the aviation training industry. Devices are categorized along two performance axes, their fidelity to the aircraft they replicate and the training skills and knowledge they are used to teach. Regulatory authorities worldwide define different criteria and standards for naming and qualifying flight simulation devices. The most widely accepted norms are the FAA's in the US and the JAA's in Europe. Regulations in other countries are mostly derived from either of these two regulatory standards.

6.1.1 Flight Training Equipment

To provide the different types of training mandated by regulators in a safe and cost-effective manner, flight simulation devices are often used extensively. The choice of simulators to use is a function of the type of training needed, cost and the regulatory standards in effect. The FAA standards, for example, define 3 categories of flight simulation devices:

1. Non-aircraft specific flight training devices: these represent the behavior of generic categories of aircraft such as a turboprops or jets. Categorical flight training devices have increasing levels of complexity ranging from level 1 to level 3 FTDs.

2. Aircraft specific flight training devices (FTDs): these are simulation devices that replicate the performance of a specific aircraft type (e.g. an Airbus A320) and a specific airline configuration also known as tail configuration. Aircraft-specific FTDs range from Level 4 system trainers to Level 7 FBSs (Fixed Base Simulators) which lack only the motion system to become FFSs. While popular in the mid 1980's to the mid 1990's, level 6 and level 7 FTDs are increasingly uncommon in training centers due to an increased use of a Level-4 and FFS combination to decrease the capital investments in training equipment.

3. Full Flight Simulators (FFSs): these have the highest fidelity level of simulation devices replicating the aircraft systems, ambient environments, visual cues and motion cues. Full Flight Simulators may be qualified to 4 levels: A, B, C and D. Level Ds are ZFT (Zero Flight Time) devices that faithfully replicate the aircraft performance and are built to replicate an aircraft manufacturer supplied advanced performance data package detailing the aircraft performance in a large number of attitudes within and outside of the normal flight envelope. Level Cs are the next most common FFS especially when the aircraft data package is still under development, as in new aircraft programs, or when the aircraft is too old to have the instrumentation necessary for producing a detailed data package. Level C simulators are non-ZFT and therefore need to be complemented by a level D FFS or actual aircraft training. Level Bs were quite rare until recently when Mechtronix, an emerging simulator manufacturer, started promoting their use as a cost-effective

device for conducting a significant portion of training traditionally conducted on a level D FFS (Anselmo, 2006; Potomac, 2006; Hughes, 2005). Mechtronix' proposal does not eliminate the need for a Level D device as some training procedures need to be conducted in a Zero-Flight Training (ZFT) environment, offered only by a level D, but reduces its market as it claims that 100% of recurrent training and 80% of initial training that are traditionally done on a Level D FFS can be carried out on a Level B. The industry has been quite slow to accept Mechtronix' proposal which started in the early 2000's and it was not until Lufthansa Aviation Training acquired one in 2006 that industry critics and specialists started giving the proposal more serious consideration (Warwick, 2006).

The JAA device guidelines, called the JAR standards, are somewhat similar to those of the FAA consisting of 3 categories:

1. Flight Training Devices (FTDs):

Similar to the FAA framework, JAR standard FTDs are intended for training on systems operation and basic procedures. Unlike the FAA though, there are only 2 levels of FTDs under the JAA, Level 1 and Level 2 and both are aircraft-specific. A JAR Level 1 FTD is comparable to a FAR Level 5 FTD while a Level 2 is comparable to a Level 6.

2. Flight Navigation and Procedures Trainers (FNPTs):

FNPTs have no equivalents under the FAR standards and are primarily geared towards teaching flight maneuvers, procedures and SOPs (Standard Operating Procedures). FNPTs are aircraft-specific and require a high level of simulation fidelity. They also have a visual system to enable out-of-cockpit view training in visual and instrument flying conditions. FNPTs are commonly used for recurrent training to offload time on the full flight simulator.

3. Full Flight Simulators (FFSs):

FFS qualification under the JAR standard is quite similar to that under the FAR. Four levels of qualification exist ranging from the preliminary A level to the ZFT D level.

6.1.2 Product selection criteria

To understand the forces behind the openness or closure of product architecture, it is important to analyze the product selection criteria in the industry and their evolution over the past 10 years. These criteria represent the market's needs from simulation device producers and therefore the driving force behind their product offering. The research has revealed that the following criteria influence buyers' decisions in the equipment industry:

1. Regulation

Satisfying regulatory requirements of pilots' training is essentially the key driver of the flight simulation industry. Following the US legislation permitting the use of flight simulators for training pilots in 1970, the industry has been driven by the training credits that the regulators grant using synthetic simulation devices. The regulators qualification of the device is a function of several variables, namely its satisfaction of the prescribed regulatory requirements, its match with the simulated aircraft performance, the client's satisfaction with its performance, its intended utilization and its positioning within the client's training curriculum. The regulators' requirements are the strongest driver of the customer needs such that the technological maturity of the industry is equivalent to the satisfaction of these regulatory frameworks.

2. Cost

As previously mentioned, customers of flight simulation device manufacturers are either airlines providing training to their own crews or third party trainers using the devices to sell training. In either case, the cost of simulators is a key consideration for these clients as it represents a fixed cost of operation.

Costs of training include three key components: infrastructure and equipment costs, crew pay and travel expenses and finally the opportunity costs of flying the aircraft with passengers.

The cost parameter has had an increasing importance as a selection criterion for airlines and independent training providers in the past few years. Since the events of 9/11 and the drastic downturn that the industry experienced, a record high number of airlines have declared bankruptcy, especially in the US. During these hard times, airlines have been trying to minimize fixed training costs to the minimum possible level while maintaining the crews' licenses to fly. In answering a question about whether airlines have changed their "shopping" habits for training, the General Manager of Lufthansa flight training said:

"They (airlines) now look at other possibilities and try to learn what other airlines are doing in the market and if there is a chance for them, with nearly no reduction in the quality, they tend to want to cut training costs".

This has favored the emergence of lower cost training alternative, such as the level B FFS as well as online delivery of training reducing travel and living expenses and the pilots' time off flying for revenue generation.

3. Pedagogy

The learning value of the flight simulation devices is another key factor that affects their acquisition decisions. While this factor may seem embedded in the regulation frameworks, it has been becoming increasingly distinct differentiation factor as flight simulation providers have attained and started surpassing the regulatory requirements. For some airlines, such as Lufthansa Flight Training, highly customized features and specific demanding requirements ensure the quality and uniformity of the pedagogical service offered to their pilots. Most clients acquire lower-cost standard configurations of flight simulators defined by the aircraft producer or the simulator producer and provide differences training to their pilots to compensate for any differences. Pedagogy-centered airlines, such as Lufthansa, would pay an additional premium to have the simulator replicate their exact aircraft configurations and even acquire maintenance contracts to ensure the continued update of the simulators to follow the evolution of their aircraft fleets.

6.2 Product architecture

A flight simulation device is composed of the following key components:

1. Flight Deck: this is the replica of the aircraft flight deck that is used for training the pilots. Panels, displays and switches range from low-cost approximations to actual aircraft parts depending on the level of fidelity of the simulator and the targeted qualification level.
2. Instructor stations: these are the computer stations on and off the simulator deck, where instructors can manipulate the simulator's systems and environment as well as observe

the students. In full flight simulators, these often consist of 2 stations on deck as well as a few off-deck instructor/engineering terminals.

3. Computer complex: traditionally, the computer complex consisted of an array of mini-computers networked to handle the massive calculations and processing necessary for simulating flight dynamics and the aircraft systems. Commercial off-the-shelf PCs have been increasingly use in the computer complex.
4. Electronics cabinets: these consist of electronic chasses and PCBs (printed circuit boards) hosting the simulation of aircraft systems and flight dynamics as well as some original software of aircraft electronic controllers sometimes.
5. Visual system: consists of image projectors, image generators, a visual host computer and a screen for projecting the out-of-window scene to complement pilots' training with the visual cues. The image generator lies at the core of the system, producing the dynamic image that closely follows the simulated aircraft position and attitude. Visual systems vary significantly from simple flat television screens connected to the image generators to fully integrated visuals depicting high levels of realism in day and night scenery.
6. Motion system: consists of the hydraulic or electric jacks, their controllers and a motion host computer that controls the flight deck movement according to the aircraft performance and operator inputs. Motion systems are often used only on full flight simulators and differ in their levels of complexity and fidelity. Military aircraft and rotorcraft simulators often have the most complex motion systems due to their diverse modes of motion including vibration.

Different simulator manufacturers define and use their own proprietary architectures at both the software and hardware levels. While many boasted their architecture innovations at industry forums, such as the Royal Aeronautics Society conferences, details remain proprietary and confidential. Despite their distinctiveness and appropriation, these architectures have been quite similar primarily due to the inevitable flow of information caused by the labor mobility within the industry (Chesbrough, 2003). The complexity of the simulation technology, and the historical limitations on programming and software architectures have also resulted in similar solutions pursued by the different players evolving over time. The resulting outcome in the industry is a few similar product architectures with no inter-operability or compatibility across the different brands.

6.3 Architecture Evolution – Detailed Findings

In the last 10 years, the aviation industry has experienced several economic pressures that have resulted in diverse effects ranging from consolidation in some segments to a record number of airlines seeking bankruptcy protection. These events have increased price and efficiency pressures on the training industry, which is usually lagging 6 months to a year behind the airlines industry. These economic pressures on the aviation training industry have resulted in the following technological and business trends:

1. *Increased Outsourcing & Off-shoring:*

   In addition to the closed product architecture of all simulator manufacturers, many manufacture the bulk of the components that made their flight simulators. One simulator manufacturer went as far as making its own power bars. However in the past 10 years, with the increased emphasis on off-shoring manufacturing to China and software development to India, manufacturers are increasingly outsourcing. CAE, for example, created a Strategic Sourcing division in 2004 with the mandate of creating and managing a supply chain for reducing the company's in-house manufacturing and hence production costs (Kamel, 2006). The division was headed by a former executive from the aircraft manufacturing industry which is highly dependent on outsourcing. CAE went even to the extent of off-shoring some of its software development by opening a division for visual systems software development in India (CAE, 2005).

It is important to distinguish between outsourcing and off-shoring on one side and opening the product architecture on the other. The increased sub-contracting of sub-assemblies or creation of foreign divisions in low-cost regions does not constitute opening the product architecture as these external entities operate at arm's length under tight contractual frameworks and, more importantly, have no visibility of the overall product architecture. The outsourcing therefore did not result in any changes in the degree of closure of the product architecture.

2. *Emergence of low-cost FTDs*

During the 80's and early 90's, simulator providers mostly competed on their technological capabilities to fulfill and surpass their clients' needs. FFS providers, therefore, competed in the FTDs market by stripping down features and components from top-of-the-line devices to make them comparable to those provided by the competition. This resulted in over-designed devices as the cost of developing simpler technologies combined with the fear of low-quality perception sometimes outweighed those of keeping existing ones from higher-level devices. While these expensive devices did not attract tight-budget airline startups and aviation schools, they appealed to traditional flag carriers due to their high fidelity and compatibility with FFSs.

During the economic downturn of the industry, the increased popularity of low-end FTDs forced the incumbent equipment providers to transform their top-down approach to a bottom-up one. Some companies used creative approaches to reduce the costs of developing new devices that barely meet regulatory standards. This bottom-up trend pushed the incumbents to challenge the traditional interpretation of regulatory standards eventually resulting in the emergence of innovative LCD-based trainers.

In the late 1990's CAE developed LCD-based FTDs, a concept that low-cost entrants experimented with and introduced in the early 1990's. These devices replaced simulated cockpit displays and panels with online representations on touch-active LCDs. The simulation logic and systems performance of both devices were nearly identical while the LCD-based ones were able to offer the following additional auxiliary features:

- LCD-based FTDs could be placed in regular office space without the need for the special flooring and power supplies that traditional FTDs needed;
- It was possible to run online courseware in a 3-D cockpit environment in LCD-based devices due to their graphical switches that are easy to toggle to any particular configuration during the course;
- The selling prices of LCD-based FTDs ranged from $300K to $800K while those of comparable tactile FTDs ranged from $2M to $5M;
- Relocation of the LCD-based FTDs was quite inexpensive and did not necessitate recertification from the regulatory authorities[6].

---

[6] Moving tactile FTDs or FFSs requires re-certification to validate the accuracy of the re-assembled flight controls LCD-based FTDs had graphical representations of controls and were therefore exempt from this requirement.

At the beginning, the absence of the tactile feeling of switches and the auditory cues of toggling them made many suspicious of the possibility of negative training[7]. However, due to their superior economies, low cost airlines were less reluctant to accept them followed by some cash-tight traditional airlines. Northwest Airlines, for example, was the first of the 5 major US carriers to embrace LCD-based FTDs. To respond to negative training concerns from his colleagues, one of Northwest's chief pilots proposed to bolt real aircraft switches to a wood panel and put it outside the FTD for the trainees to familiarize themselves with after their non-tactile training sessions. As Christensen's disruptive innovation theory suggests, the technological and pedagogical inferiority of the non-tactile panels were gradually out-weighed by their cost and flexibility advantages.

3. *Shift of emphasis from FFSs towards integrated solutions*

Following the 1970's regulated use of full flight simulators, the Zero-Flight Time concept was considered as the safest approach in synthetic simulation training. It took until the mid 1980's to regulate the use of FTDs acknowledging that their limited fidelity can still prove useful for training a specific subset of skills and procedures. The training providers' developed distinction between areas of knowledge and process familiarity on one hand and motor skills on the other hand, have permitted an increased reliance on FTDs, especially that they reduce the overall cost of training. The typical configuration of flight training devices used in recurrent training has emerged from complete reliance on the FFS, to a combination of the FFS and several lower level FTDs seamlessly integrated in an integrated suite. The FAA has placed an increased emphasis on regulating these integrated suites fitting the individual devices within the existing frameworks (Philips, 2002).

---

[7] Negative training refers to the possibility that the pilots make a false learning or acquire an incorrect reaction to a cockpit event. The consequences of negative training may prove disastrous in a real flight.

The three trends do demonstrate the industry's behavior and its compliance with the pattern described by disruptive innovation theory at first, with the emergence of low-cost FTDs, but how this did not allow the entrants from displacing the incumbents. Rather, the incumbents were able to respond by leveraging their understanding of the pedagogical aspects of training and the wide scope of their products by offering integrated solutions, thereby shifting the competition away from individual devices and their costs.

6.4 Technological maturity of the industry

Christensen defines technological maturity as the stage when the suppliers are able to meet the needs of the majority of customers in the industry (Christensen, 1997). A few traditional clients will always push suppliers to continue to advance their products for their own specialized needs but for the majority, other considerations such as cost, convenience and size of the product become the key differentiators chosen for.

In the aviation training industry, as explained above, customer needs are mostly driven by the regulatory requirements of training as well as some pedagogic aspects. The industry experts interviewed in this research all concurred that the industry has satisfied the regulatory requirements and, to some extent, pedagogic needs during the last 7 and 10 years ago. It is hard to identify a particular event or year when the industry has attained this stage primarily because of the iterative nature of the majority of its innovations rendering it difficult to pinpoint a particular new product as the answer to the market needs. However, this conclusion is also supported by the observations made above about the emergence of low-end products during a trend of increased emphasis on cost and convenience over quality and technological advancement.

Price has been an increasingly important factor of differentiation due to the economic pressures on the industry discussed above. In the absence of radical technological differences, price has been the key competency of several start-ups in the industry. In fact some simulator providers, such as Mechtornix Systems, openly market their devices almost entirely based on their price merits (Anselmo, 2006). Convenience has also been increasingly in demand as training providers seek to lower their customers' travel bills by providing local and internet-based training facilities. The integrated solutions' seamless update potential has also been a key success factor for the integrated product suites offered on the market.

The observations made above and the interviews with the industry experts all converged to the same conclusion that the industry has attained technological maturity during the last few years. The technological innovation, currently underway, happens in an incremental mode, surpassing the needs of the majority of customers and catering to the few specialized ones.

6.5 Conclusion - Industry architecture

According to Christensen's disruptive innovation theory (Christensen, 1997; Christensen and Raynor, 2003), the technological maturity attained in the industry should have resulted in a shift in the competition away from product quality towards price and convenience. This shift should result, in turn, to an opening of the product architecture in the industry by entrant firms that seek to reduce costs and benefit from the commoditization of the product. Christensen cited the disk drive industry and its eventual architecture opening following the diffusion of the 3.5" disk drives initially slated for laptops and lower-performance machines.

As shown above, the technological maturity of the flight simulation products industry did lead to the emergence of entrants competing on cost and convenience factors rather than the traditional quality and technology axes. Lufthansa flight training, for example, has received new clients from eastern European countries and from China as stated by its General Manager.

However, the emergence of these entrants has failed to open the industry architecture as proposed by Christensen's theory. The flight simulation products continued to exhibit a closed architecture with a few competing proprietary designs in the market. None of the industry interviews, literature, discussion forums or in-field observations has suggested any change in the product architecture in the openness direction. For example, the General Manager of Lufthansa Flight Training describes the situation as follows:

"*...when we buy a new simulator from Thales or CAE there is no standard interface from these manufacturers. So we have to put a lot of effort into it to connect it to another stand alone system. There are a lot of proprietary designs behind the simulators, even if they use standard PCs that can be bought anywhere. Integration of some off-the-shelf parts into the simulator shows how they are very specific. It is not easy to exchange things or redesign something or even add a new element or feature.*"

The following five factors that explain the divergence of this industry from Christensen's model are discussed below elaborating, from the research conducted, their relevance to the peculiar behavior that the industry has exhibited:

1. The high value of accumulated learning in the industry, favoring sustaining to disruptive innovations (Christensen and Raynor, 2003);

   Disruptive innovation theory, as implied by its name, predicts an industry's behavior in response to a disruptive innovation where the incumbents' core competencies are rendered obsolete by new metrics of competition introduced by the entrants. In the aviation training industry, the high traction of accumulated learning makes sustaining innovations the most common and disruptive ones an exception, if possible at all. With every new simulator, the efficiency, track record and competitiveness of its producer are increased, thereby improving its positioning and likelihood to win the next simulator contract available. In an industry where software constitutes between 35 and 65% of the cost of the simulator, the breadth of software libraries that the company has on its shelves can significantly offset its production costs and hence competitive advantage. This innate characteristic of the industry favors the presence of a few large players engaged in a positive feedback loop continuously improving their competitiveness and market share. Most innovations are produced by this oligopoly of producers (Miller & Olleros, 1993) and are therefore sustaining in nature.

For entrants to introduce disruptive innovations, they have to drastically change the way synthetic simulation is done to offset the cost advantages of the incumbents' existing software libraries and hence be able to make commercial success out of their disruptive innovation. Other than Link's initial disruptive innovation that gave birth to this industry replacing aircraft training, no such disruptions have occurred. All changes made were incrementally done through the coordination between suppliers, customers and regulators. This natural bias against disruptive innovation in the industry does not permit the entrants to create cost and convenience value more than their incumbent competitors.

2. The need for regulatory approval of innovations, therefore limiting the influence of the market selection force on disruptive innovation waves;

In Christensen's research on the disk drive industry, market selection forces initially favored quality and technology (represented by storage capacity) until a certain inflection point where the market preferred criteria such as cost and convenience instead (Christensen, 1997). This then launched the sequence of events leading to the opening of the product architecture. In the aviation training industry, the tight regulation of the devices required (before they create value to their customers) puts an intermediary layer between the market pull forces and the suppliers' response. The slow pace of evolution of the regulations and their aversion to risk slows down the market's influence on product selection forces and reduces the chances that they occur too fast for the incumbents to react.

3. The expertise level of all the industry customers and their involvement in the design and building of the simulation products, also undermining the effect of market selection forces present in Christensen's model:

   Customers of the flight simulation equipment industry are quite involved in the design and building of their devices. Some customers possess sophisticated internal capabilities developed over the years of acquiring and maintaining simulation devices that they are capable of modifying or updating their own simulation equipment. The heavy involvement of customers in the definition of their products puts them in more direct touch with their suppliers and therefore hindering entrants' introduction of disruptive innovations that meet customers' needs but that incumbents were not responding to.

4. The market thinness (i.e. the insufficiency of production volume for the emergence of a component supplier base to transfer the modularity from the product to the industry):

Despite the current modularity of the flight simulation device within the proprietary desisgns, the total number of simulators sold per year is too small to lure many competitors into the simulator components market. For example, the FFS market has historically ranged between 12 and 49 simulators sold annually. This market volume is too small to be divided amongst more than a handful of players. For generic components, most suppliers overcome the small market by being involved in other larger markets, such as military simulation or commercial applications, to justify their economics. For example, Barco, the key supplier of projectors for most FFS visual systems, is also diversified in the media & entertainment, medical, education and transportation industries (Barco, 2007). For specialized components, however, the market is too small to justify the presence of competing component suppliers and therefore these are usually manufactured by the simulator integrators themselves.

5. The public safety and legal liability considerations involved in aviation training that make an open architecture a potential security threat:

An open architecture permits the dissemination of information and public access to interface standards. It also shifts part of the onus of quality control in product integration from system integrators to the market forces. These two factors, information availability and reduced control on quality, may expose the public to safety hazards and airlines to consequent legal liability. In an industry where the possibility of negative training is deemed to be an unacceptable risk, losing control over product quality is not a viable scenario. This risk may not seem to be a key decision criterion for airlines but it is certainly one that regulators are sensitive to.

The above factors and specificities have influenced the industry's behavior not to fit with Christensen's model of disruptive innovation, leaving the product and industry architectures closed at the simulation device level.

CHAPTER 7 RESEARCH FINDINGS - THE SIMULATION PRODUCTS SUITE

7.1 Definition

The simulation products suite can be defined as the complete set of tools and synthetic training devices used to train crews on operating and maintaining aircraft. A suite is composed of three categories of components: simulation devices, training aids and curriculums. Simulation devices are the synthetic trainers replicating aircraft performance at varying degrees of fidelity. Training aids are other electronic or non-electronic tools used as pedagogical aids for explaining aircraft behavior to trainees. Examples of training aids include actual aircraft parts that are used for maintenance trainees to assemble and disassemble. Curriculums are the descriptions of which simulation devices and training aids will be used for obtaining a certain level of regulatory qualifications or acquiring a certain skill.

7.2 Regulation

Regulatory authorities qualify a training provider's curriculum first before qualifying any particular devices within it. This is to ensure the overall cohesiveness of the different components of training and their collective satisfaction of the regulatory training requirements. Following the curriculum qualification, each individual device is qualified based on its fulfillment of the regulatory requirements corresponding to its target qualification level. Therefore, even though there is no training products suite qualification per se, it is taken into consideration by the regulators in the qualifications of the individual training devices.

7.3 Product selection criteria

The research has shown that training providers' decisions in acquiring a training products suite are influenced by the following factors:

7.3.1 Training Market Segment

Different training providers cater to clients from different niches or market segments. Lufthansa, for example, often caters to quality-seeking airlines and flag carriers and has therefore been traditionally known for its heavy use of full flight simulators to maximize fidelity to the aircraft throughout the trainee's sessions. The General Manager of Lufthansa Flight Training said about the experience they try to deliver to their students: "*...they need to touch and feel the essence of the real aircraft cockpit.*"

Flight Safety, on the other hand, has the largest installed base of business jet simulators in the industry and is therefore more dependent on FTDs to minimize the overall costs for their more cost-sensitive trainees. The training provider's market segment is therefore a key parameter in its choice of a training suite and the breakdown of its different components.

7.3.2 Total Cost

The costs incurred, for acquiring a training product suite, were traditionally optimized either by changing its composition or the price tags of its individual components. As the composition is linked to the training provider's market segment and regulatory approval, the individual prices of training devices are often the lever used to control the cost of the training suite. Training providers also have varying price sensitivities for the different components of the suite. Decisions on full flights, for example, are not as easily swayed by price variations as FTDs and DTDs are. The level of sophistication of the training conducted on the full flight, and hence its overall impact on liability and training quality, is higher than specific mission FTDs.

7.4 Traditional Product Architecture

Aviation training suites were traditionally custom-built with their composition and architecture varying based on the training provider's market position, type of aircraft trained and clients' business models. Independent training providers, also referred to as third party providers, often make their training suites as generic as possible to accommodate the largest number of aircraft configurations of their clients, minimizing differences training and simulator changes. This not only affects the configuration[8] of the full flight simulators purchased but more importantly results in more reliance on flexible flight training devices within the suite. Equipment fleets of airline training facilities, on the other hand, are usually less accommodating and more specific to the airline's aircraft fleets.

Irrespective of the specificity of the training suite, it was traditionally made up by combining different level devices made by different suppliers around a training curriculum as shown in figure 10 above.

7.5 Recent Industry Trends

Similar to the case of training products, changes in the external economic and technological environments have affected the industry and its architecture at the product suite level. These external changes and their effects are described below.

1. Integrated Sourcing:

---

[8] Tail configuration is a term referring to the way a particular airplane is setup. Avionics controllers, optional features and some cockpit panels may vary between different tail configurations of the same aircraft. Airlines usually order several airplanes with the same tail configuration to maximize fleet commonality and facilitate maintenance.

The difficulties that the airlines industry has experienced over the past few years has resulted in increased cost awareness and consequently increased price pressures on the upstream training industry. Terrorism, SARS, and war have amplified the airline industry's difficulties with maintaining the hub-and-spoke model devised in the 1970's. The increased efficiency pressures on training providers have therefore resulted in efforts to better manage costs through supply chain consolidation (Kamel, 2006). This has given a competitive edge to simulation product companies that are able to provide complete integrated suites of training products that reduced transaction and support costs.

2. Computing technologies

The latest advances in computing technologies have bridged the gap between computers used in simple desktop simulation devices and those used in full flight simulators. This computing platform compatibility has enabled companies to affordably offer software commonality across different devices of a training product suite. Not only does this reduce the negative learning side-effect but it also reduces the costs of fleet updates to match aircraft changes.

3. Emphasis on overall training value

The technological maturity attained by synthetic simulation devices has been increasingly shifting the focus of clients and regulators from technological features of simulation devices to the pedagogical value that they create. The quality of a training provider's product suite is increasingly measured by what it can help students to learn rather than the technological features of its individual components.

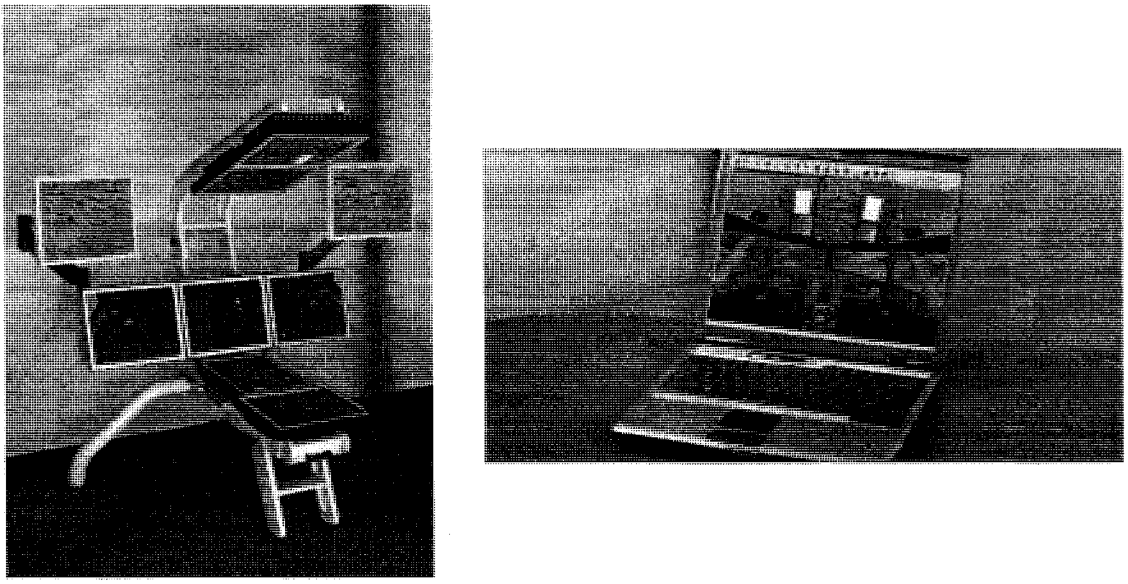
7.6 Maturity & evolution of the industry architecture

The configuration of the training suite was traditionally decided by the airline or the training provider using different equipment from different suppliers as explained above. This has been gradually transforming into integrated solution offerings made by the large incumbent simulator manufacturers such as CAE and Thales. As the simulation devices matured technologically, these companies started to offer integrated training solutions that address their clients' needs beyond the technological level. The maturity of the simulation and computing technologies allowed running high fidelity simulation models, which formerly needed mainframe computers, on desktop PCs and hence permitted building the integrated solutions containing different levels of devices all sharing the same simulation models' fidelity.

In 1999, CAE launched a new business unit called Integrated Training Solutions (ITS) with the mandate of developing lower-level simulation devices[9] (CAE, 2000). By the end of 2001, the new division launched the IPT (Integrated Procedures Trainer), the VSIM (Virtual Simulator) and SBC (Simulation-Based Courseware). Pictures of these devices are shown below in Figure 11.

---

[9] Lower-level simulation devices refer to synthetic simulation equipment of lower fidelity and hardware complexity than the traditional full flight simulators (FFSs) or flight training devices (FTDs). Equipment such as LCD-based cockpit trainers, desktop virtual simulators and PC-based courseware are examples of lower level simulation devices.



CAE Simfinity™ IPT (Gulfstream V)

Figure 7.1: CAE's Integrated Procedures Trainer (IPT) and Virtual Simulator (VSIM)

These PC-based devices were built based on a common core architecture where the high fidelity flight models and systems simulation from full flight simulators were ported onto a PC environment to run with simulated graphical displays of the cockpit interface. The virtual simulator created (termed VSIM) was the core layer of the new devices with each device consisting of the VSIM and different combination of other components built on top of it. The VSIM allowed pilots free-play practice of flight procedures and systems operation at the same simulation fidelity level as the full flight simulators yet at a small fraction of the cost. Integrated Procedure Trainers (IPTs) consisted of a VSIM whose panels were divided amongst touch-sensitive LCDs spatially orientated to resemble a cockpit configuration. Special hardware actuators (such as engine throttle levers or control columns) may be added in response to special client requests to add tactile fidelity to the IPT. Simulation-Based Courseware (SBC) was also introduced consisting of a VSIM with an additional instructional layer of narration, instructions and performance-based evaluation tests on top. All the various devices were built by adding different layers on top of the same simulation core that powers the hardware simulations and panels used on high fidelity full flight simulators. Figure 12 below depicts the common-core architecture of the integrated training suite that CAE offered.

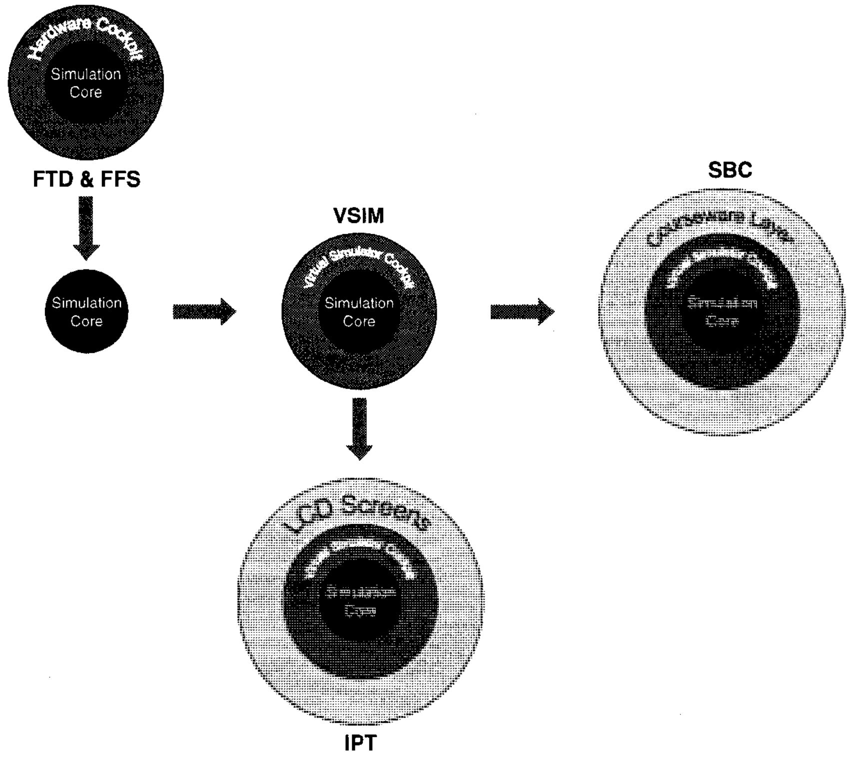


Figure 7.2: Graphical depiction of the common-core configuration of CAE's integrated products training suite

After CAE, Mechtronix launched MatriX and FlightSafety introduced the Integrated Architecture. This has switched competition to complete platforms instead of individual products. The commonality of the simulation core across the different devices of the training suite did not only improve the quality of the overall training but also made updating the simulation software easier and less costly.

In 2003, following the success and increased adoption rate of the integrated training suite concept, CAE launched its Advanced Training Curriculum: a training methodology based on the integrated training suite (CAE, 2007). An integrated training solution was created by the combination of the advanced curriculum and the integrated training suite of products. Some airlines that formerly configured their own training suites were starting to show interest in the integrated solution. This allowed them to acquire a turn-key solution that provides higher quality of training and ease of updates, all at a lower cost. The traditional approach of assembling the suite from different suppliers satisfied the needs of clients and was in use for approximately 15 years. The new one however, not only satisfied regulatory requirements but exceeded them by providing pedagogical value, cost efficiency and ease of maintenance and updating. It is hard to determine whether the new integrated solution exceeded clients' expectations or merely fully satisfied them as opposed to the former compromise solution. However, it is evident that the maturity of the simulation technology and its satisfaction of clients' needs have created the opportunity for suppliers to go beyond individual devices and offer integrated solutions with closed proprietary architectures that satisfy clients needs more than their predecessor client-assembled ones. The technological maturity of simulation and computing technologies resulted in closure of the product's architecture as the incumbents leveraged their accumulated learning and coordination capabilities to close the architecture and capture value.

7.7 Conclusion

Unlike the simulation device industry where the technological maturity did allow the emergence of low-cost entrants in the industry, the technological maturity of the suite level only allowed the incumbents to introduce their integrated solutions. This is primarily because the FFS components of the suite and the innovative integration know-how are beyond the capabilities of incumbent low-level device manufacturers, let alone new entrants. The accumulated learning that the big players possessed permitted them to reconfigure the simulation devices around the new proprietary closed architectures.

CHAPTER 8 RESEARCH FINDINGS - AVIATION TRAINING SERVICES

8.1 Definition

Aviation training services is at the downstream most position in the aviation training industry offering training to flight and maintenance crews of airlines and other aircraft operators. The industry emerged as flying became more commonplace and regulated. The industry has been traditionally divided into two distinct sub-industries: *ab-initio* training on one hand and recurring & type-rating training on the other. The *ab-initio* sub-industry teaches "laymen" the basics of airmanship up to the point when they can attain a private or a commercial flight license. The latter caters to commercially licensed pilots by providing them with specific-aircraft training in the case of type-rating, or the periodic refresher training required for maintaining their licenses. The growth of the training services industry and the flight simulation industry was triggered when the US Air Force acquired Edwin Link's PilotMakers to train its military pilots for delivering mail in 1934 (Rolfe and Staples, 1986). Since then, the training services industry has grown to become an $8 Billion industry in 2001 and the flight simulation industry $500 Million one (Velocci, 2001)

Ab-initio training service providers are generally small operators that make little or no use of simulation technology. Light single propeller aircraft is typically the first step for students of these schools following their classroom ground school training. Since the mid 1980's some of the more sophisticated schools have acquired low-cost flexible flight training devices (FTDs) provided by some lower-level device manufacturers, such as Frasca International (Frasca, 2007).

Recurring and type-rating training has been traditionally conducted by airlines at their own training facilities. As commercial airlines started to become more popular in Europe and the USA after World War II, they started to build their own training facilities increasingly using the simulation technologies available at the time. As these facilities grew, some airlines' leveraged their excess capacity for generating revenues by training other airlines. Some even went to the extent of spinning off their training providers to operate them as profit centers to offload their huge financial burdens. Lufthansa Flight Training is one of the most successful of these service-provider spin-offs that has been independently operating since 1997. Other dedicated flight schools, such as Schreiner, FlightSafety and Simuflite, also emerged catering to one of the following 3 categories of pilots:

1. Additional needs of traditional airlines in excess of their own centers caused by seasonal needs, hiring campaigns and cash flow constraints;
2. Small or regional airlines whose economies do not justify investing in creating a training center;
3. Business or private jet pilots who do not belong to any airline but still need the training for maintaining their pilot licenses.

8.2 Regulation

Regulators have to approve a service provider's training curriculum, along with the product suite and facilities that go along with it. FAA Part 142 licenses are granted to training centers that meet the detailed requirements covering qualification metrics ranging from the training curriculum to the qualifications of the training center's management.

8.3 Product selection criteria

The product selection criteria for both sub-sections of the training services industry are very different as they cater to different markets, different clientele and are therefore described separately below.

For the *ab-initio* market, clients are individual students seeking private or commercial licensure. The criteria most relevant to them therefore are:

1. Cost: the costs of the full training, including both the ground school and the minimum flight hours, may range from \$90,000 to \$180,000 depending on the geographical location, sophistication of training aircraft and licenses sought[10] (Fiorino, 2005(1)). Students normally finance these costs individually through personal savings, family support or bank loans. The Executive Director and the Director of Sales at Oxford Aviation Training indicated that some flight schools gain a competitive advantage in the marketplace by providing convenient financing options through partnerships with financial institutions. The General Manager of Lufthansa confirms as he notes that the margins have decreased by up to 20% to attract customers, whose "*main requirement right now is to reduce the cost*".
2. Reputation of School and Partnership with Airlines: a significant portion of *ab-initio* flight students aim to make a career out of flying and are therefore conscious of their employment prospects when choosing the flight schools. Some flight schools have traditionally maintained strong relationships with major airlines supplying them with their new hire pilots needs. Oxford Aviation Training, for example, has traditionally

---

[10] Typically students get first a VFR private license that allows them to fly during day time but not for commercial profit. An IFR license is obtained next allowing increased reliance on instruments and hence night flying. A multi-engine license is then sought before a commercial license is granted allowing pilots to fly commercially with passengers.

supplied British Airways with new pilots. In more recent years the school has made similar partnerships with growing low-cost airlines such as Ryainair, EasyJet and Thomas Cook. The airlines are given the opportunity to interview students at the beginning of their careers and pre-select a number of candidates based on their character profiles and aptitude tests. The school then provides airline-specific courses to these students for training them on procedures such as the airline's SOPs (standard operating procedures) and emergency procedures. Such partnerships have proved quite beneficial to all parties involved: to increase the students' employment perspectives, to allow airlines to secure future human resources and save on their initial training costs and to give the school a competitive advantage amongst its competitors.

3. Quality of training: the quality of the training facilities, instructors, aircraft and simulation instructional devices are other differentiating factors for flight schools in attracting students. Some schools pride themselves in operating Level 4 FTDs to better prepare their students for real flying. However, most schools use little or no flight simulation given their high initial investment and operating costs compared with single propeller engine aircraft traditionally used for training.

For Recurring and Type-Rating training, clients are typically airlines and commercial aircraft operators seeking to attain and maintain regulatory approvals of their flight crews at the highest efficiency level possible. The main selection criteria for these clients are:

1. Availability of specific training: flight training centers provide training on wide-body, regional and business jets using FFSs and FTDs as well as other instructional tools. The availability of the simulation devices as well as the type-rating and competencies of the

instructors determine the training center's ability to offer training on a particular aircraft type and hence attract clients operating that aircraft. Furthermore, airlines also seek training providers whose simulation devices are configured similarly to their aircraft fleets. The flight-deck configuration, avionics suite used and the particular options available on the simulator may render it in close resemblance to the aircraft configuration of a particular carrier thus more efficient for that carrier to use. Differences between the airline's aircraft configuration and that of the simulators are usually covered through difference training courses offered to pilots following their simulator sessions. Some training centers acquire re-configurable full flight simulators where different hardware and software kits can be re-loaded to change the aircraft configuration reflected by the simulators and thus appeal to more clients. Lower-level simulation devices are often less complex to reconfigure due to their lower fidelity level and less hardware content.

2. Cost: in the wake of the economic hardships that the airline industry has faced in the past few years, cost has been an increasingly important factor in the selection of training providers. The economic recession in 2001, followed by the terrorism events of 9/11, SARS in the Far East, the wars in Asia and the record-high prices of fuel have imposed further constraints on an already-strained traditional industry operating a hefty hub-spoke model facing serious competitive threats from a few low-cost point-to-point airlines. These circumstances have resulted in several of the world's major airlines and flag carriers to declare bankruptcy or at least announce major re-organization schemes. Even for the most profitable airlines though, the inevitable overhead costs of training constitute a significant cost of their total revenues. Airlines are therefore increasingly conscious of their training costs composed of their simulator operation costs as well as other expenses such as wages of personnel during training and travel and living expenses.

3. Quality: the quality of the training offered is a key selection criterion of training providers. The quality of facilities, instructors, simulators and value-add services may significantly influence an aircraft operator's choice of training provider.

8.4 Product architecture:

The different training services that make part of an entire training program have been traditionally loosely connected with regulatory approval. Students seeking to pursue pilot careers follow *ab-initio* training in one of the numerous flight schools, alongside private license seekers. While some simulation is sometimes available, flight schools rely heavily on light single-crew, single-engine cockpit aircraft hours to fulfill regulatory flight requirements. Pilots complete their commercial license requirements with between 140 and 180 hours of real flight, 40 to 50 hours of simulator time and approximately 60 hours of ground school time. They are then expected to accumulate between 1500 and 1700 flight hours before airlines will consider their candidacy. This additional flight experience is often gained in flight schools, instructing student pilots, or flying light general aviation aircraft, such as regional carriers in remote areas or pesticide-spraying aircraft. The pilots' need for these hours renders their working during this period quite hard. It is during this period that most pilots quit the domain and just maintain their private licensure for leisure purposes. Some pilots avoid this path by joining the armed forces and flying for the military. An Air Canada pilot interviewed describes his circumstances during this period:

> "...I flew a small regional aircraft up North for 18 cents a mile. My role included most of the aircraft-related tasks from doing the pre-flight checks around the aircraft, to fueling it to preparing coffee for the passengers before

> take-off. Some other pilots flew for free. Airlines know that you need the hours so they don't pay you for flying. You almost have to pay them."

Upon accumulation of these additional hours, a pilot may be recruited as a first-officer in an airline, flying to the right hand side of a more experienced captain. The airline career then starts for this pilot including sporadic type-rating training sessions and periodic recurring training sessions to maintain airmanship. In summary, pilots go through four different phases of pilot training: a*b-initio*, experience-gaining, type-rating and recurring.

The tools, instructors, methodologies and curriculums are typically not aligned together except at the level of their pedagogical objectives dictated by the regulatory authorities. The self-reliance attitude and dial cockpit skills acquired in the first two phases have to be replaced with multi-crew cooperation skills and typically the ability to manage a computerized cockpits centrally controlled by a flight management computer. Suppliers of the training at different phases did not need to communicate amongst themselves or coordinate their services any more than strictly adhering to the training standards published by the regulators. The resulting open-architecture service provided the pilot with the skills and knowledge that the regulators intended without any need for collaboration or cooperation between providers of complementary services.

8.5 Recent Industry Trends:

In the past few years, the efficiency and effectiveness of the traditional flight training cycle (the industry's open architecture setup) has been increasingly questioned. Several concurrent trends, in the industry and its surroundings, have fuelled this debate:

1. Economic pressures on airlines:

As mentioned above, airlines have experienced increasing economic pressures over the past few years. The 9/11 terrorist attacks, SARS, the wars in Asia and the Middle East have all had a negative impact on the demand for flying. Low-cost and no-frill airlines have increased this economic challenge by offering a more efficient alternative to the hub-and-spoke system. The result was an increasing pressure on airlines to lower their human resources costs mostly crew salaries and training costs. The efficiency of overall training and the costs incurred during its learning-unlearning cycles were therefore highly scrutinized.

2. The out-sourcing trend of airlines:

The rapid surge in the number of small low-cost airlines in recent years has also resulted in the growth of the independent training services industry. These airlines often do not have the necessary scale to justify investing in their own pilot training facilities and therefore resort to outsourcing to independent trainers or airlines with excess capacity in their facilities. This has attracted many players in the industry, such as simulator manufacturers CAE and Thales and aircraft manufacturers, like Boeing, to enter the training market through establishing their own training centers. It also gave room for existing players, such as FlightSafety International to grow. Training service providers are therefore becoming increasingly efficient and are developing the necessary scale and accumulated learning to attract even the established large airlines whose training fleets are becoming obsolescent or who need more training than what their facilities can provide. The net result is a significant growth in the outsourcing of training in the industry over the past few years, and hence increased competition and pressures on efficiency.

3. Vertical Integration of Training Providers:

In recent years, the two traditionally segregated sub-industries of *ab-initio* and professional training have experienced increased amalgamation. Some *ab-initio* trainers, such as Oxford Aviation Training in the UK, have taken the initiative to coordinate with major airlines to synchronize their training syllabuses providing seamless training for students. The airlines are invited to pre-select student pilots based on interviews and aptitude tests. These are then given airline-specific training as well as their standard courses.

The other concurrent trend in recent years has been the partnership of *ab-initio* training schools with independent professional training providers. CAE, the world's second largest training provider, has made a series of partnership agreements with *ab-initio* flight schools in Europe, North America and Asia (CAE, 2007). The company is therefore capable of providing end-to-end training to its clients enabling them to outsource their entire training function with improved quality and at reduced costs.

4. Retirement of the Baby-Boomers generation of pilots:

Similar to many other domains, the retirement of baby-boomers, looming since the beginning of the 21st century has alerted many to the upcoming need to train new pilots fast enough to replace them. Industry forecasters estimate the need for 140,000 new pilots in the 2002 to 2012 period (Fiorino, 2005(2)). At the current duration of 18 to 26 months to complete ab-initio training only, let alone the consequent months spent in acquiring the necessary flying time to be considered by a regional airline, the industry is believed to be unable to fulfill its staffing needs over the next few years. This shortage is also attributed to the airlines traditional absence at the early stages of pilot recruitment and training. Oxford Training

Services' program of collaboration with airlines at the *ab-initio* phase is still considered innovative in an industry that has had a surplus of licenses pilots for the past few decades.

5. Multi-Pilot License (MPL) Working Group:

The Multi-crew Pilot License (MPL) is an ICAO initiative that is currently being formulated by a forum of industry experts from airlines, aviation training providers, simulation providers and regulatory bodies (Lekic, 2007). The new license integrates the multi-crew glass cockpit skills in the initial *ab-initio* pilot training. The ICAO website states that the license "allows a student pilot to exercise the privileges of a co-pilot in commercial air transportation on multi-crew aeroplanes" (ICAO, 2007). Rather than learning single-crew cockpit skills only to unlearn them in a multi-crew setting, the MPL accelerates the program by putting the student in the cockpit he/she will most likely fly right away. The program is also intended to allow more use of simulation technologies early-on in the training cycle (Fiorino, 2005(2); Lekic, 2007).

The MPL is estimated to reduce training costs and duration by approximately 50% and thus enable the industry to meet the high demand for pilot that emerging markets like China and India have created (Fiorino, 2005(2); Lekic, 2007; Chennai, 2005). Simulation and training providers have already positioned their services to accommodate the MPL. Mechtronix Systems has announced that its Integrated Training Architecture (ITA) will enable MPL training (Mechtronix, 2007) while Alteon, the training subsidiary of Boeing, has announced that it will be graduating the first 6 MPL-licensed pilots (Alteon, 2007).

The MPL harmonized the ab-initio portion of flight training with the air carrier portion. The former has traditionally been conducted in isolation using light single-engine aircraft with little or no change over the past 100 years (Fiorino, 2005(1)). The maturity of the simulation technology though has created the impetus for "modernize training because simulation devices are now so sophisticated that they can be used in most of it" as Captain Jean Benoit Toulouse, an Air France pilot mandated with in creating a French MPL program, says (Lekic, 2007). The technological maturity of the industry has therefore resulted in closing the architecture of the training services around the pedagogical element of pilot training.

In summary, the integration of the training services architecture is taking place through 2 distinct movements as illustrated in figure 13. The MPL, encouraged by the technological maturity of simulation technologies, is harmonizing the *ab-initio* with the type-rating and recurrent training allowing training providers to offer turn-key training. Parallel to that, training providers in air carrier market are vertically integrating backwards into the lucrative *ab-initio* market due to its prospected growth opportunities over the next few years. Both movements are bridging the gap and closing the product architecture of the training services industry into one where integrated training solutions are made available for airlines.

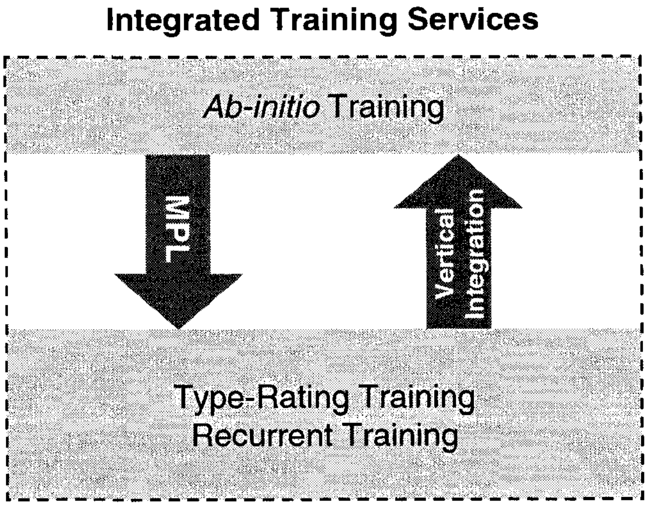


Figure 8.1: Parallel movements by MPL and vertical integration resulting in closing the product architecture of aviation training services.

8.6 Conclusion

The efficiency and effectiveness of the traditional open architecture of the aviation training industry is currently being questioned. A new closed architecture is emerging for increasing the speed and training quality of pilots to bridge the gap between the supply and demand foreseen over the next few years. The industry incumbents, such as CAE, are leveraging their expertise in the pedagogical aspect of training and are offering seamless training, across all phases, that makes more intense use of simulation technologies. This trend only emerged following the industry's attainment of technological maturity and the satisfaction of the clients' needs and the regulatory guidelines for simulation technologies. The resulting confidence in the simulation fidelity was also the driving force behind the MPL working group's guideline of increasing the use of simulation technologies throughout the new integrated training program.

CHAPTER 9 DISCUSSION

Disruptive innovation theory has been one of the most influential themes in the last few years. With roots in the disk drive industry (Christensen, 1998; Chesbrough, 2004), the theory has been extended to attempt to interpret various trends and phenomena in several other industries (Christensen *et al*, 2004). The theory predicts that when industries mature technologically and incumbent suppliers start to exceed mainstream customer expectations in favor of their large accounts with specialized customers, new entrants find the opportunity to provide lower-cost products that barely meet mainstream customers or that appeal to non-customers to enter the market. As these become the mainstream, the entrants displace the incumbents out of the market shifting competition from technological advancement towards other parameters such as low cost or flexibility. In an attempt to increase their efficiency in the new market dynamics, entrants open the product architecture shifting the technological advancement pressures upstream to their component suppliers. Eventually as the new open architecture matures, the entrants - now the incumbents - face disruptive pressure themselves from new entrants offering a new product architecture that they cannot compete with. This pushes back the industry in integration mode to compete at the architectures level until one is chosen by the market thereby launching its maturity journey. This alternation between open and closed product architectures is triggered by the maturity of the technology within the framework of a product architecture.

The validation of applicability of this theory to other industries was then attempted in "*Seeing What's Next: Using the Theories of Innovation to Predict Industry Change*" (Christensen *et al*, 2004). An example of an industry analysis was the aviation industry and the rise of the low-end regional jet manufacturers (Christensen *et al*, 2004). Christensen argued that regional jets started as the low-end disruptive innovations that started to encroach on the mainstream industry and threaten the incumbents, namely Boeing and Airbus. In response to this disruption and to ensure a sustainable market position, three options were presented to the incumbents: 1. Develop a small airplane internally to compete, 2. Create a subsidiary company capable of introducing a regional jet, 3. Buy a regional jet provider and allow it to operate independently to gain a foothold in the emerging low-end market. Four years have passed since this book was published and Boeing has not pursued any of the options suggested but yet continues to be the world's largest aircraft provider. Moreover regional aircraft has not been able to replace, or at least significantly eat away from the market share of, wide-body aircraft. The inherent flaw in Christensen's analysis, which can now be proven in retrospect, is the confusion between two distinct market segments and a rising low-end market. The regional jets market was never a low-end segment of the wide-bodies aircraft that was encroaching on its market share. For airlines, both wide-bodies and regional jets are important components of their fleets that cater to two types of routes, long-haul and short-haul respectively. Indeed, they can be likened to a bus and a taxi car in the vehicles fleet of a transportation company. Each is a different vehicle for a different type of service and different clientele. The fact that regional jets became more popular consequent to the airlines industry downturn in 2001 is attributed to 3 main reasons that are quite distant from technological innovation:

4. Airlines were trying to maximize their loading on the short-hauls in light of the prevalent fear of flying, that many passengers developed, and the subsequent decrease in passengers' volume in domestic and short-haul flights. Using a 100-seater regional jet with 80% loading was more efficient that using a 200-seater with 40% loading.

5. Large airlines and flag carriers were more actively seeking to exploit smaller routes that may be more profitable for recovering their losses on the international ones that they still had to operate although at a loss. This shifted their focus towards better-suited aircraft for these routes.
6. With the sudden surge in insurance and fuel prices and the subsequent increase in airline ticket prices, consumers became more interested in low-cost and no-frills airlines. This boost in demand for these airlines which fly standard point-to-point short-haul routes resulted in a corresponding surge in demand for regional aircraft. This was not encroaching, at least to a significant degree, on the market for larger wide-body aircraft since the majority of passengers are not likely to change their destinations as a function of price and the two categories of aircraft types (wide-body and regional) are not interchangeable for the majority of routes.

Other than the recursive reference to disruptive innovation theory to interpret the change, the book did not offer proofs of its applicability to the aviation industry. In fact, history has shown that the surge in regional jet sales, observed by Christensen, was nothing more than a transient shift that soon died returning the market quite close to its pre September 11th distribution of regional and wide-body jets.

The research presented above tested the applicability of this cyclical model in complex product industries using the aviation training industry as a case study. The key steps and constructs of the industry were listed and ten exploratory questions were listed against them for verifying their applicability in the case of CoPS industries. Where divergence was hypothesized between the theory and the behavior of CoPS industries, a reason for the divergence was hypothesized based on preliminary observations from the industry. Five hypothesized reasons for divergence emerged. In chapter 5, the answers to the ten questions from the research were presented and in the subsequent chapters, their particularities for each of the three sub-industries studied were also presented. The five hypothesized reasons for divergence are revisited below in light of the research questions answered above.

1. The need for regulatory approval of innovations.

It has been shown that regulatory requirements are one of the strongest determinants of customer needs at various levels in the industry. Regulations determine the duration, simulation equipment used and skills acquired at every phase of pilot training starting from the preliminary *ab-initio* training to the advanced type-rating and recurrent training. Regulations also qualify the entire training products suite in light of the training curriculum it supports as well as the individual training devices that it contains. Attaining the technological needs of mainstream clients is therefore equivalent to satisfying the regulatory requirements behind them.

These regulatory requirements also act as filters of innovation as they only allow new products and technologies complying with them to create value for the end users. This not only limits the emergence of disruptive technologies but also slows down the process of bringing innovations to the market. In fact, in the strict sense of disruptive technologies (ones that render the core competencies of the incumbents obsolete), there have not been any disruptive innovations throughout the history of the industry. The majority of innovations was incremental and introduced by the incumbents themselves. The entrants' new designs and concepts were merely challenging the classical interpretations of certain clauses of the regulations and offering lower cost alternatives to satisfy them. The incumbents were always able to match the new products, though, offering better quality and more features by leveraging their existing software libraries and diversified product portfolio. The incumbents' response was also helped by the slow process of introducing innovations that the regulatory qualifications impose.

For example, the process of qualifying the new LCD-based FTDs (called IPTs) to level 4 took CAE around 2 years. The innovative concept of using touch-sensitive LCDs was first introduced by WICAT, a low-level device producer. After seeing it at WICAT, an airline training director asked CAE if they can produce a similar device at a comparable price. After months of planning for the new product, CAE launched the new FTD and announced its intention to qualify it to a level 4. The process started with finding a client to sponsor the technology and demonstrate its value within his own training curriculum to the authorities. Then CAE started a lobbying process with the authorities to challenge the classical interpretation of the requirements using tactile panels (original aircraft or simulated) to satisfy the "cockpit panels" requirement in level 4 FTDs. Once this was completed, the regulators' test pilots tested the machine and wrote a detailed report that was presented to the authorities and CAE with necessary changes to be made to certain features. Some of these changes required developing new technologies before the regulators came back for a final inspection and approval of the device. Throughout this period, both WICAT and CAE continued to market the device to different customers and at various industry trade shows. It was not long before all the other suppliers in the industry had their different versions of the technology. The 2 years time lag did not allow the disruptive technology to fly under the radar of the incumbents. On the contrary, the incumbents' strong relationships with the regulators and their proven track record accelerated their qualification process compensating for the delay in launching the new concept FTD.

2. *The direct involvement of clients in the design of products and services*

Most airline clients have built significant expertise in simulation technologies over the years. The involvement of customers such as Swissair, Lufthansa or KLM in the product design of their simulation devices has reached the extent of their engineers helping with the debugging of the simulation source code. This intimate involvement allows sufficient communication of needs and expectations between the clients and the simulation product providers allowing the latter to respond promptly to needs and expectations. This type of "pull" market does not provide sufficient room for unnoticed overshooting of the needs of mainstream customers. Unlike consumer electronic products where suppliers can only rely on marketing and sales information to identify the needs and expectations of the market, suppliers in CoPS industries are in direct communication with their expert clients and are often well guided by them throughout the product lifecycle.

3. *Public safety and risk liabilities*

Public safety has been one of the key reasons behind the emergence of the synthetic simulation industry. As mentioned above in the historical background section, Link's own safe landing at Newark airport was instrumental for winning the contract with the US Air Force. Safety and public liability considerations continue to be at the forefront for regulators and government authorities in charge of aviation. For aircraft operators, simulation providers and trainers, the fear of negative, or faulty, training entails the safety aspect without having to go as far as considering its potential catastrophic failure consequences. This fear of negative training also reinforces the competitive position of the incumbents' tested technologies and hampers the industry's acceptance of innovations introduced by entrants lacking this proven track record.

4. *The sustaining value of accumulated learning*

Accumulated learning of the suppliers in the industry has a major effect on their competitiveness. It improves the market's perception and confidence in the company, its ability to amortize its development investments and its skills in systems integration. In an environment where building a simulator is a complex project that spans 12 to 24 months at a cost of tens of millions of dollars, the company's proven track record is essential for gaining the customers' confidence. In addition to the market's perception of accumulated learning, a company's possession of the simulation software can reduce its cost of developing a simulator by 20 to 50%. The large investment that companies make in developing the simulation models of a particular aircraft type make economies of scale an important factor in its competitiveness. Every additional simulator allows further amortization of the development investments. Therefore, accumulated learning increases the path dependence of companies' competitiveness and helps to reinforce their strategic position against low-cost entrants competing for market share. Accumulated learning also increases the suppliers' integration skills and gives it a strong competitive edge especially in projects where the customers are more quality-concerned than cost-sensitive. In aircraft development programs, for example, airframe manufacturers have always chosen one of the two largest suppliers in the industry to work in parallel with them on developing the first generation simulators for delivering the entitlement training on the new aircraft. These programs are extremely complex and require iterative development of simulation models for every revision of the aircraft configuration and controllers. The airframe manufacturers' level of confidence in the simulator suppliers again plays an important role as the formers use the simulator as a test-bed for design modifications to the aircraft. Accumulated learning therefore is a key competitive advantage of the incumbents and a barrier to entry for new entrants.

5. The thinness of the market

CoPS industries, by definition, are unique complex products that involve several orchestrated suppliers. This makes market thinness also an intrinsic characteristic of these industries. For some industries, component technologies may be used in several applications. Suppliers in such industries leverage their R&D investments and high development costs across several industries to remain profitable. For example, providers of steel beams used in building bridges are often also involved in commercial and domestic construction as well giving them the business volume necessary for survival. For the aviation industry, this leveraging across different industries is significantly reduced by the regulatory requirements that the suppliers have to comply with. These compliances are quite costly and are of no value outside the industry. In fact, except for general parts, such as screws and nuts, most specialized components used to make a flight simulator are quite specific to the industry. They often resemble aircraft components in form, fit and function but are more complex in their interface and controllers to allow them to simulate reality. With an average market volume of 30 products per year, it is quite uncommon to find a supplier of specialized components, such as simulated avionics controllers for example, who is not a systems integrator as well. This type of thin markets does not lend itself to architecture openness where a network of specialized suppliers independently produces innovative components based on a set standard.

According to disruptive innovation theory, industries evolve into an open architecture as their products mature technologically (Christensen, 1998) and that this transformation from a closed architecture to an open architecture is cyclical along the lifecycle of the industry (Chesbrough, 2004). The implicit assumption behind this theory is that the closure of the technological architecture is not an inherent trait of the industry but rather a function of its technological maturity which is turn is relative to its customer requirements. When industries are still on their way towards maturity, their technological architectures are still closed and are therefore in need of integration at the firm level. As they mature, their modularity increases to a level that allows integration to be managed at the industry level. This relativity of the interdependence of technological architecture has been an implicit assumption in the studies of Christensen, Chesbrough and others who studied consumer electronics and similar appliance industries (Christensen, 1997; Chesbrough, 2004).

The aviation training industry has diverged from this pattern. Its closed product architecture has persisted throughout its technological maturity evolution history. In fact, the only change it has exhibited has been towards further closure as demonstrated above. The factors favoring closure, studied above, point to the inherent need for a firm to actively assume the integrator role for managing the high number of components and disciplines needed to build a complex product industry. These factors are the regulation, the accumulated learning, the direct involvement of clients, public safety and risk concerns and market thinness.

While the above presented research is insufficient to prove the inherence of architecture closure in CoPS industries, it is sufficient to disprove that architecture closure is a function of the technological maturity phase in all industries. The exception provided by the aviation training industry demonstrates that some of the implicit assumptions of disruptive innovation theory may not be applicable to at least some industries. The characteristics of CoPS industries need to be thoroughly analyzed before any further conclusions can be made about their categorical exception from the existing theory.

CHAPTER 10 CONCLUSIONS, LIMITATIONS & FURTHER RESEARCH

10.1 Conclusions

The research presented in this thesis has demonstrated that complex product system (CoPS) industries do not necessarily fit with disruptive innovation theory as proposed by Christensen and Chesbrough. Through a study of the aviation training industry spanning 4 years, the industry was observed to attain, and begin to exceed, the technological maturity needed by its clients. This, however, did not result in low-level market entrants to take over the mainstream segment of the market as the theory suggests. Furthermore, no openness of the product architecture was observed at any of the product levels. In fact, the industry is moving in the direction of further closure of its products, suites and training programs.

In a complex industry where collaboration is a key to innovation, the disruptive innovations introduced by industry entrants had to be coordinated with the various industry players and therefore failed to fly under the radar of the incumbents. Mainstream clients and regulators continued to be heavily involved throughout the design and build lifecycle of the product therefore leaving little room for disruptive innovation. More importantly, the incumbents' accumulated tacit and codified knowledge, in the form of coordination skills and simulation software libraries, allowed them to close the industry architecture further around their pedagogical competencies offering turn-key training solutions for their clients and off-setting the cost advantages that the low-cost entrants offered.

The disruptive innovation theory, therefore, is not adequate for predicting the pattern and consequences of disruptive technologies on players in complex product industries. A generalized theory needs to pay special attention to their particular features such as collaboration, accumulated learning, customer involvement in design and market concentration.

10.2 Limitations

The main limitation of this research is that a single industry was studied and found to be an exception to disruptive innovation theory. This is not sufficient for building an alternative theory to be formulated to describe the behavior of CoPS industries in response to technological maturity. A more comprehensive research encompassing multiple industries from different games of innovation is needed.

10.3 Recommendations for Further Research

Christensen's disruptive innovation theory was built from single-case inductive research focused on the disk drive industry, which is a consumer technological product. While theoretical sampling[11] is adequate for constructing a theory about disruptive innovation, its generalizability will be quite limited (Eisenhardt and Graebner, 2007). A multiple-case study would have provided a stronger base for theory building (Yin, 1994) especially if the cases covered a diversified carefully-selected array of product and industry architecture configurations across different innovation games (Eisenhardt and Graebner, 2007).

Therefore a multiple-case research is needed to build a robust theory of disruptive innovation whose constructs, propositions and their underlying logical arguments are more widely applicable and permit broader exploration of research questions. This broader investigation of industrial cases has to occur early-on at the theory formulation stage while using additional cases to amplify

---

[11] Theoretical sampling means that decisions about which data to collect next are determined by the theory in progress (Eisenhardt and Graebner, 2007)

the analytical power (Eisenhardt and Graebner, 2007) rather than what Christensen et al tried to achieve by applying the single-case theory to a wide array of industries and trying to fit the theory to their observations and their interpretations (Christensen *et al*, 2004). The research presented above has revealed that games of innovation could form an interesting basis for selecting the cases to cover different patterns of behavior in response to technological maturity.

Games of innovation are classified based on 2 principal axes: product architecture and market lifecycle stage. On the product architecture axis, products from stand-alone product industries (such as medication pills for example) and products from modular product industries (such as the PC software industry) are needed. Together with the aviation training industry, these industries will cover the variety of product architectures intrinsic to the product, i.e. integral or modular and the special case of modular products which is tightly integrated products. The latter does not lend itself to architecture openness due to some of the factors identified in the research such as liability risks, direct involvement of clients and high value of accumulated learning.

The other axis of games of innovation that should serve as a guide for industry sampling for building a global theory of disruptive innovation should be the market maturity phase. At the beginning of the industry lifecycle, while there is still a performance gap between the products and the needs of the mainstream clients, industries are still in the technological race phase. As the market matures and technology attains the needs of the mainstream clients, some industries are commoditized, others evolve towards services while others get concentrated around new niches of the mass markets. These categories should form the guide for the other 3 industries needed for the uniform sampling of industries necessary for building a universal theory of disruptive innovation. The seventh game identified (i.e. innovation support) can be represented by a business consulting or accounting firm supporting the overall production and operations.

The other venue for expanding this research is towards building a theory of disruptive innovation in CoPS industries. While the research presented above confirms an exception to the prevalent theory, it does not provide an alternative due to its single-case nature. A multiple-case research on complex industries would help reach such an alternative model by investigating the consequences of technological maturity on CoPS industries that have different combinations of the five divergence reasons studied in this research. Studying other industries that, for example, are not regulated but have directly involved clients, high liability risks, high value of accumulated learning and have think markets would reveal the impact of singling out the regulation factor on the product architecture and its evolution consequent to product maturity.

10.4 Management Implications

There are two main lessons that can be drawn from this research for management, one that is broad and another that is more specific to managers in CoPS industries. The broad lesson is that a lot of management theories are not universal and are therefore not applicable for all industries and throughout different evolution phases. The characteristics of the industry and sector, where the research leading to the theory was conducted, need to be taken into consideration to understand the theory and its applicability to other industries. For CoPS industry managers, this research demonstrates that value creation is often achieved by understanding the needs of the end consumer, in the case of aviation training the pilot, and offering turn-key solutions that create value for that end user. Along this path, knowledge accumulation is key as it strengthens the company's competitive position.

BIBLIOGRAPHY

ABERNATHY, W.J., and CLARK, K. B. (1985). Innovation: Mapping the Winds of Creative Destruction. *Research Policy*, 14, 3-22.

ABERNATHY, W.J., and UTTERBACK, J. (1978). Patterns of Industrial Innovation. *Technology Review*, 2, 40-47.

ACHA, V. (2004). Technology Frames: The Art of Perspective and Interpretation in Strategy. *SPRU Electronic Working Paper Series*, SPRU, Sussex, UK, Paper no. 109.

ADAMS, W. J. and YELLEN, J. L. (1976). Commodity Bundling and the Burden of Monopoly. *Quarterly Journal of Economics*, 90, 475-498.

AGARWAL, R. and GORT, M. (2001). First-Mover Advantage and the Speed of Competitive Entry, 1887-1986. *Journal of Law and Economics*, 44(1), 161 – 177.

AGHION, P., and HOWITT, P. (1998). *Endogenous Growth Theory.* MIT Press, Cambridge, Massachusetts.

ANSELMO, J. C. (2006). A little Competition. *Aviation Week & Space Technology*, 165(22), 53.

AUTRY, N. (2002). CAE will Supply Aviation Training Services. *Aviation Week & Space Technology,* 156(20), 68.

BALDWIN, C. Y. and CLARK, K. B. (2000). *Design Rules - Vol. 1. The Power of Modularity.* MIT Press, Cambridge, Massachusetts.

BANGS, K. (2004). Outlook: Flight Training More Distance Learning, More Simulator Offerings, and Development Training as Well. *Business & Commercial Aviation*, 95(2), 44 – 46.

BANGS, K. (2004). Outlook: Insurance An Improved Short-Term Outlook. *Business & Commercial Aviation*, 95(2), 42 – 43.

BARGIGLI, L. (2005). *An Evolutionary Model for the Dynamics of Vertical Integration and Network-Based Production.* White Paper, University of Sussex, UK.

BARNEY, J. B. (1986). Strategic Factor Markets: Expectations, Luck and Business Strategy. *Management Science*, 32, 1231 – 1241.

BARRON, D. (2003). Evolutionary Theory. In *Oxford Handbook of Strategy, Volume I: A Strategy Overview and Competitive Strategy* by David O. Faulkner and Andrew Campbell (Eds). Oxford University Press.

BAUMOL, W. J. (2001). When is inter-firm coordination beneficial? The case of innovation. *International Journal of Industrial Organization*, 19, 727-737.

BELL, G. (2005). Clusters, Networks and Firm Innovativeness. *Strategic Management Journal*, 26(3), 287-295.

BENOFF, D. (2003). Maintenance Training, Bombardier Style: A New Curriculum and a New Simulator Reserved for Technicians only Underscore a New Emphasis on Training Maintenance Personnel. *Business and Commercial Aviation.* 92(1), 85-87.

BORDEN, N.E, (1968). Air Mail Emergency 1934: An Account of 78 Days in the Winter of 1934 When the Army Flew the United States Mail. The Bond Wheelwright Company, Freeport, Maine.

BRADY, T., DAVIES, A., GANN, D., (2005). Can Integrated Solutions Business Models Work in construction? *Building Research and Information*, 33, 571-579.

BRADY, T., DAVIES, A., GANN, D., (2005). Creating Value by Delivering Integrated Solutions. *International Journal of Project Management,* 23, 360 - 365.

BRANDENBURGER, A.M., and NALEBUFF, B.J. (1995). "The Right Game: Use Game Theory to Shape Strategy". *Harvard Business Review on Managing Uncertainty*, 67-105.

BRUSCO, S., (1982). The Emilian Model: Productive Decentralization and Social Integration, *Cambridge Journal of Economics*, 6, 167 – 184.

BRUSONI, S. (2003). Authority in the Age of Modularity. *SPRU Electronic Working Paper Series*, SPRU, Sussex, UK, Paper no. 101.

BRUSONI, S., MARENGO, L., PRENCIPE, A. and VALENTE, M. (2004). The Value and Costs of Modularity : A Cognitive Perspective. *SPRU Electronic Working Paper Series*, SPRU, Sussex, UK, Paper no. 123.

BRUSONI, S. and PRENCIPE, A. (2005). Making Design Rules: A Multi-Domain Perspective. *SPRU Electronic Working Paper Series*, SPRU, Sussex, UK, Paper no. 136.

CAE Annual Reports. 1965-2004. CAE Inc. Consulted between 2005 and 2007 on http://www.cae.com/

CARR, N. G. (2008). The Google Enigma. *Strategy + Business Magazine*. Booz Allen Hamilton.

CHENNAI. (2005). Indian Aviation Boom: The Myth and Reality. *Businessline*. July 4th, 2005.

CHESBROUGH, H. (2003). *Open Innovation, The New Imperative for Creating and Profiting from Technology*. Harvard Business School Press, Boston.

CHESBROUGH, H. (2004). Towards a Dynamics of Modularity—A Cyclical Model of Technical Advance. In *The Business of Systems Integration*, edited by Andrea Prencipe, Andrew Davies and Mike Hobday (Eds). Oxford University Press.

CHRISTENSEN, C. (1998). Strategies For Survival in Fast-Changing Industries. *Management Science*, 44(12), S207 -S220.

CHRISTENSEN, C. M., (1997). *The Innovator's Dilemma.* Harper Business Essentials.

CHRISTENSEN, C. M., ANTHONY, S. D. and ROTH, E. A. (2004). *Seeing What's Next: Using Theories of Innovation to Predict Industry Change.* Harvard Business School Press, Boston.

CHRISTENSEN, C. M., and RAYNOR, M. (2003). *The Innovator's Solution.* Harvard Business School Press.

CHRISTENSEN, C. M.; RAYNOR, M; and VERLINDEN, M. (2001). Skate to Where the Money Will Be. *Harvard Business Review.* Harvard Business School Publishing Corporation.

COLLIS, D. J. (1994). Research Note: How Valuable Are Organizational Capabilities. *Strategic Management Journal*, 15, 143-152.

CONNER, K. (1991). A historical comparison of the resource-based theory and five schools of thought within industrial organization economics: Do we have a new theory of the firm? *Journal of Management*, Sage Publications, 17, 121 - 154.

CUSUMANO, M. A. and GAWER, A. (2003). The Elements of Platform Leadership. *Engineering Management Review*, 31(1).

DAVIES, A. (2001) *Integrated Solutions – The New Economy Between Products and Services*, SPRU – Science and Technology Policy Research.

DAVIES, A. (2004). Integrated Solutions—The Changing Business of Systems Integration. In *The Business of Systems Integration*, edited by Andrea Prencipe, Andrew Davies and Mike Hobday (Eds). Oxford University Press.

DAVIES, S., (1979). *The Diffusion of Process Innovations*, Cambridge University Press, Cambridge.

DOSI, G., HOBDAY, M., MARENGO, L., and PRENCIPE, A. (2004). The Economics of Systems Integration—Towards an Evolutionary Interpretation. In *The Business of Systems Integration*, edited by Andrea Prencipe, Andrew Davies and Mike Hobday (Eds). Oxford University Press.

DUNCAN, J. C. and FETERLE, L. C. (2000). The Use of Personal Computer-Based Aviation Training Devices to Teach Aircrew Decision Making, Teamwork, and Resource Management. *Proceedings of the IEEE 2000 National Aerospace and Electronics Conference*, Dayton, Ohio, pp. 421 – 426.

EISENHARDT, K. M. and GRAEBNER, M. E. (2007). Theory Building from Cases: Opportunities and Challenges. *Academy of Management Journal*, 50(1), 25 – 32.

ESLER, D. (2002). Outlook: Technology Drives Training; Trainers and Expanding and Updating Facilities, and Flight Departments are Concerned about Training Costs. *Business & Commercial Aviation*, 91(2), 54 – 56.

FANG, H. and NORMAN, P. (2003). To Bundle or Not to Bundle. *Cowles Foundation Discussion Paper.* Cowles Foundation for Research in Economics. Yale University, New Haven, CT.

FARROW, D. R. (1997) The Expanding Role of Lower Fidelity Simulation Technologies in Aviation Training. *Proceedings of the 1997 IEEE Sixth Conference on Global Perspectives of Human Factors in Power Generation*, IEEE, Orlando, Florida, pp. 16/1 – 16/6

Federal Aviation Administration. FAA Historical Chronology. On the website of the *Federal Aviation Administration.* [On-line]. http://www.faa.gov/aboutfaa/History_Chron.cfm (Page consulted 20 July 2006)

FIORINO, F. (2005). MPL Training. *Aviation Week & Space Technology.* 163(21), 56.

FIORINO, F. (2005). Sum of FAA Parts. *Aviation Week & Space Technology*, 162(6), 59 – 60.

FOSTER, J. (1997). The Analytical Foundations of Evolutionary Economics: From Biological Analogy to Economic Self-Organization. *Structural Change and Economic Dynamics*, 8, 427-451.

FREEMAN, C. (2003). A Schumpeterian Renaissance? *SPRU Electronic Working Paper Series*, SPRU, Sussex, UK, Paper no. 102.

GALBRAITH, J. R. (2002). Organizing to Deliver Solutions. *Organizational Dynamics*, 31(2), 194-207.

GARUD, R., KUMARASWAMY, A, and Langlois, R. N. (2003). *Managing in the Modular Age, Architectures, Networks and Organizations*, Blackwell Publishing.

GAWER, A., and CUSUMANO, M. (2002). *Platform Leadership: How Intel, Microsoft and Cisco Drive Industry Innovation.* Harvard Business School Press.

GEORGE, F. (2003). Getting the Most Out of Your Simulator Training Pre-enrollment Preparation: Skills, Practice and Extra Effort Pay Off During Part 142 Training. *Business & Commercial Aviation.* 92(4), 93 – 97.

GEORGE, F. (2003). Outlook: Training More Capacity and New Programs from the Trainers. *Business & Commercial Aviation*, 93(2), 42.

GEROSKI, P. (2003). The Evolution Of New Markets, *Oxford University Press.*

GEROSKI, P. (2000) "Models of technology diffusion", *Research Policy*, 29, 603-625.

HAMEL, G. and PRAHALAD, C.K. (1994). *Competing for the Future.* Harvard Business School Press, Boston.

HAMEL, G. and PRAHALAD, C.K. (1990). The Core Competency of the Corporation. *Harvard Business Review*, 33, 79-91.

HANNAN, M. T. and FREEMAN, J.H. (1977). The Population Ecology of Organizations. *The American Journal of Sociology*. 82, 929-964.

HUGHES, D. (2005). Lower-Cost Simulators for Low-Cost Airlines. *Aviation Week & Space Technology,* 162(16), 72.

IMECHE. Aerospace Industry Overview. On the website of the *Institute of Mechanical Engineers*. [On-line]. http://www.imeche.org (Page consulted in April 2006)

International Civil Aviation Organization. FAA Historical Chronology. On the website of the *International Civil Aviation Organization*. [On-line]. http://www.icao.int (Page consulted August 2006)

JOHNSON, S. B. (2004). Systems Integration and the Social Solution of Technical Problems in Complex Systems. In *The Business of Systems Integration*, edited by Andrea Prencipe, Andrew Davies and Mike Hobday (Eds). Oxford University Press.

KAMEL, M. (2005). Evolution of Architecture and Innovation in the Aviation Training Industry, *Proceedings of the Flight Simulator Conference*, Royal Aeronautical Society, London, UK.

KAMEL, M. (2006). Collaboration for Innovation in Closed System Industries: The Case of the Aviation Industry. *Engineering Management Journal*, 18 (4), 16-22.

KAMEL, M and MILLER, R. (2004). The Evolution of Games of Innovation in Regulated Complex Industries: The Case of Aviation Training. Proceedings of the International Mechanical Engineering Congress and Exhibition. American Society of Mechanical Engineers (ASME), Anaheim, CA, November 04.

KANDAMPULLY, J. (2002). Innovation as the core competency of a service organization: the role of technology, knowledge and networks. *European Journal of Innovation Management*, 5 (1), 18-26.

KATZ, J. S. (2005). Indicators for Complex Innovation Systems. *SPRU Electronic Working Paper Series*, SPRU, Sussex, UK, Paper no. 134.

KINDLEBERGER, C. P. (1983). Standards as Public, Collective and Private Goods. *Kyklos International Review for Social Sciences*, 36 (3), 377-396.

KING, L. (2001). Canada's CAE buys Simuflite. *The Daily Deal*, New York, December 18th, 2001.

KRETSCHMER, M. (1998). Game Theory: The Developer's Dilemma, Boeing vs. Airbus. *Strategy + Business Magazine*, Second Quarter, 1998, Reprint No. 98212.

KWON, T.H. and ZMUD, R.W. (1987), Unifying The Fragment Models Of Information Systems Implementation, in Boland, R.J. Jr and Hirscheim, R.A. (Eds), *Critical Issues in Information System Research*, Wiley, New York, NY, pp. 227-51.

LANGLOIS, R. N. (2003). The Vanishing Hand: The Changing Dynamics of Industrial Capitalism. *Industrial and Corporate Change,* 12 (2), 351-385.

LARSON, G. C. (2006). Why Simulators are so Darned Good. *Business & Commercial Aviation,* 99 (4), 44-48.

LAVITT, M. O. (1998). PC-Based Trainers Help Students Build IFR Time. *Aviation Week & Space Technology*, 148 (23), 64.

LEKIC, S. (2007). New Pilot Training Plan Sparks Worries, *Associated Press Online*, Brussels, Belgium, Aug 22nd 2007.

MALERBA, F. (2006). Innovation and the Evolution of Industries. *Journal of Evolutionary Economics*, 16, 3-23.

MANSFIELD, E. (1968). *Industrial Research and Technological Innovation.* W.W. Norton, New York.

MCPHERSON, J. M. (1983). An Ecology of Affiliation. *American Sociological Review*, 48, 519–35.

MILLER, R. and OLLEROS, F. (2008). The Architectural Imperative in Managing Innovation. *Research & Technology Management*, Industrial Research Institute, May – June 2008.

MILLER, R., and OLLEROS, F. (1993). Internally Coherent System of Innovation: The Case of Flight Simulation. American Institute of Aeronautics and Astronautics. AIAA Flight Simulation and Technologies Conference. Monterey. pp. 12-28.

MILLER, R., HOBDAY, M., Leroux Demers, T., and OLLEROS, X. (1995) Innovation in Complex Systems: The Case of Flight Simulators, *Industrial and Corporate Change*, 4, 363–400.

MINTZBERG, H., AHLSTRAND, B., and LAMPEL, J. (1998). Strategy Safari: A Guided Tour through the *Wilds of Strategic Management.* The Free Press. New York.

NELSON, R. R., and WINTER, S.G. (1982). *An Evolutionary Theory of Economic Change.* Belknap Press, Harvard University, Massachusetts.

NELSON, R. R., and WINTER, S.G. (1997). An Evolutionary Theory of Economic Change. In *Resources, Firms, and Strategies: A Reader in the Resource-Based Perspective*, edited by N. J. Foss (ed). Oxford University Press.

NESTA, L. and MANGEMATIN, V. (2004). The Dynamics of Innovation Networks. *SPRU Electronic Working Paper Series*, SPRU, Sussex, UK, Paper no. 114.

NEUMAN, J.V., and MORGENSTERN, O. (1944). *Theory of Games and Economic Behaviour.* Princeton University Press. West Sussex.

NORDHAUS, W. D. (1969). *Invention, Growth and Welfare.* MIT Press, Cambridge, Massachusetts.

NORDWALL, B. D. (2001). Technology Ushers in a Simulation Revolution. *Aviation Week & Space Technology*, 154 (3), 450 – 452.

OLIVA, R. and KALLENBERG, R. (2003). Managing the Transition from Products to Services. *International Journal of Service Industry Management*, 14 (2), 160-172.

OLLEROS, X. F. (2007), The Power of Non-Contractual Innovation, *International Journal of Innovation Management*, 11 (1).

Opinicus. Corporate profile. On the website of Opinicus. [On-line]. http://www.opinicus.com (Page consulted June 2006)

PARNAS, D. L. (1972). On the Criteria to be Used in Decomposing Systems into Modules. *Communications of the ACM,* 15, 1053-1058.

PAVITT, K. (2004). Specialization and Systems Integration—Where Manufacture and Services Still Meet. In *The Business of Systems Integration*, edited by Andrea Prencipe, Andrew Davies and Mike Hobday (Eds). Oxford University Press.

PETERAF, M. A. and BARNEY, J. B. (2003). Unravelling the Resource-Based Tangle. *Managerial and Decision Economics,* 24. 309-323.

PHILIPS, E. H. (2002). FAA Proposes Major Shift in Regulating Simulators. *Aviation Week and Space Technology,* 157 (23), 54–55.

PORTER, M.E. (1980). *Competitive Strategy: Techniques for Analyzing Industries and Competitors*. The Free Press. New York.

PORTER, M.E. (1985). *Competitive Advantage: Creating and Sustaining Superior Performance*. The Free Press. New York.

PORTER, M.E. (1990). *The Competitive Advantage of Nations*. The Free Press. New York.

PORTER, M.E. (1998). Clusters and the New Economics of Competition. *Harvard Business Review*. Harvard Business Press, Boston.

PORTER, M. E. and RIVKIN, J. W. (2000). Industry Transformation. *Harvard Business School Notes*. Harvard Business School, Rev: July 10, 2000.

PORTER, M. E. (2007). Understanding Industry Structure. *Harvard Business School Notes.* Harvard Business School, Rev: August 13, 2007.

POTOMAC (2006). Canadian Simulator Maker Uses Discards from Arizona Desert. *Regional Aviation News,* 24 (9), 1.

PRENCIPE, A. (2004). Corporate Strategy and Systems Integration Capabilities—Managing Networks in Complex Systems Industries. In *The Business of Systems Integration*, edited by Andrea Prencipe, Andrew Davies and Mike Hobday (Eds). Oxford University Press.

PRENCIPE, A. (2004). Change, Coordination and Capabilities. *SPRU Electronic Working Paper Series*, SPRU, Sussex, UK, Paper no. 120.

RAYNOR, M. E. and CHRISTENSEN, C. M. (2002). Integrate to Innovate: The Determinants of Success in Developing and Deploying New Services in the Communications Industry. *Deloitte Research.* Deloitte Consulting and Deloitte & Touche LLP.

ROBERTSON, P. L. and LANGLOIS, R. N. (1995). Innovation, Networks and Vertical Integration. *Research Policy*, 24, 543-562.

ROGERS, E. M. (1962). *Diffusion of Innovation.* New York, Free Press of Glencoe.

ROGERS, E. M. (1986). Three Decades of Research on the Diffusion of Innovation: Progress, Problems, Prospects. Paper Presented at the DAEST Conference, Venice, April 1986.

ROGERS, E. M. (2003). *Diffusion of Innovation,* The Free Press. New York.

ROLFE, J.M., and STAPLES, K. J. (1986). *Flight Simulation.* Cambridge University Press. New York.

ROSENKOPF, L. and TUSHMAN, M. (1998). The Coevolution of Community Networks and Technology: Lessons from the Flight Simulator Industry. *Industrial and Corporate Change*, 7 (2), 311 – 346.

SAPOLSKY, H. M. (2004). Inventing Systems Integration. In *The Business of Systems Integration*, edited by Andrea Prencipe, Andrew Davies and Mike Hobday (Eds). Oxford University Press.

SCHMIDT, G.M., and DRUEHL, C.T. (2005). Changes In Product Attributes And Costs As Drivers Of New Product Diffusion And Substitution. *Production and Operations Management*, 14 (3), 272-285.

SCHUMPETER, J.A., (1934). *The Theory of Economic Development.* Harvard University Press. Cambridge, MA.

SELZNICK, P. (1957). *Leadership in Administration.* Harper & Row, New York.

SHEPHERD, C. and AHMED, P. K. (2000). From Product Innovation to Solutions Innovation: A New Paradigm for Competitive Advantage. *European Journal of Innovation Management.* 2, 100-106.

SHIBATA, T., YANO, M. and KODAMA, F. (2005). Empirical analysis of evolution of product architecture Fanuc numerical controllers from 1962 to 1997. *Research Policy,* 34, 13-31.

SIMON, H., FASSNACHT, M., and WUBKER, G. (1995). Price bundling. *Pricing Strategy & Practice*, 3 (1), 34-45.

SIMON, H. A. (2004). The Architecture of Complexity. In *Managing in the Modular Age. Architectures, Networks and Organizations*, by Garud, Kumaraswamy and Langlois (Eds), Blackwell Publishing, pp. 15-44.

SPANOS, Y.E., and LIOUKAS, S. (2001). An Examination into the Causal Logic of Rent Generation: Contrasting Porter's Competitive Strategy Framework and the Resource-Based Perspective. *Strategic Management Journal*, 22 (10), 907-934.

STONEMAN, P. and KARSHENAS, M. (1995). Technological Diffusion. In *Handbook of the Economics of Innovation and Technological Change.* Stoneman, P. (Ed). Oxford, Basil Blackwell.

STREMERSCH, S and TELLIS, G. (2002). Strategic Bundling of Products and Prices: A New Synthesis for Marketing. *Journal of Marketing*, 66 (1), 55 – 72.

TEECE, D.J., (1987). Capturing Value from Technological Innovation: Integration, Strategic Partnering, and Licensing Decisions, *Technology and Global Industry*, National Academy Press, Washington DC.

TIDD, J. and HULL, F. (2002). Organizing for Service Innovation: Best-Practice or Configurations? *SPRU Electronic Working Paper Series*, SPRU, Sussex, UK, Paper no. 77.

ULRICH, K. T. (1995). The Role of Product Architecture In The Manufacturing Firm. *Research Policy,* 24, 419 - 440.

US Centennial of Flight Commission. History of Flight. On the website of the *US Centennial of Flight Commission.* [On-line]. http://www.centennialofflight.gov/index.cfm (Page consulted July 2006)

UTTERBACK, J. M. (2007). Innovation and Industrial Evolution. Excerpted from *Mastering the Dynamics of Innovation.* Harvard Business School Press, Boston, MA.

VELOCCI, A. L. (2001). CAE Pursues Multiple Paths to Sustain Growth. *Aviation Week and Space Technology,* 154 (8), 58.

VELOCCI, A. L. (2001). Simuflite buy Pivotal for CAE. *Aviation Week & Space Technology,* 155 (26), 151.

WARWICK, G. (2006). Lufthansa Low-Cost Order will Test Industry Opinion. *Flight International*, 169 (5032), 25.

WERNERFELT, B. (1984). A Resource-Based View of the Firm. *Strategic Management Journal,* 5, 171-180.

WILKINSON, N. (2005). *Managerial Economics: A Problem-Solving Approach.* Cambridge University Press.

WISE, R. and BAUMGARTNER, P. (1999). Go Downstream – The New Profit Imperative in Manufacturing. *Harvard Business Review.* Harvard Business School Publishing Corporation.

XU, J. and QUADDUS, M. (2005). A Six-Stage Model For The Effective Diffusion Of Knowledge Management Systems, *Journal of Management Development*, 24 (4), 362-373.

YIN, R. K. (1994). *Case Study Research: Design and Methods (2nd edition).* Sage Publications, Newbury Park.

ZOLLO, M. and WINTER, S. G. (2002). Deliberate Learning and the Evolution of Dynamic Capabilities. *Organization Science*, 13 (3), 339-351.

APPENDIX A DATA SOURCES

Interviews Conducted

#	Position	Company
1	Director	AAMSI
2	General Manager	Aerospace Industrial Development Corporation
3	Director, Flight Training & Standards	Air Canada Jazz
4	Director, Business Operations	Alteon Systems
5	Manager of Operations	BAE Regional Aircraft
6	General Manager	Becker Avionic Systems
7	Manager	Boeing Aircraft
8	VP, Integrated Training Solutions	CAE Inc.
9	CEO	CAE Inc.
10	President, Aviation Training	CAE Inc.
11	Product Manager, Integrated Training Solutions (ITS) division	CAE Inc.
12	Product Director, ITS	CAE Inc.
13	Marketing & Sales Director, ITS	CAE Inc.
14	President, Simulation Technologies	CAE Inc.
15	Sales & Marketing Manager	CAE Inc.
16	Sales & Marketing Director	CAE Inc.
17	Chief, Flight Trainnig	Canadian Ministry of Transport (CMOT)
18	Simulator Certification Officer	Canadian Ministry of Transport (CMOT)
19	Officer	Civil Aviation Authority (UK)
20	Managing Director	Diamond Aircraft
21	Head of Aeronautics	European Commission
22	Manager	Europrop
23	Head of Simulator Qualification Department	Federal Aviation Administration (FAA)
24	Commercial Director	Farnborough Aircraft Corporation Ltd
25	Director of Operations	FlightSafety International (FSI)
26	Director of Flight Training	FlightSafety International (FSI)
27	Training Manager	FlightSafety International (FSI)
28	Editor of Aviation Intelligence	Jane's
29	Officer	Joint Aviation Administration (JAA)
30	Vice President	L-3 Communications
31	Dean of Aviation Faculty	London Metropolitan University
32	Chief Simulation Engineer	Lufthansa Flight Training
33	General Manager	Lufthansa Flight Training
34	President	Mechtronix Systems
35	General Manager	Onera
36	Director of Sales & Marketing	Oxford Aviation Training

37	Executive Director	Oxford Aviation Training
38	Senior Fellow	Pratt & Wittney Canada
39	Director of Sales	Rockwell Collins
40	Head of MPL working group	Royal Aeronautical Society
41	Director, Flight Training Center	Southwest Airlines
42	VP Strategy	Thales Training & Simulation
43	Sales Director	Thales Training & Simulation
44	Chief Pilot	TUIFly Airlines - Happag Lloyd

A brief description of the organizations where research interviews were conducted is provided below:

Associated Aircraft Manufacturing & Sales Inc. (AAMSI)

AAMSI (www.aamsi.com) is a company that provides airframe and avionic components to airlines for refurbishing and repairing aircraft. With a facility in Florida, the company is specialized in the rotor-wing and military domains.

Aerospace Industrial Development Corporation (AIDC)

AIDC (www.aidc.com.tw) is a state-owned company in Taiwan acting as an assembly facility for several commercial, military and rotary-wing aircraft. With products such as the Sikorsky S-92 civil helicopter, the Airbus A321 and Bombardier's Learjet 45, AIDC is a strong Chinese player in the aircraft industry.

Airbus

Airbus industries (www.airbus.com) is the second largest commercial aircraft manufacturer in the world. Part of the multi-national company EADS, Airbus has been competing with Boeing for the leadership position in the commercial aircraft market. The company produced an array of aircraft ranging from the A319 to the A380, its most recent development.

Air Canada Jazz

AC Jazz (www.flyjazz.ca) is another key North American regional airline. It was a spin-off of Air Canada but soon became more profitable than its parent airline and competed with it in some markets. Its low cost business model is one that is becoming increasingly popular in regional airlines, especially in North America.

Alteon

Alteon (www.alteontraining.com) is the wholly-owned training subsidiary of Boeing Company that was formed by the termination of Boeing's joint venture with FSI (named FSBTI: Flight Safety Boeing Training International). The newly formed Alteon retained all the wide-body aircraft training facilities while FSI kept the business and regional jet facilities.

BAE Regional Aircraft

British Aerospace Regional Aircraft (www.baesystems.com) is a subsidiary of BAE Systems specialized in providing regional turbo-prop airplanes such as the Avro Jet, BAE 146 and Jetstream and support services to regional airlines. The company offers its clients a range of support services including engineering, technical support, logistical support and asset management services.

Becker Avionics

Becker avionics (www.becker-avionics.com) is a German producer of avionic instruments. The company has a wide-variety of products and an established customer base in the areas of communication, navigation, ATC (air traffic control) and SAR (search and rescue) equipment. A sole proprietorship founded in Germany, Becker now has divisions in Europe, the USA and China (Becker, 2007).

Boeing

Boeing Aircraft company (www.boeing.com) is the largest aircraft manufacturer in the world. Boeing's lines of business span commercial aircraft, military aircraft, flight training (through their Alteon subsidiary) and aircraft logistics. In the military domain, Boeing is a key defense contractor and supplier of the US military.

Civil Aviation Authority of the UK (CAA)

The UK CAA is one of the most stringent and influential aviation authorities in Europe. Like other European regulatory authorities, it is gradually being phased into the EASA.

CAE Inc.

CAE (www.cae.com) is the world's largest flight simulator manufacturer. Since its acquisition of Link Simulations in the 1980's, CAE has attained and maintained the leadership position in the flight simulation market, notably in the full flight simulators segment of it (CAE, 2005). The company has had a significant role in the evolution of both the product technology as well as the industry organization. In 2001, CAE acquired Schreiner Aviation Training and Simuflite Training International, two of the major flight training providers globally (Velocci, 2001(2); King, 2001). Along with a few independent training centers and joint ventures, these acquisitions made CAE the second largest training provider in the world. The company has since then continued to invest in training centers and established joint ventures with local airline training centers. At the time of writing this thesis, the company was running a network of 27 training facilities in 4 continents (CAE, 2007).

Canadian Ministry of Transport (CMOT)

The Canadian Ministry Of Transport is the aviation regulation authority in Canada. The CMOT training and simulation standards are very similar to their neighboring FAA.

Diamond Aircraft

Diamond aircraft (www.diamondair.com) is an emerging aircraft manufacturer based in Toronto, Canada. With roots in motorized gliders, Diamond has recently launched their jet aircraft targeting the small executive aircraft market. Modeled after Lufthansa, Diamond has launched its own training division operating as a distinct entity in Austria.

European Commission on Aeronautics

The European Commission's Aeronautics program (www.ec.europa.eu/transport/air_portal) is the arm of the European Union that leads and coordinates research in air transport and aviation domains.

Europrop

Europrop International (www.europrop.aero) is an aircraft engine producer formed as a joint venture of 4 of the largest aircraft engine manufacturers: Rolls Royce in the UK, Seneca in France, ITP in Spain and MTU Aero Engines in Germany. The company focuses primarily on military aircraft engines and Airbus is one of its key clients (Europrop, 2007).

FAA (Federal Aviation Administration):

The Federal Aviation Administration is the aviation authority of the USA and the leading aviation authority around the world. The strategic importance of the USA in the historical evolution of the aviation industry has given the FAA a leading role in defining many of the simulation and training standards.

Farnborough Aircraft Corporation

Farnborough aircraft (www.farnborough-aircraft.com) is a start-up supplier of light turboprop aircraft in the UK. Encouraged by the promising growth of air-taxi services, the company is currently working on the design of its F1 flagship, a single-engine 6 passenger light aircraft. Richard Noble, the founder and CEO of the company, has pursued innovative ways to raise funds for his new project including soliciting support online from aircraft enthusiasts and industry visionaries who share his hopes of a growing air taxi business.

FlightSafety International

Flight Safety International (www.flightsafety.com) is the largest provider of aviation training services in the world and one of the key producers of business jet and light aircraft simulators. Based in Florida, FSI has the largest network of flight simulators globally. The second-largest simulators network, operated by CAE, had approximately half the number of simulators of FSI at the time of writing this thesis (FSI, 2006; CAE, 2006). The training arm of Flight Safety International operates more than 43 training centers worldwide running a fleet of over 230 flight simulators most of which replicate business aircraft.

JAA (Joint Aviation Administration)

The Joint Aviation Administration is an organization composed of the aviation authorities of the European Union. Based in the Netherlands, the JAA is closer to an industry forum that provides a link between the various European aviation authorities than a regulatory body. The JAA is gradually transforming into the EASA (European Aviation Safety Agency), which is a joint authority with an area of jurisdiction covering the member countries of the EU.

Jane's Industry Intelligence

Jane's (www.janes.com) is an industry intelligence and publications company that is specialized in, among others, the aviation training industry. Jane's publishes several important magazines and publications of the industry containing the latest trends, analyses and databases of world airlines.

L-3 Communications

L-3 Communications (www.l-3com.com) is a diversified company offering a wide scope of technologies, from on-board communications equipment to military flight simulations. L-3 has acquired the marine simulation division from CAE in 2003 to strengthen its capabilities in this domain (L-3, 2004). It is also a prime contractor for military programs especially in the US and Canada.

London Metropolitan University

London Metropolitan University (www.londonmet.ac.uk) is an educational institution in London offering, amongst other things, pilot training courses and aviation management programs. The university's Center for Civil Aviation operates an *ab-initio* flight school while providing the students access to the university's other programs and departments.

Lufthansa Flight Training

Lufthansa Flight Training (www.lufthansaflighttraining.com) is an independent training provider wholly owned by Lufthansa Airlines. The company provides exclusive training to its parent airline but also third party training to many other airlines in Europe and North Africa.

Mechtronix Systems

Mechtronix Systems (www.mechtronix.com) is a Montreal-based privately-owned flight simulator company established by two engineering Master's students following the completion of their research about simulation. The company was a provider of lower-level flight training devices until 2004 when it announced its first full flight simulator. In 2006, Mechtronix surprised the industry with its sale of a Level B full flight simulator to Lufthansa Training GmbH for conducting recurrent training, a concept that it has been pitching to the industry for several years (Warwick, 2006; Potomac, 2006).

Onera

The French national aerospace research center, Onera (www.onera.fr), is a government agency responsible for conducting research in the aeronautics field on behalf of the industry. Onera's funding comes primarily from aerospace companies in France and the rest of Europe while the government provides 40% of its annual budget (Onera, 2007).

Oxford Aviation Training

Oxford Aviation Training (www.oxfordaviation.net) is a UK-based school offering *ab-initio* training to student pilots. The school is regarded as a pioneer in the industry as it was one of the first to establish strong relationships with airlines in Europe for providing them with cohorts of new pilots. The airlines were given the chance to inspect the training, interview the students and supervise the training quality while the students were given better chances of employment following their costly training.

Pratt & Whitney

Pratt & Whitney (www.pwc.com / www.pw.utc.com) is the aircraft engines division of technologies mogul UTC (United Technologies Corporation). The company is one of the key aircraft engine suppliers and its products cover most market segments ranging from light to wide-body aircraft and spanning both commercial and military aircraft.

Rockwell Collins

Rockwell Collins (www.rockwellcollins.com) is a key avionics and instruments provider with a significant share of the world market. Based in Cedar Rapids, Iowa, Rockwell Collins has been an increasingly important player in the aviation industry notably after it won the bid for supplying the entire avionics deck for Boeing's Dreamliner the B787, Airbus's A380 and China's ARJ (Advanced Regional Jet) (Rockwell Collins, 2007). In 2003, Rockwell acquired NLX, a Canadian producer of flight simulators, hence expanding its operations to the aviation simulation and training industry. Since then, it has also acquired the simulation business unit of Evans and Sutherland, a world leader in visual system technologies (RockwellCollins, 2006) thereby positioning itself as a key player in the future of the industry.

Royal Aeronautical Society

The Royal Aeronatical Society (www.raes.org.uk) is an important industry forum where industry leaders meet to discuss new trends, technological advances and industry concerns. Despite its lack of any judicial authority over its members, the RAeS is a powerful association with several subcommittees that collaboratively influence the industry and the regulators. Members of the RAeS are typically the executives of simulation producers, flight training providers, airlines and regulators.

Southwest Airlines

Southwest Airlines (www.southwest.com) is a key customer in the new aviation era. Founded in the late 70's with a revolutionary business model of point-to-point flights on popular routes, Southwest Airlines has demonstrated a remarkable capability to remain profitable throughout numerous industrial and economic downturns of the industry.

Thales Training & Simulation

TT&S (www.thales-tts.com) is the second major player in the FFS market and the dominant in certain European and Middle-Eastern markets. TT&S provides a products suite that is almost as comprehensive as that of CAE but controls a significantly smaller share of the market.

TUIfly

TUIfly (www.tuifly.com) is a European low-cost airline that is owned by the shipping and logistics giant Hapag Lloyd to penetrate the booming European air travel industry. The airline has one of the most extensive networks operating 56 airplanes making it the third largest German carrier after Lufthansa and Air Berlin. The company has already expanded into international routes outside Europe and is eyeing an even wider expansion into other popular international destinations.

A Sample of Industry Documents Consulted

- Transcript of address made by Mr. Derek Burney (CEO of CAE 1997 to 2001) to shareholders
- Flight Magazine inventory of Flight Simulators
- Deloitte Aerospace and Defense Update, Quarterly 2006 – 2007
- CAE Annual Reports 1964 – 2007
- Thales Training & Simulation Annual Reports 1991-2007

Industry Presentations Made

- ASME IMECE Conference, November 2004
- Presentation to CAE Sales & Marketing team: June 2005
- Royal Aeronautical Society Conference, November 2006
- Presentation to Thales Training & Simulation Marketing & Strategy team: November 2006

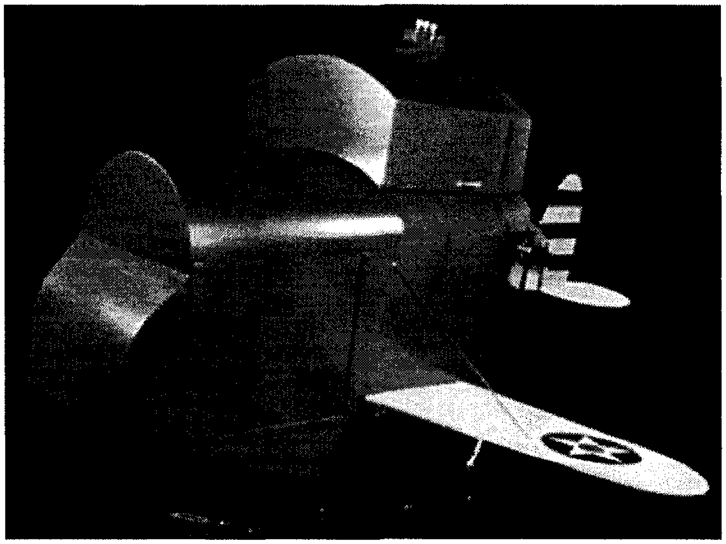
APPENDIX B RESEARCH INSTRUMENT

ÉCOLE
POLYTECHNIQUE
MONTRÉAL

MINE PROJECT
MANAGING INNOVATION
IN THE NEW ECONOMY

Product Maturity and Architecture Evolution in Complex Industries

Research
Instrument



Introduction & Definitions

Personal Introduction

Thank you for taking the time for this research interview. I am studying the relationship between product architecture and technological maturity in the aviation training industry for my doctoral research and would like to ask you for your insights about certain aspects and recent changes in the industry.

MINE Research Introduction

This study is a part of the MINE (Management of Innovation in the New Economy) research program which is studying innovation practices in approximately 20 industries worldwide. The aviation training industry is one of these industries studied.

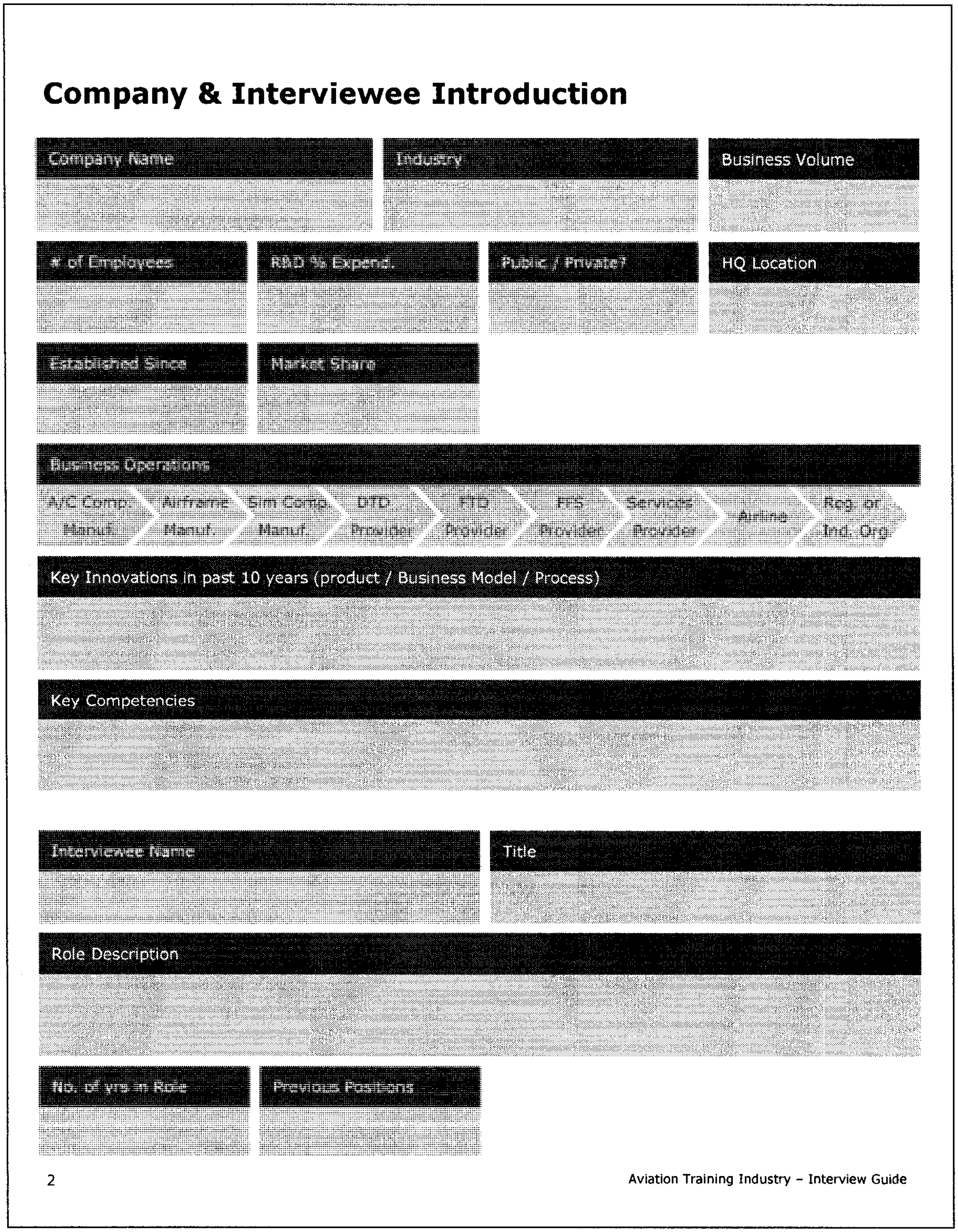
Research Objectives

My main objectives of the research are to establish whether the industry has attained technological maturity or not and to investigate the consequences of attaining this stage on the product architecture. I want to validate a management theory that was developed in the context of another industry within the commercial aviation training industry.

Product Levels Definition

For the sake of the research, I have divided the aviation training industry into 3 sub-industries:

1. The Simulation Device industry: this is the industry that develops the individual training devices (whether FFSs, FTDs or other simulation devices) for pilot and maintenance training.
2. The Training Products Suite industry: this is the industry that develops entire training product suites composed of the various training devices integrated around a training curriculum as well.
3. The Training Services industry: this is the industry that provides training services to student pilots at the various phases of training (i.e. ab-initio, type-rating and recurrent training).



Company & Interviewee Introduction

Company Name

Industry

Business Volume

# of Employees

R&D % Expend.

Public / Private?

HQ Location

Established Since

Market Share

Business Operations

A/C Comp. Manuf.
Airframe Manuf.
Sim Comp. Manuf.
DTD Provider
FTD Provider
FFS Provider
Services Provider
Airline
Reg. or Ind. Org.

Key Innovations in past 10 years (product / Business Model / Process)

Key Competencies

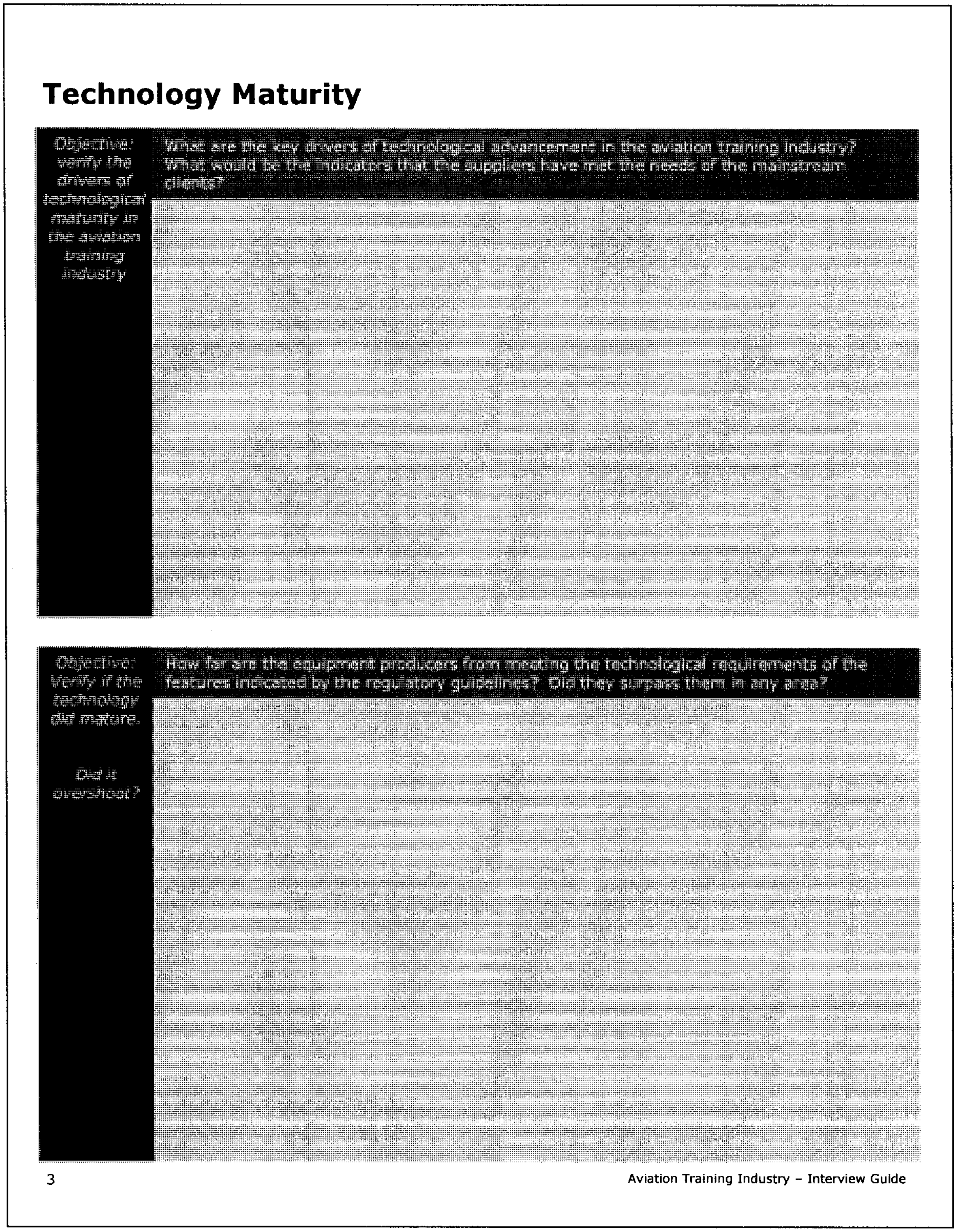
Interviewee Name

Title

Role Description

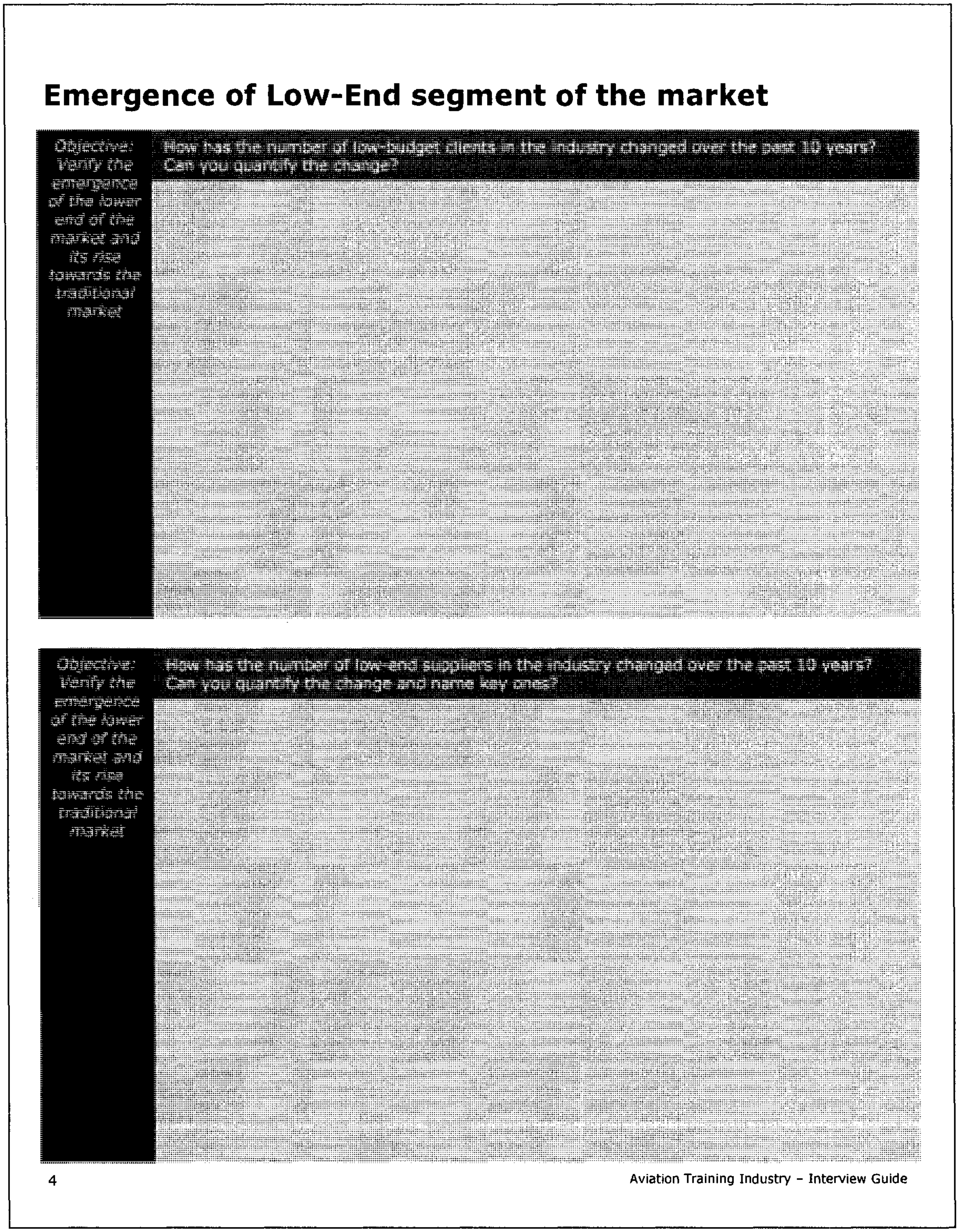
No. of yrs in Role

Previous Positions



Technology Maturity

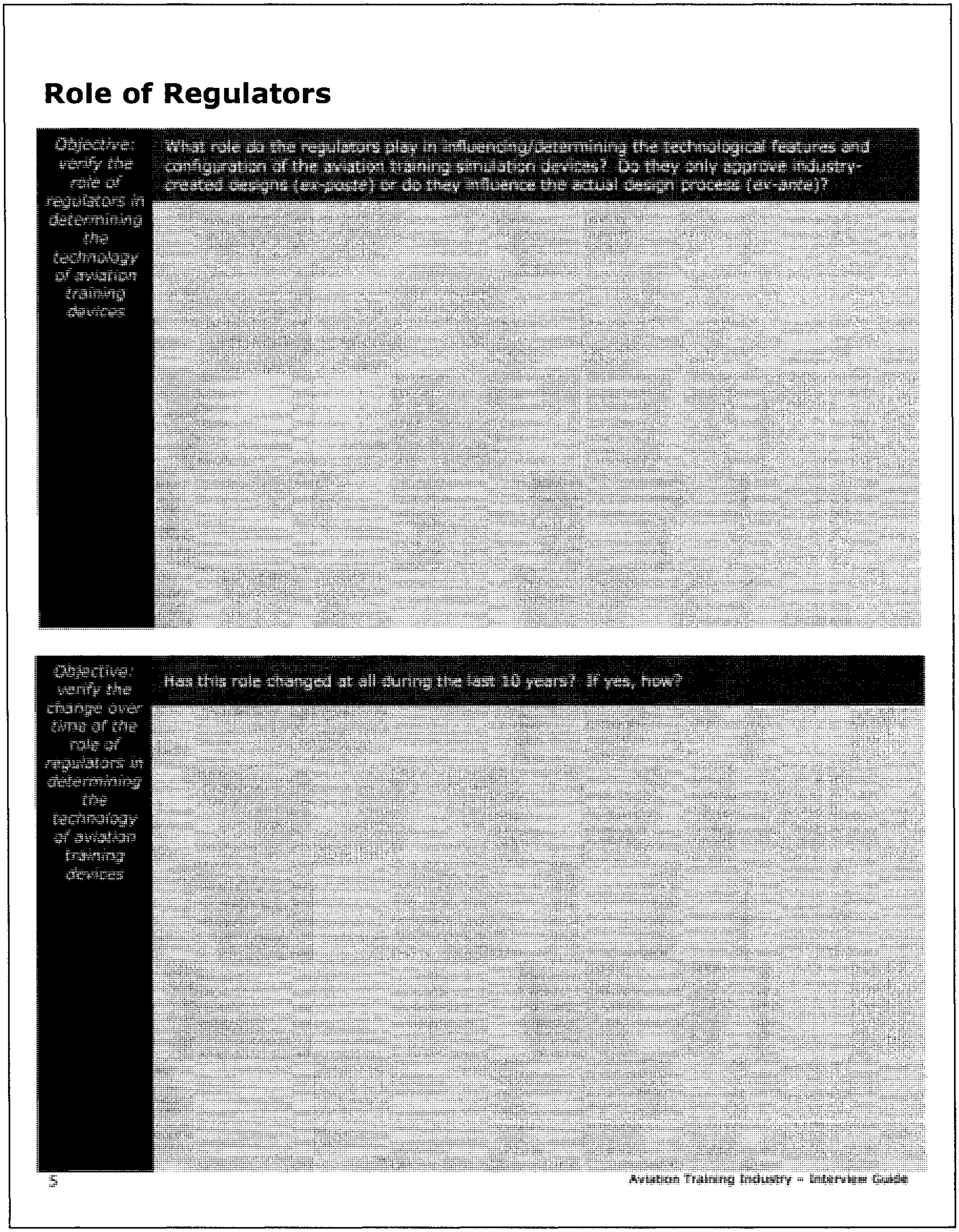
Objective: verify the drivers of technological maturity in the aviation training industry	What are the key drivers of technological advancement in the aviation training industry? What would be the indicators that the suppliers have met the needs of the mainstream clients?
Objective: Verify if the technology did mature. Did it overshoot?	How far are the equipment producers from meeting the technological requirements of the features indicated by the regulatory guidelines? Did they surpass them in any area?



Emergence of Low-End segment of the market

Objective: Verify the emergence of the lower end of the market and its rise towards the traditional market	How has the number of low-budget clients in the industry changed over the past 10 years? Can you quantify the change?

Objective: Verify the emergence of the lower end of the market and its rise towards the traditional market	How has the number of low-end suppliers in the industry changed over the past 10 years? Can you quantify the change and name key ones?



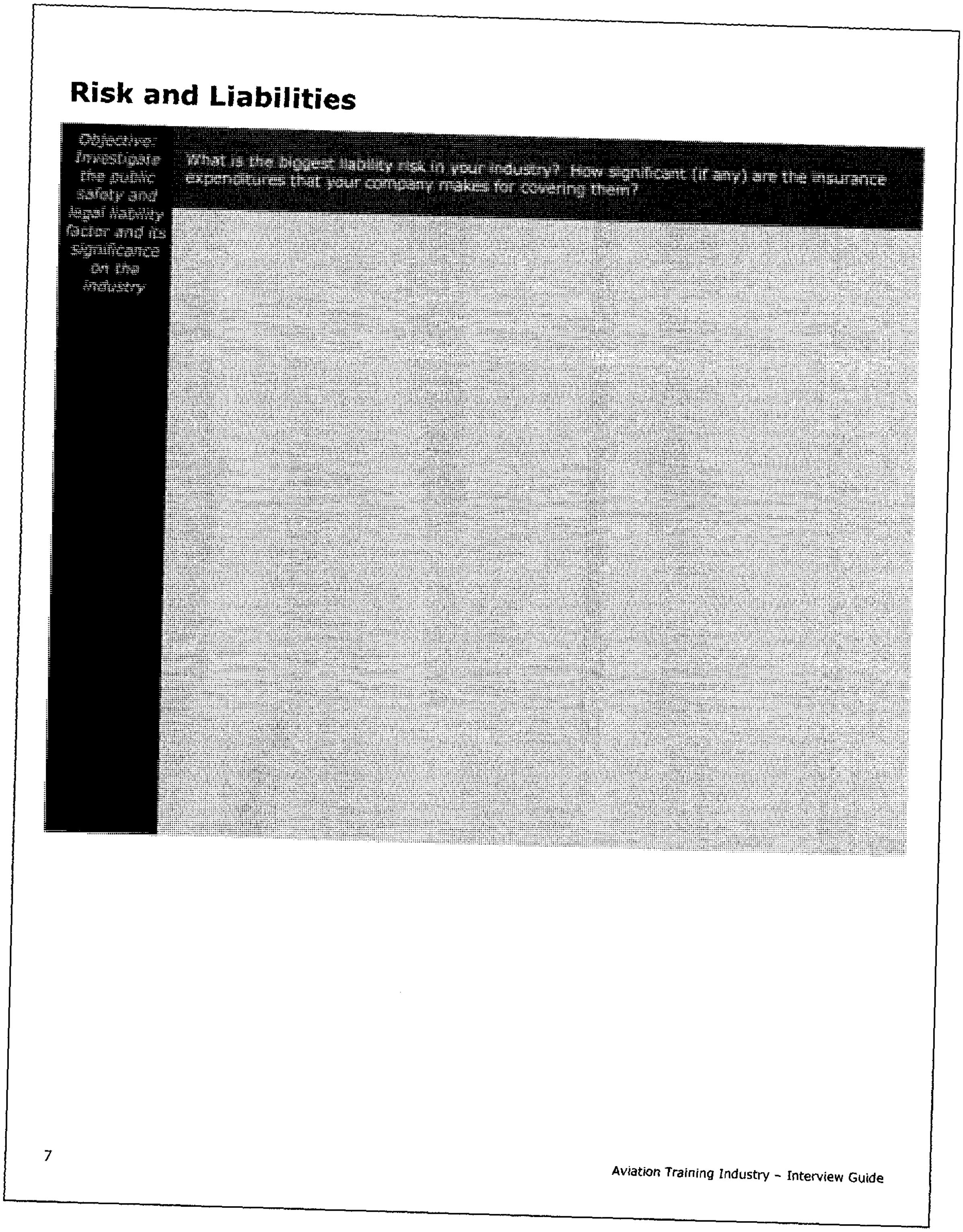
Role of Regulators

Objective: verify the role of regulators in determining the technology of aviation training devices	What role do the regulators play in influencing/determining the technological features and configuration of the aviation training simulation devices? Do they only approve industry-created designs (ex-poste) or do they influence the actual design process (ex-ante)?
Objective: verify the change over time of the role of regulators in determining the technology of aviation training devices	Has this role changed at all during the last 10 years? If yes, how?

Role of Clients

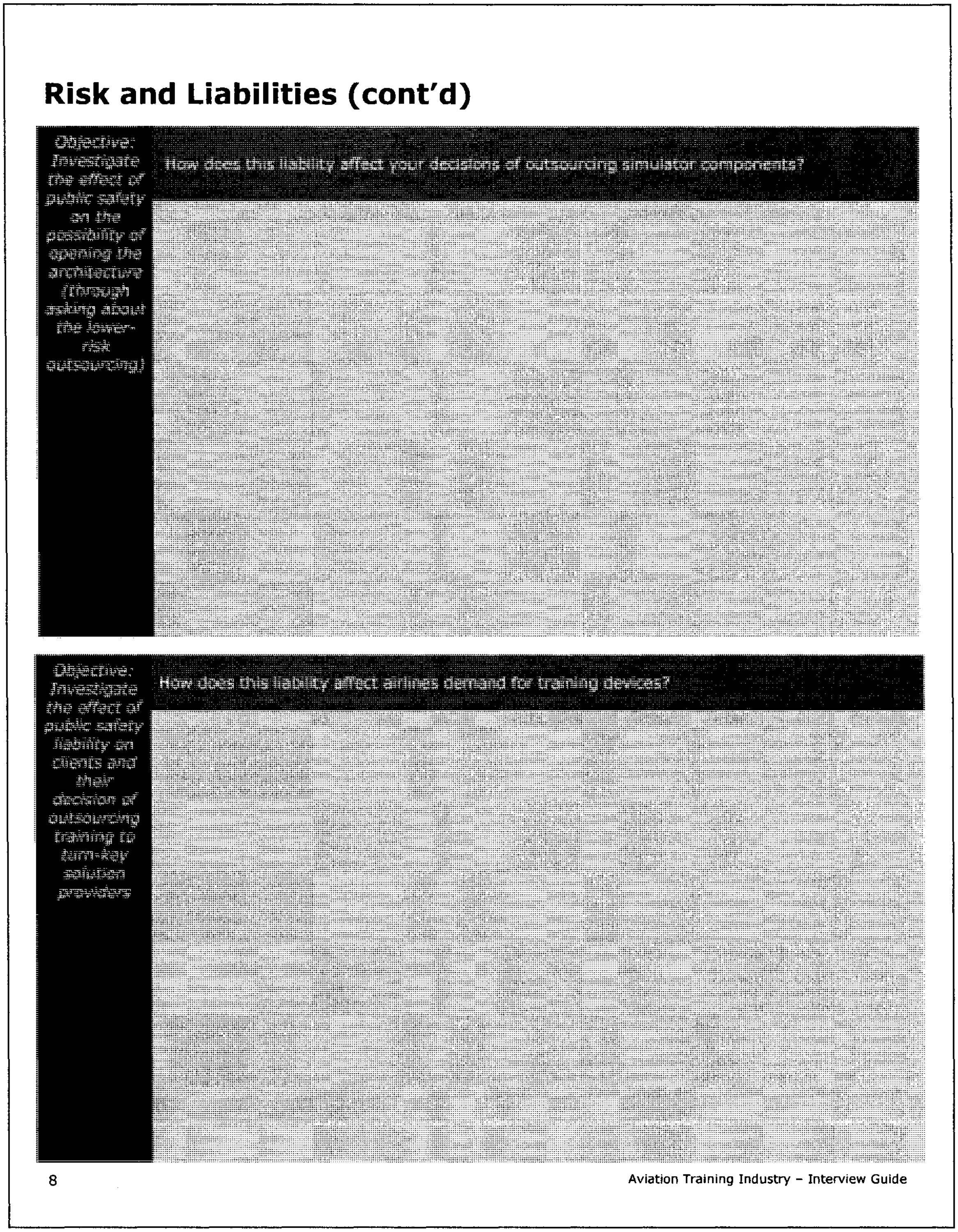
Objective: verify the involvement of clients in the design of aviation training products	How involved are the industry's clients (airlines, independent training providers, etc.) in the design and specifications of the aviation training products?

Objective: verify the change over time of the involvement of clients in the design of aviation training products	Has this role changed at all during the last 10 years? If yes, how?



Risk and Liabilities

Objective: Investigate the public safety and legal liability factor and its significance on the industry	What is the biggest liability risk in your industry? How significant (if any) are the insurance expenditures that your company makes for covering them?



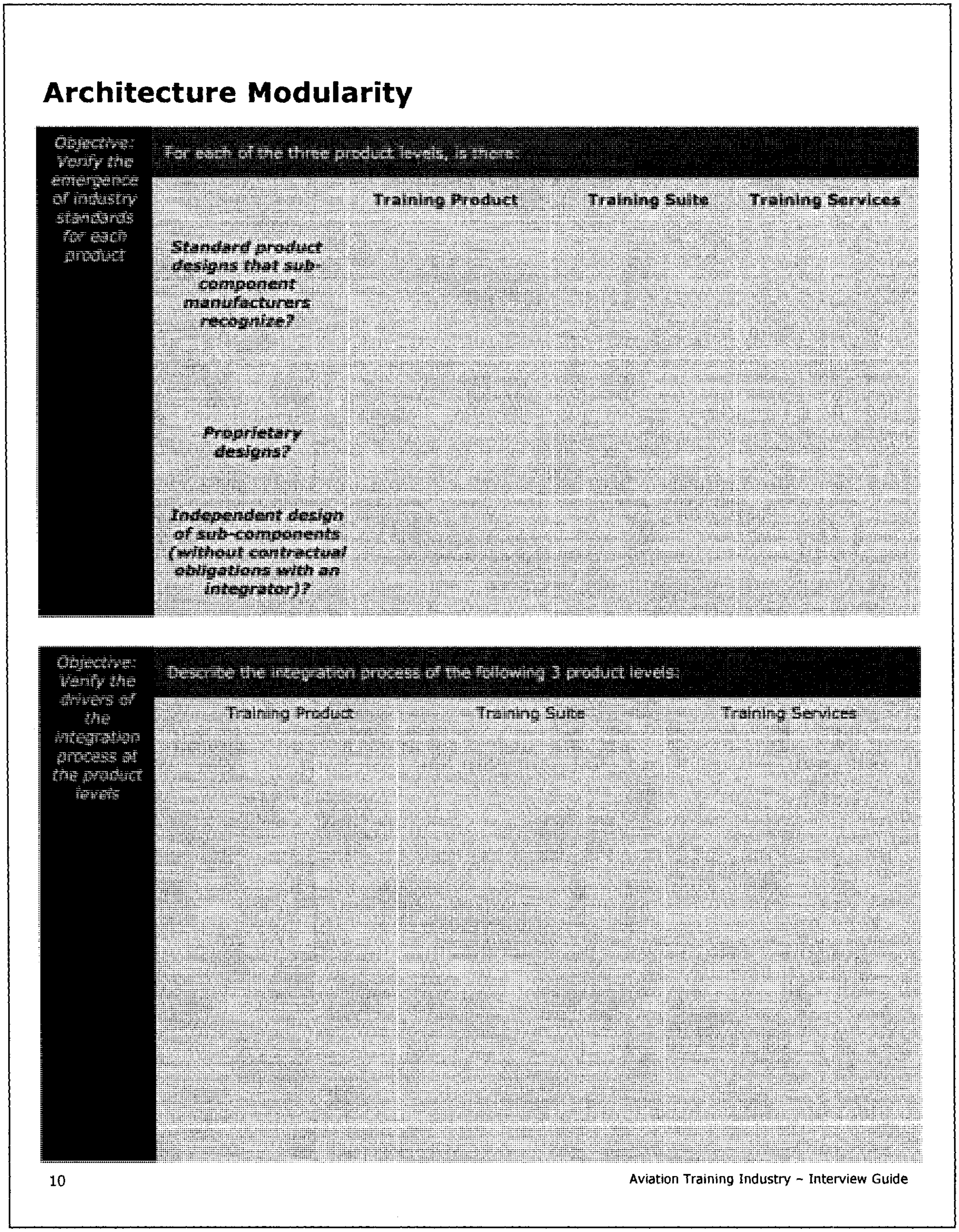
Risk and Liabilities (cont'd)

Objective: Investigate the effect of public safety on the possibility of opening the architecture (through asking about the lower-risk outsourcing)	How does this liability affect your decisions of outsourcing simulator components?

Objective: Investigate the effect of public safety liability on clients and their decision of outsourcing training to turn-key solution providers	How does this liability affect airlines demand for training devices?

Accumulated Learning

Objective: Investigate if accumulated learning entrenches the company's market position by continually reducing their costs of production	What percentage of the cost of a simulator is the software component? How much savings can a supplier make when selling the second simulation device of the same aircraft type?



Architecture Modularity

Objective: Verify the emergence of industry standards for each product

For each of the three product levels, is there:

	Training Product	Training Suite	Training Services
Standard product designs that sub-component manufacturers recognize?			
Proprietary designs?			
Independent design of sub-components (without contractual obligations with an integrator)?			

Objective: Verify the drivers of the integration process at the product levels

Describe the integration process of the following 3 product levels:

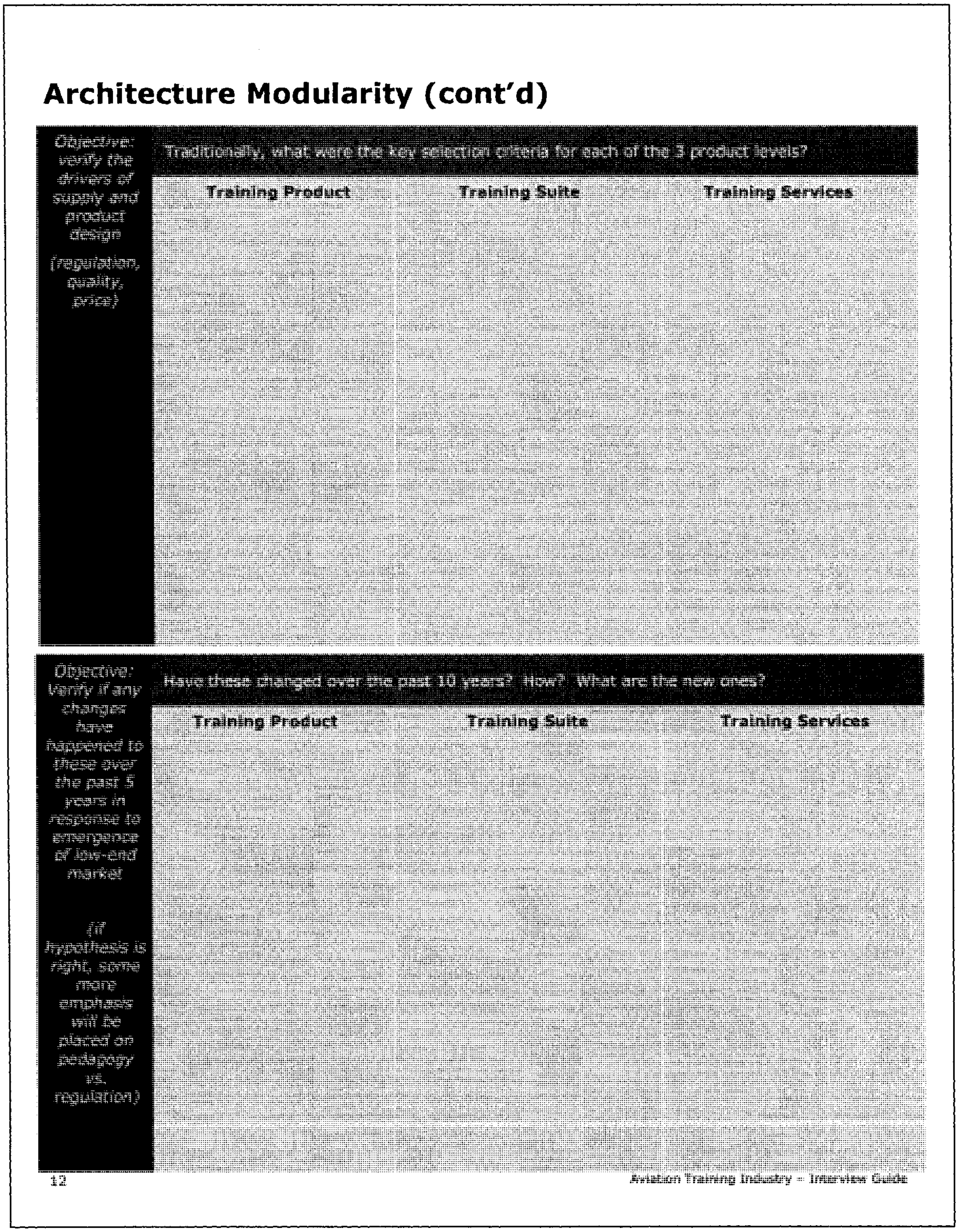
Training Product	Training Suite	Training Services

Architecture Modularity (cont'd)

Objective: Verify the evolution of these integration competencies and patterns over the last 5 years in response to emergence of lower end market (if there is a trend towards openness)

How has this process changed over the past 5 years for each of these products?

Training Product	Training Suite	Training Services



Architecture Modularity (cont'd)

Objective: verify the drivers of supply and product design

(regulation, quality, price)

Traditionally, what were the key selection criteria for each of the 3 product levels?

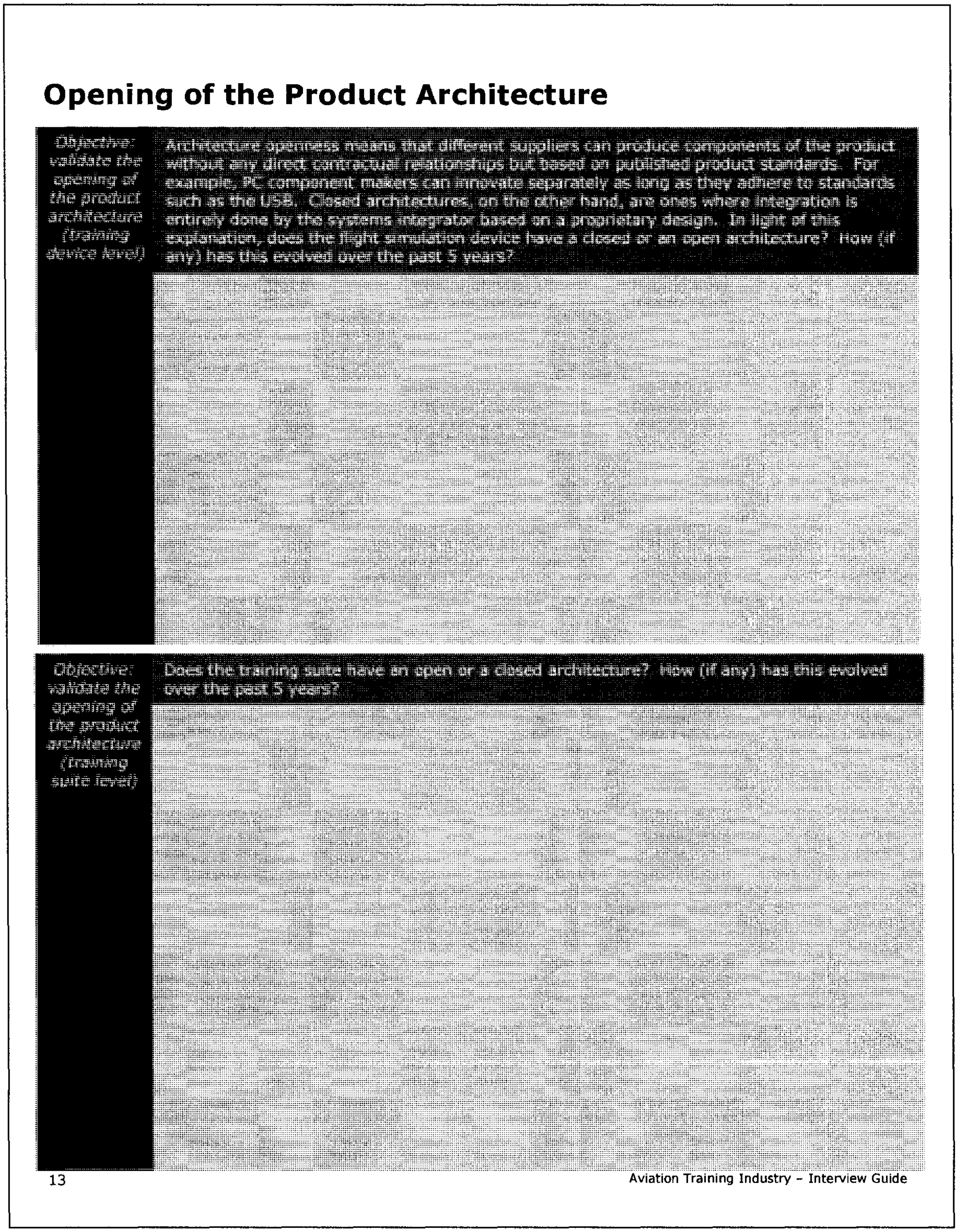
Training Product	**Training Suite**	**Training Services**

Objective: Verify if any changes have happened to these over the past 5 years in response to emergence of low-end market

(if hypothesis is right, some more emphasis will be placed on pedagogy vs. regulation)

Have these changed over the past 10 years? How? What are the new ones?

Training Product	**Training Suite**	**Training Services**



Opening of the Product Architecture

Objective: validate the opening of the product architecture (training device level)	Architecture openness means that different suppliers can produce components of the product without any direct contractual relationships but based on published product standards. For example, PC component makers can innovate separately as long as they adhere to standards such as the USB. Closed architectures, on the other hand, are ones where integration is entirely done by the systems integrator based on a proprietary design. In light of this explanation, does the flight simulation device have a closed or an open architecture? How (if any) has this evolved over the past 5 years?

Objective: validate the opening of the product architecture (training suite level)	Does the training suite have an open or a closed architecture? How (if any) has this evolved over the past 5 years?

Opening of the Product Architecture (cont'd)

Objective: validate the opening of the product architecture (training service level)	Does the training service have an open or a closed architecture? How (if any) has this evolved over the past 5 years?