Questioning the Innovation of Complex Products and Systems

with a

Case Study of the Boeing 737 Airplane

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ABSTRACT

Questioning the Innovation of Complex Products and Systems with a Case Study of the Boeing 737 Airplane

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Complex Products and Systems (CoPS) is an established category of products that are recognized to be underserved in the area of innovation. CoPS tend to be highly costly projects that are characterized by difficult development uncertainties and low rates of production. As a result traditional innovation theories are not seen to be easily applicable particularly as manufacturers of CoPS can tend to struggle with accomplishing dominant designs and enjoying the downstream fruits of product maturity such as commoditization. To further investigate this concern, a case study is performed on the Boeing B737 airplane which is the most successful selling commercial jet airplane series in history. The amazing part of the story is that it has been able to do this and maintain competitive parity in the face of competition from the Airbus A320 airplane which has a design origin close to 20 years ahead of the B737. To perform this study, a review of innovation theory, particularly Disruptive Innovation, is done together with the concept of product platforms and product families. The results show that the challenge of CoPS can in fact be potentially overcome by employing an appropriate strategy of product platforms and continuous upgrading of product architecture.

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I am eternally indebted to the many people I have been fortunate to meet in my studies that have not just enabled this thesis, but also enriched my life in appreciation of other subjects and things in life that should be enjoyed.

I am particularly grateful to Professor Margaret Graham (McGill University) for introducing the wonderful world of innovation to me, to Dr. Jamshid Etezadi for his never failing guidance and advice especially when I had personal issues, and Dr. Dennis Kira for being my mentor and support ever since I joined the program.

My wife Paulin and my children Tabitha and Darryl, put up with many hours, days and weeks of missed family time that went instead to this dissertation. Hence I am dedicating this work to them with the hope that someday Tabitha and Darryl may in fact be able to use the knowledge I have gained.

Finally, none of this would have been possible without the support from my parents in their blind love to give me a better future. My father who supported me to obtain my first degree when it was extremely difficult financially and my mother who laboriously copied and bound several boxes of my first set of aircraft technical manuals to allow me to study at a time when photocopiers were still an expensive novelty.

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1. Thesis Overview

1.1. *Introduction*

Complex Products and Systems or CoPS are a category of products that are characterized by high costs, high customization, low production rates and high uncertainties as far as commercial profitability despite longevity in service due to the high costs. Typical of these products are flight simulators, aircraft engines, submarines, ships, nuclear power stations, air traffic control systems, telecommunication exchanges etc. (Miller et al, 1995; Hobday, 1998).

Because of these characterizations, CoPS proponents tend to argue that traditional innovation theory that often use mass consumer products as examples and case studies do not necessarily apply. In particular because CoPS product types may not reach high production numbers, dominant designs and subsequent commoditization may not occur and hence a typical life cycle that would be seen on a mass consumer product may never be seen. The implication is that there is insufficient research into this area and CoPS deserves specialized theory for innovation.

One could argue however that CoPS is simply at the beginning of a traditional life cycle and it is just a matter of time. However cases abound where products that could be classified as CoPS seem to do very well commercially and enjoy high production rates as well as establishing dominant type design configurations.

One such product is the Boeing B737 ("B737" is used instead of just "737" as the "B" prefix is used to signify Boeing airplanes as a convention, and to differentiate against Airbus airplanes that have "A" prefixes) which is the most successful commercial jet in history in terms of sales and continues today to be produced in large numbers. This is despite having its origins from the 1960s and a strong competitor in the form of the Airbus A320 which was introduced with designs and technologies nearly some 20 years later in the 1980s. When it was first introduced the A320 featured many new technologies such as fly-by-wire flight controls, high bypass turbofan engines, new modern cabin interiors and new materials. In response, Boeing did not develop an all-new model to compete. Instead it chose to incrementally improve the B737 and it has continued to do so successfully up to the present day where it is not unusual for the B737 to outsell the A320.

Whether intentionally it did so or not, studies show that Boeing focused primarily on improving only the features of the B737 that needed to be developed to attain competitive standing with the A320. These features were those that would provide the highest values to the customer in terms of the customers' businesses. In the end Boeing was so successful in this process that the B737 would eventually threaten Boeing's own higher end products such as the B757. Hence a case study of the B737 is performed to analyze in detail how Boeing succeeded in this particular instance,

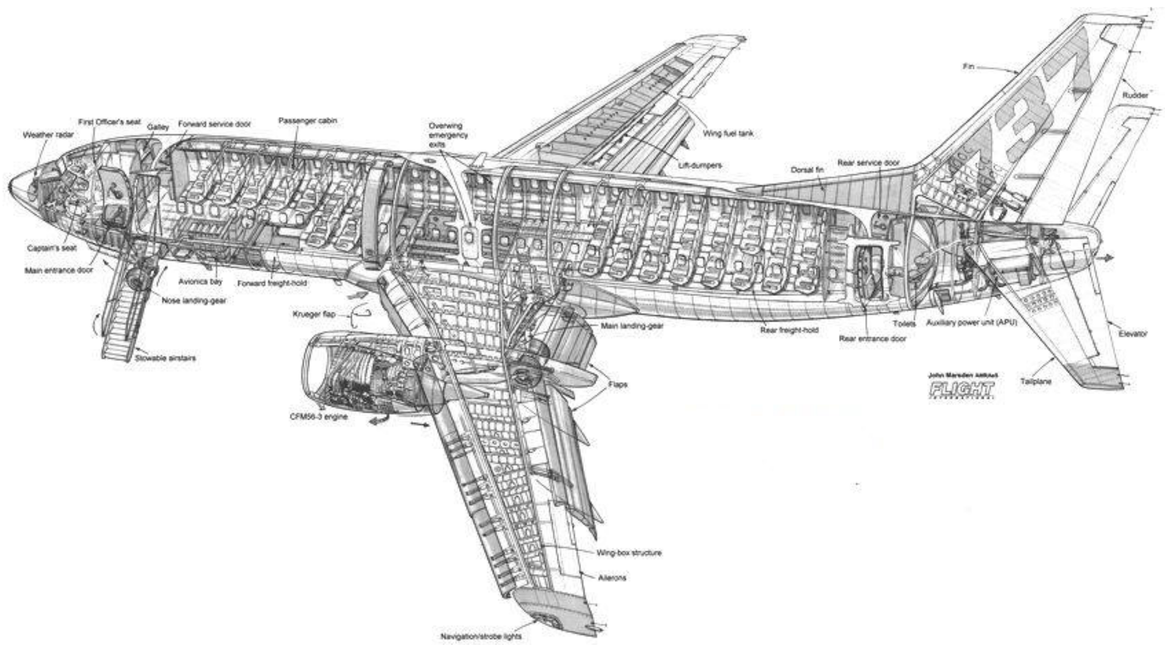


Figure 1.1

Boeing 737-300 Cutaway

(http://www.flightglobal.com/imagearchive/Image.aspx?GalleryName=Cutaways/Civil%20Aviation/Civil%20Aviation%201949-2006&Image=Boeing-737-300)

Combined with this study is a review of Disruptive Innovation (Christensen, 1997; Christensen and Raynor, 2003) to consider the competition environment as Boeing sought to maintain marketability of the B737. In Disruptive Innovation new entrants can enter a market with lesser performance capability than existing products on the market, but with a lower price offering, or a different performance attribute that new markets may desire. The argument is that the existing product may improve beyond customer needs and hence the new product will eventually become more attractive as it too will improve in performance and eventually enter the mainstream market.

A new consideration is the concept of *Reverse* Disruptive Innovation, in the sense that the incumbent firm may be under attack if the new entrant's product has in fact better performance attributes for the mainstream market, and the incumbent chooses to fight back with improvements to the old product but with just enough to satisfy the customers. Boeing appears to have done exactly that with the B737 when the A320 was introduce to the market with more advanced technology and better performance attributes such as lower fuel burn, higher cruise speed, and ability to climb to higher cruise altitudes. In improving the 737 so much though in attributes such as increased capacity to carry more passengers, Boeing threatened other products such as the B757 in its own product line.

The extent of how Boeing developed the improvements is perhaps the most interesting. It did not try to match the A320 in terms of technology but primarily focused on those performance attributes that meant the most to its customers. By keeping many of the older technology features in successive upgrades, Boeing was able to use those features to maintain existing customers with the attraction of commonality in spare parts, training, and operations. In concert Boeing also employed "new" technologies or components in the upgrades, but often they were proven designs borrowed from other product lines.

A feature of the B737 history of improvements is the concept of a product platform. From its inception many of the B737s features were driven by cost considerations and initial upgrades by chance followed the commonality strategy to minimize development costs. This was so successful that as an emergent strategy (Mintzberg 1978; Mintzberg and Waters, 1985), it was used for later upgrades.

In this thesis a review is performed in Chapter 2, of the relevant literature, particularly as related to Disruptive Innovation and CoPS, and supplemented by some mini case examples such as the Lockheed Skunk Works “Have Blue” prototypes for the F-117 Nighthawk “Stealth” fighter, the Ford Model “T” car, and the Bell AH-1 Cobra and UH-1 Huey story. Chapter 3 covers the methodology and the decision to use the case study method and the B737 as the case subject.

In Chapter 4, short histories of Boeing and Airbus are given primarily prior to the advent of the B737 and A320, followed by a detail case study on the three generations of B737s, the “First Generation” (B737-100, -200), “Classic Generation” (B737-300, -400, -500), and the “Next Generation” (B737-600, -700, -800, -900, -900ER), as well various executive and military variants. Details of the improvements and nature of those improvements, and the parts that were deliberately not improved or modified to maintain commonality with previous generations, are the main thrust of the study.

While detailed, the writing is deliberately simplified for a wider reading audience to ensure that the main ideas, theoretical concepts, and findings are not lost in technical jargon. Appendices offer references to those familiar with aircraft technology and performance for further technical detail.

The analysis of the case study in Chapter 5 is provided with particular reflections on the product Family Concept, Brian Arthur’s “The Nature of Technology”, Reverse

Disruptive Innovation, Performance (attributes of the product), and Product Platforms. Following the analysis, Chapter 6 offers a strategy formulation and discussion, including a review of the research questions. Finally the conclusions in Chapter 7 include the limitations of the research, and potential future research questions as a result.

1.2. Purpose of the Research

It would be extremely interesting to investigate in this case how the traditional and somewhat negative views of CoPS innovation could be challenged, and if so it could positively impact the huge investments that typically go into the development of CoPS products. By performing a case study on the development of the B737 we may gain insight into unexplored strategies that may thus far been difficult to view easily due to the technical complexity of the product. The big question would be is this just a once off anomaly or is there a strategy or strategies that Boeing employed that could be used by other CoPS manufacturers?

Of particular interest is that Boeing did not invest in an all-new model. A new commercial jet costs billions of dollars to develop. Hence by simply continuing to adapt an existing 40 year old design, Boeing has saved considerable investment costs compared to the costs its all-new competitor must have incurred. Price parity with an all-new competitor with a derivative airplane also suggests high profits.

It is not expected that the results of this research be a one and end all to the solution of CoPS. However if a rough strategy can be determined from the study to improve the likelihood of commercial success of a CoPS product, a new theory can be developed that could be utilized at least as a starting point by future CoPS manufacturers and or developers.

1.3. Case Study

For this thesis a case study of the B737 airplane is chosen to further investigate the observations noted prior, particularly about reverse disruptive innovation, CoPS characterizations, and the concept of product platforms and families, since both Boeing 737s and Airbus A320s possess product families of derivatives and variants. The airplane is particularly interesting from several viewpoints.

Firstly in CoPS, frequent products mentioned are flight simulators and aircraft engines. Both of these are actually up-stream products of the eventual final use of an airplane. Hence if flight simulators or aircraft engines can be classed as CoPS, then an aircraft that the flight simulators simulate, or an aircraft on which the engines are used, is surely more complex and suitably characterized as a CoPS product.

Flight simulators are typically used by airlines for simulating commercial jet aircraft cockpits for training by pilots. A case study on a light single engine piston powered propeller aircraft such as the Cessna 152 hence may not be as suitable a candidate compared to a “heavy” B737 jet airplane.

Secondly the B737 has undoubtedly the most impressive record of a production run in commercial jet history with over 8,000 orders logged as of the date of writing this thesis. It is incredibly still in production and in high demand with current production rates approximately producing one B737 a day. Boeing is currently designing yet another generation of the B737 by fitting a new more fuel efficient engine (Ostrower, 2011), in response to a re-engine effort by Airbus on the competing A320 (Reals, 2010).

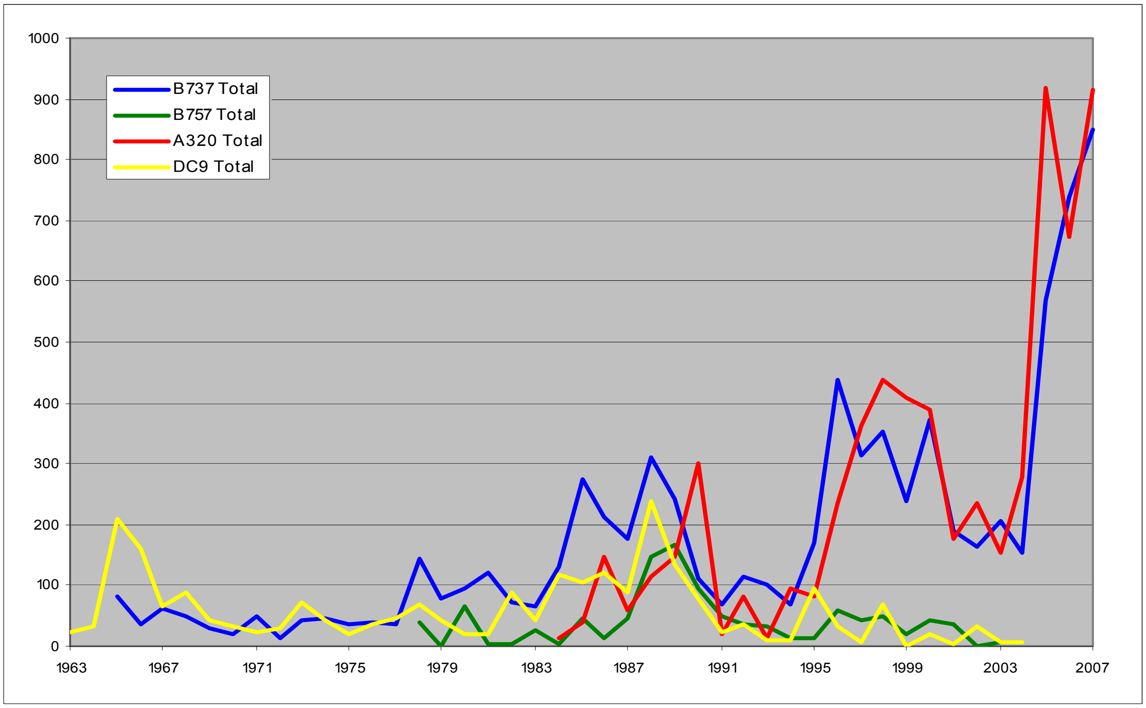
Hence like the Ford Model T, the B737 represents in the aircraft world an anomaly to the CoPS innovation question. Perhaps the way the airplane’s model development was managed will reveal a strategic clue to managing innovation of CoPS. Christensen (2006) describes well the opportunity and importance of analyzing anomalies. A purely military airplane would not be suitable as commercial market forces could not be relied upon when investigating the order rate. Some B737s have been built for military purposes but the number is an insignificant minority compared to the commercial orders.

If the airplane had a monopoly, the production run might perhaps not be as interesting as the customers would not have had a choice. However the B737 has had healthy competition throughout most of its history. The most notable is the A320 (Airbus A320) family which had its first orders in 1984, just shy of 20 years later than the B737’s first orders in 1965. Despite the gap in original design dates, the B737 maintains commercial parity in orders with the A320.

Three generations of B737 families with executive and military variants make the case rich for analysis particularly with the longitudinal aspect and what decisions were made to select certain features of the aircraft to upgrade. In-between generations of families, Boeing also continuously added improvements to enhance the capability of the aircraft as well as to open more markets, such as developing cargo and "combi" (able to carry both passengers and cargo in combination on the fuselage main deck) versions and fitting gravel kits to allow the aircraft to operate to unpaved runways in remote areas of Canada and Africa.

Figure 1.2 below illustrates the sale orders statistics of the various aircraft types in the Boeing B737/Airbus A320 class size of aircraft. All the aircraft types shown are twin-engine commercial jet aircraft in the single-aisle narrow body class. Except for the 3-engined narrow body single-aisle B727, the next bigger models for Airbus, Boeing or McDonnell Douglas are/were twin-aisle wide-bodied jets (A330/A340, B767, DC-10/MD-11 respectively) with some having 3 (DC-10/MD-11) or 4 engines (A340).

The blue and red lines illustrate how the B737 and A320 respectively have been a runaway success for both manufacturers. Notably the other competitors ceased production in the early 2000s including Boeing's own 757s with the success of the improved performance and capabilities of the B737 and A320 families.



Model \Year	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
B727 Total	187	149	125	66	64	48	26	119	92	88	50	113	133	125	98	68	38	11	1			
B757 Total														38	0	64	3	2	26	2	45	13
747-400 All																						
737-100	21	0	8		0	0	0	0	1													
737-200 All	62	35	53	49	28	21	48	14	41	47	35	39	37	145	78	95	101	65	44	22	30	14
737-300																	20	6	20	109	244	126
737-400																						72
737-500																						
737-600																						
737-700 All																						
737-800 All																						
737-900 All																						
B737 Total	83	35	61	49	28	21	48	14	42	47	35	39	37	145	78	95	121	71	64	131	274	212
A320																				14	39	146
A321																						
A319																						
A318																						
A320 Total																				14	39	146
DC-9 All	209	159	66	88	44	34	24	28	73	41	21	35	22	41	27	6	2					
MD-80 All													23	27	14	14	19	87	43	117	106	120
MD-90 All																						
717-200																						
DC9 Total	209	159	66	88	44	34	24	28	73	41	21	35	45	68	41	20	21	87	43	117	106	120

Model \Year	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
B727 Total																					
B757 Total	46	148	166	95	50	35	33	12	13	59	44	50	18	43	37	0	7				
747-400 All						14	58	47	43	51	120	31	23	2	16	32	56	36	15	35	26
737-100																					
737-200 All	11																				
737-300	87	89	56	59	28	65	29	32	22	61	51	8	1								
737-400	24	149	52	36	33	25	7	3	15	41	23	4	2								
737-500	55	74	133	16	9	24	2	4	10	53	5	2	2								
737-600									27	10	7	9	3	0	0	0	0	8	5		
737-700 All							63	6	37	78	105	127	81	202	71	35	122	50	106	210	248
737-800 All								22	58	195	115	170	145	170	107	125	78	94	426	457	532
737-900 All											8	34	3	2	10	2	6	0	33	71	70
B737 Total	177	312	241	111	70	114	101	67	169	438	314	354	237	374	188	162	206	152	570	738	850
A320	58	116	126	183	15	72	13	33	39	128	74	195	183	158	98	78	104	180	568	312	676
A321			20	117	3	9	0	20	12	50	50	52	40	69	31	9	7	28	103	104	40
A319								42	30	57	240	190	65	120	46	148	44	67	206	253	185
A318													120	41	0	0	0	4	41	4	13
A320 Total	58	116	146	300	18	81	13	95	81	235	364	437	408	388	175	235	155	279	918	673	914
DC-9 All																					
MD-80 All	88	239	135	50	23	10	10	9	14	17	2	24									
MD-90 All				27	0	26	0	0	39	17	3	4									
717-200									42	0	0	41	0	21	3	32	8	8			
DC9 Total	88	239	135	77	23	36	10	9	95	34	5	69	0	21	3	32	8	8			

Figure 1.2

Chronology Aircraft Orders Boeing/Airbus/McDonnell Douglas 1965-2007

(Developed from Airbus and Boeing websites, 2010)

1.4. Key Research Questions

Key research questions are:

- How could Boeing's strategy with the B737 be replicated for other companies and products? If this is a possibility, the economic impact on companies developing and manufacturing CoPS type products could be improved dramatically.

- Did Boeing employ a strategy to improve the B737s longevity in terms of competition and if so how did it do it? Was it by developing a family or families of models in terms of product platforms, variants of basic models, platform derivatives?

- Was the competitive edge of the B737 maintained by radical or incremental innovations to its design?

- What were the downsides if any of its strategy? For example in its quest to maintain competitiveness and improve product performance, did it lose efficiency in certain market segments? For the same reason were other product lines in Boeing's product lines affected?

- Was the lineage of the B737 an advantage or disadvantage? It may for example be that the infrastructure required to support the aircraft was common to successive generations and hence the user would save on training, tooling, and spare parts costs on a somewhat familiar product. Technology implications however could mean that one could be stuck with obsolete technology.

The first question is really the point of the thesis. Hopefully by analyzing this particular case, a company could maintain product longevity and competitiveness even on an old product line, without having to invest significantly in an old new design. In a CoPS scenario this investment savings would be greatly significant.

1.5. Expected Contribution

While there exists an abundance of innovation literature and CoPS literature, much of the literature that combines both CoPS and innovation usually refer to the problem of CoPS being an oddity where the standard or widely accepted modes of innovation theory may not be applicable. This is mainly due to the high cost, low instances and low rate production of CoPS type products.

This thesis on the other hand offers a potential solution to the problem itself. That is not to say that potential solutions are not already offered in existing literature. However it is rare to find papers that offer concrete evidence of how historically the solutions can be implemented. The problem is that CoPS products by nature are complex and it is probably difficult for the average researcher to study a product that may require in-depth technical knowledge and experience to interpret the data. In fact references to these products such as commercial jet aircraft in published papers are typically superficial in nature. Prencipe (2000) and Miller et al (1995) exceptionally do offer in-depth observatory analysis of the technical issues (aircraft engine control issues and flight simulators respectively) but do not offer real solutions or strategies to respond.

For example one of the solutions offered in this case study is the use of product platforms and the employment of product families. Ulrich and Eppinger (2012) refer to the development of Products Platform as well as Complex Systems but not necessarily in combination as both can exist independently of each other. A non-CoPS commodity type product such as an MP3 player can feature product platforms and families, while it is not necessary for a CoPS product such as a flight simulator to have a product platform or family. Likewise Christensen (1997), Christensen and Raynor (2003), and Christensen et al, (2004) offer good examples of cases for disruptive innovation but not necessarily CoPS type products.

Thus the combination of CoPS, Reverse Disruptive Innovation and Product Platforms is perhaps a unique one where a deliberate strategy is proposed. The case study also offers many smaller cases where a company can use as examples for application to its own unique projects.

A key advantage of such a strategy is to minimize investment expenditure. Hence in an environment of competition companies can use the strategy to assist in defending their product lines. Conversely companies can also use it as a method of offense to encroach upon CoPS type product competitors that are less prepared.

Importantly the strategy proposed as a result of these findings are not proposed as a one and end-all solution. However it is proposed that knowledge of such a strategy and the reasoning behind it could assist company management, particularly those with product development decision making.

“It is true that one cannot think a thought before it has been thought. All that must be asked of a theory, however, is that it helps to evaluate a technology after it has been conceived or to evaluate a business venture after it has been proposed or launched. The theory must provide the ability to predict what will happen to the incumbents and entrants in the future if they take different actions relative to the innovation. The earlier these predictions can be made after conception, of course, the better” (Christensen, 2006).

1.6. *Summary of Results*

The analysis and strategy formulations resulting from the case study of the three generations of the B737 product families show that the traditional theory of CoPS can be improved upon from observing characteristics of low innovation and production rates to a more pro-active role. Using the success of Boeing in managing the B737 product generations and improvements over five decades and fending off the Airbus A320 which has a 20 year later heritage design, a 5 point strategy is proposed.

The strategy consists of taking advantage of the product's heritage, employing product platforms to increase the rate of innovation and production as well as reducing development and manufacturing costs, planning appropriate product family variants, exploiting commonality benefits such as spares support and training to increase attractiveness to the customer, and deciding on next generations of the product platform.

Designing in proven designs of sub-systems from other product lines also mean improved overall production rates for those parts while at the same time reducing development costs. A hybrid design of components to be considered is a "carry over-modified" part which in essence is an old design but adapted to a new requirement to enhance its performance. This way much of the commonality and proven design of the old part is maintained and obsolescence is averted.

Reverse Disruption Innovation is offered as a new strategy to be used for older products being attacked by newer technology products. In this scenario, the roles of the defending incumbent and the attacking new entrant are reversed from traditional Disruptive Innovation theory. The incumbent can defend by improving existing designs just good enough using the strategies outlined above to maintain customer appeal.

Accordingly a contribution to CoPS theory is offered in that a product manager can use these strategies to develop a CoPS project or maintain an otherwise aging product line without the investments required for a completely new development design.

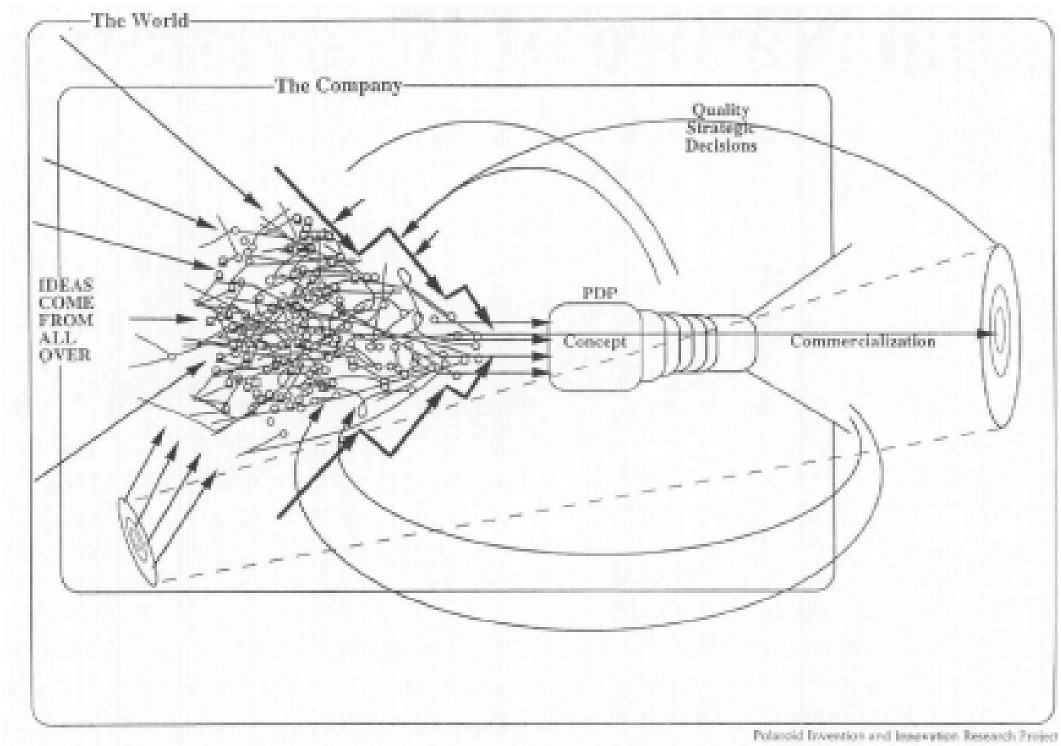
2. Literature Review & Interpretations

2.1. Permutation as Innovation

Innovation is often misconceived as something to do with inventions or new technology. While technology certainly is often part of it, it doesn't necessarily have to be new. The Austrian Economist Josef Schumpeter (1947) presented a distinction between an inventor and entrepreneur. "The inventor produces ideas, the *entrepreneur* 'gets things done', which may but need not embody anything that is *scientifically* new". The term *entrepreneur* implies commercialization of the technology, which may or may not necessarily be recent. "Getting things done" also implies a whole slew of activities from development and manufacturing to sales and support.

Similarly Freeman (2004) notes "An invention is an idea, a sketch or model for a new or improved device, product, process or system. Such inventions may often (not always) be patented but they do not necessarily lead to technical innovations. In fact the majority do not. An innovation in the economic sense is accomplished only with the first commercial transaction involving the new product, process system or device, although the word is used also to describe the whole process."

This helps set a model that includes the notion of combining a technology with commercialization. Higgins (1995) confirms by saying "Innovation is the process of something new that has significant value to an individual, a group, an organization, an industry, or a society. Innovation is how a firm or an individual makes money from creativity."



Innovation flows through three very different phases in order to produce eventual commercial success. But organizations become less innovative as they age.

<u>Figure 2.1</u>

<u>Polaroid Invention and Innovation Research Project</u>

<u>(Buckler, 1997)</u>

Rothwell (1986) includes the "market" factor as a necessity in his definitions of innovation, noting for example that increased R&D rates alone do not necessarily increase innovation rates. Schumpeter observed that a characteristic of entrepreneurship can be "the doing of things that are *already* being done in a *new way* (innovation)"

(Schumpeter, 1991). This is also a key point towards recognizing that the commercialization aspect depends on the *application* of that technology. Hence a simple model of innovation can be visualized as below. While simplistic, the model does indicate that innovation can occur with relevant combinations of any or several of these combinations.

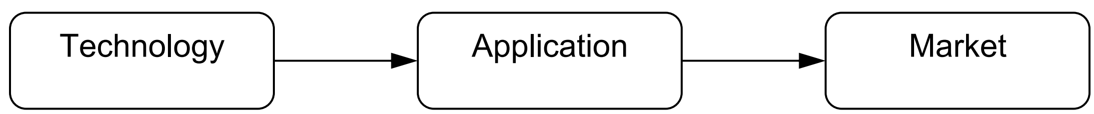


Figure 2.2
Basic Innovation Model

Notably Schumpeter observed that "the 'new thing' need not be spectacular or of historic importance". This simple observation gives a realization that the model above can be permutated without a date stamp to develop what could be called a new innovation. In other words an old technology can be used with a different application (also not necessarily new), to develop a new market.

As an example, a relatively old technology light bulb normally used to produce light, can be also used in a different application to give warmth to baby chicks from the heat it gives out. Similarly a laser beam can be used in a myriad of applications and markets from tool alignment to eye surgery.

Levinthal (1998) quotes “A key element of innovative activity is the identification of promising domains of application for existing technologies”. Hence we see that it is the new permutation commercialized that is the innovation, rather than the individual newness of any of the components of Technology, Application, or Market. This implication is crucial towards understanding how seemingly “old” products such as the Boeing 737 can be maintained in a competitive environment.

Figure 2.3 illustrates these permutation possibilities. Scenario ‘I’ shows a singular technology, application, and market. Scenario ‘II’ gives an example where a new technology ‘B” is introduced but is used with the same application and market. Scenario ‘III’ offers a new application ‘B’, and subsequently a new market ‘B’ for technology ‘B’.

This does not prevent the ‘old’ technology ‘A’ to be used for a completely different application ‘C’ in a new market ‘C’ in Scenario ‘IV’. Nor does it prevent any of the previous combinations, say technology ‘B’ with application ‘A’ to be applied to yet another different market ‘D’ as in Scenario ‘V’. Hence the permutations provide the expansion of possible innovations as illustrated by the diverging dashed lines in scenario ‘V’. Notably the notion of ‘new’ or ‘old’ technology is not an issue. It is the newness of the permutation combining the components of technology, application, and market, that determines the newness of the innovation.

Arthur (2009) describes similarly that novel technologies are made possible by a combination of existing technologies, and “that technology creates itself out of itself”.

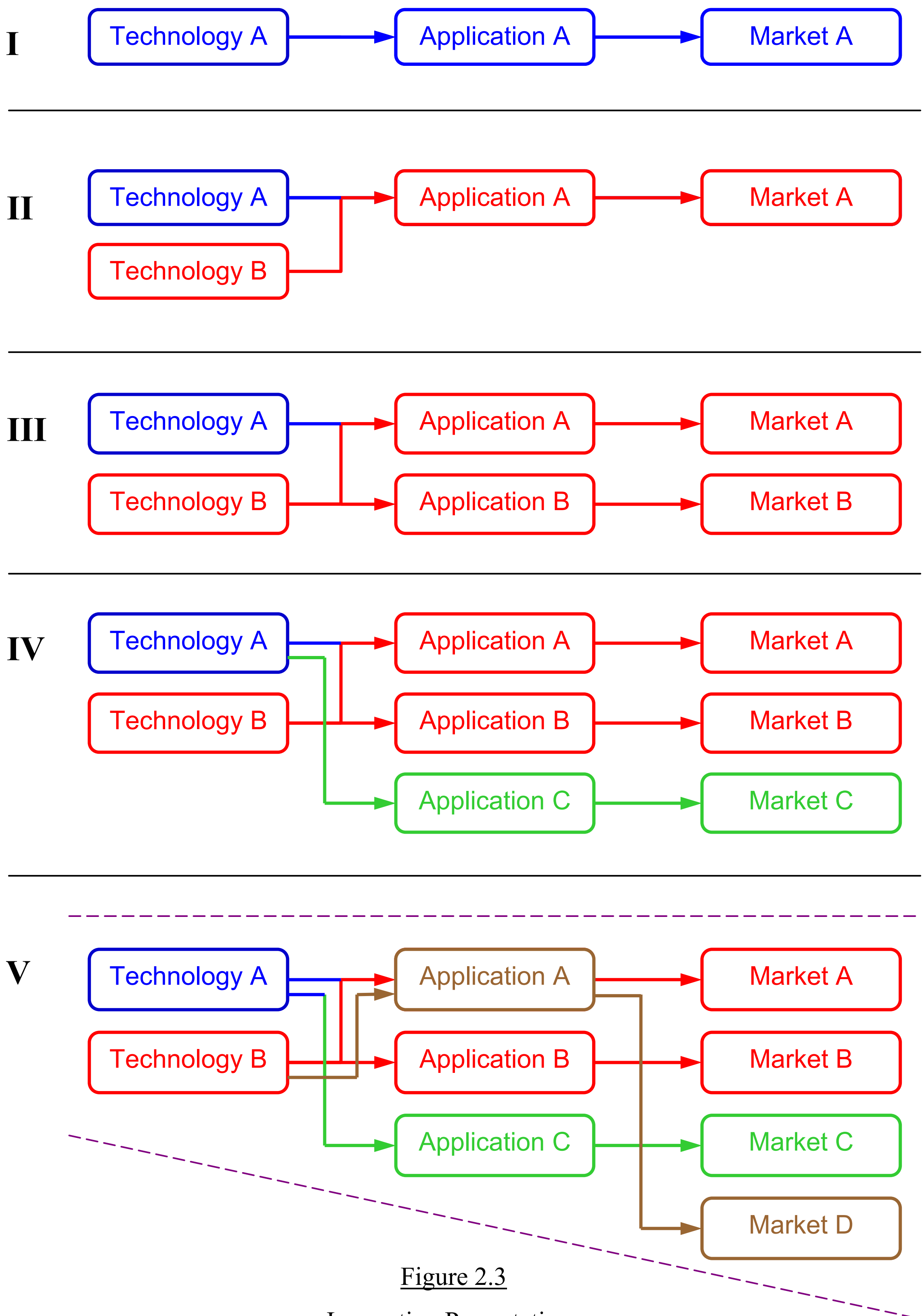


Figure 2.3

Innovation Permutations

2.2. Types of Innovation

There are different interpretation variations of innovation, depending on the nature of the study. For example Zawislak et al (2008) suggest a slightly different model to include entrepreneurship, institutions, capabilities, and capital. Damanpour (1991) and Higgins (1995) refer to innovation characteristics that refer to the organization rather than just a product. Howells (2000) describes innovation with reference to services provided.

The Oslo Manual (OECD-Eurostat, 2005) states that "The minimum requirement for an innovation is that the product, process, marketing method or organizational method must be new (or significantly improved) to the firm. This includes products, processes and methods that firms are the first to develop and those that have been adopted from other firms or organizations" and defines four types of innovations; product innovations, process innovations, organizational innovations, and marketing innovations.

"Product innovations involve significant changes in the capabilities of goods or services." Importantly, "Both entirely new goods and services and *significant improvements to existing products* are included." Meanwhile "Process innovations represent significant changes in production and delivery methods." Also "Organizational innovations refer to the implementation of new organizational methods. These can be changes in business practices, in workplace organization or in the firm's external relations." While "Marketing innovations involve the implementation of new marketing methods. These can include changes in product design and packaging, in product promotion and placement, and in methods for pricing goods and services."

In this thesis the focus will be more on the product type of innovation. However the separation between product and process innovations is not mutually distinct. "Indeed process innovation may often result in subsequent product innovation and vice versa" (Neely et al, 2001). Similarly market innovation is somewhat intertwined in this thesis since the study is on how to develop existing product designs for evolving markets. Johne (1999) for example notes that a customer may be served with essentially the same core product but differentiated slightly to extract different revenues, e.g. between first and economy class travel on an airplane. "Each usage need presents a potential market opportunity" (Johne, 1999).

Beyond a basic model, successful innovations can also have different effects on an industry. Small changes can be deemed as incremental with minor effect, while others can be significant, resulting in closures of businesses and meteoric improvements of others. The latter reflects Schumpeter's theory of "Creative Destruction" where he postulates that new ways of doing things can destroy existing firms and infrastructures based on old knowledge and distribution channels (Schumpeter, 1942; Schumpeter, 1991). Hence considering the issues of existing knowledge and experience can assist understanding the distinction between radical versus incremental innovation.

Incremental innovations take the form of simple and minor changes to the product or application. Zirger (1997) describes well the advantages of incremental innovations that take advantage of an organization's existing know-how and furthermore promotes the benefits of experience via "Building on experience provides competitive advantages in three areas: strengthening core competencies, reducing product costs and improving time to market for new products."

Radical innovation is not simple to define however. Dewar and Dutton (1986) for example note two significant differences between radical and incremental innovation are the impacts to knowledge and risk. In radical innovations, often the knowledge base is different and in doing so the risk can be higher. Using a different knowledge base means that companies have to change completely their core competencies to adapt to the new innovation. However the context here is mostly technological and the relation to the basic model described earlier which includes the ability to permute technologies, applications and markets is not clear.

Alternatively the radical component can mean a significant jump in product performance, leading a customer's perception of a greatly improved product that could mean like significant changes and associated benefits in the way they use the product. Anderson and Tushman (1990) termed "Technological Discontinuities" as innovations that dramatically advance an industry's price vs. performance frontier. Ehrnberg (1995) quotes "The lower the price and the costs of switching over to the new substitute and the higher its technical performance, the higher is the new product's relative advantage".

		Performance Improvement	
		Low	High
Scope of New Knowledge	Small	Incremental innovation	Radical innovation (sense of Performance)
	Large	Radical innovation (sense of Knowledge)	Radical-Square (r^2) Innovation

Figure 2.4

Types of Radical Innovation Model

(Murmann et al, 2006)

Murmann et al (2006) combines both knowledge and performance concepts as above. In fact they coin an innovation that has both a significant performance gain and a requirement for new knowledge as *radical-square* (r^2) innovation.

A more sophisticated model is given by Abernathy and Clark (1985) who include the notion of preserving or replacing linkages as well as competencies. “Architectural Innovation” as they define, disrupts the technological knowledge bases as well as the linkages for suppliers, distributors, markets together with supporting and downstream industries. However such innovations revert to “regular” innovations after awhile when a dominant design appears as relative new knowledge and experience accumulate with time.

Utterback and Abernathy (1975), Utterback and Suárez (1993), Anderson and Tushman (1990), Murmann et al (2006), all discuss dominant design but a common theme is that the firm with that dominant design can have a more monopolistic run in the beginning, while the activity of firms adopting similar design configurations peak shortly after.

Following this standardization occurs and this then creates an industry in both the supply and demand side that can handle the production of this design configuration. With time, the industry continues to improve the process and product in incremental type innovations and thus matures the design. A “mature” *design* however does not mean radical *innovations* are not possible, keeping in mind again that innovation is not just about technology or a design.

What is interesting about the Abernathy and Clark’s 1985 paper is that they look for a “de-maturity” events, i.e. changes that can afford new innovations with existing product-application-market environments. This is quite exciting theory for a company with a product and market that may perhaps be quite mature with expectations of an eventual decline in business. The three changes quoted are:

a) Technical options that open up possibilities in performance or new applications that the existing design concepts could meet only with great difficulty or not at all.
b) Changes in customer demands that may impose requirements best met with new design approaches.

c) Regulatory changes that may set technical requirements or demand performance standards that favour revolutionary or architectural strategic development. De-regulation may have the same effect.

It will be seen later that all three of these points affected the Boeing 737's evolution towards de-maturity to maintain competitiveness.

Henderson and Clark (1990) summarize four types of innovation neatly as shown in the figure below. They describe Modular Innovation briefly as one where the product can change but linkages remain as in replacing an analogue telephone with a digital one.

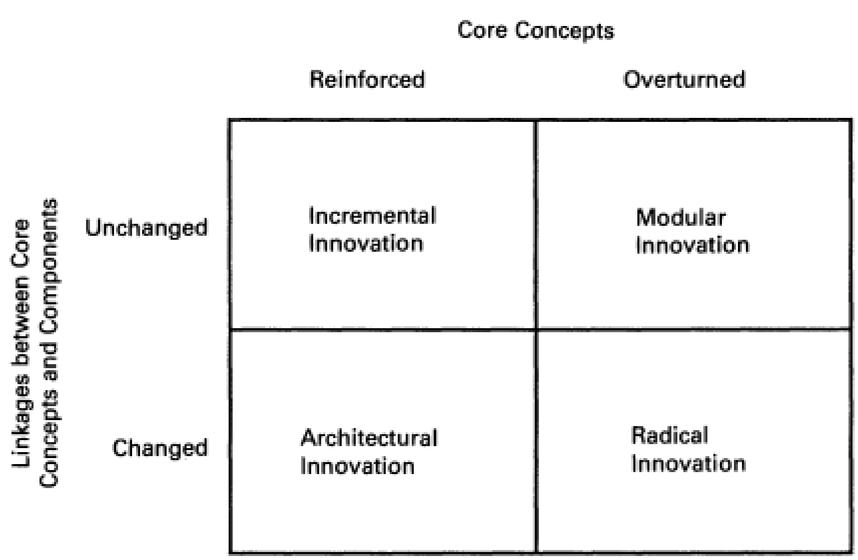


Figure 2.5

Innovation Framework

(Henderson and Clark, 1990)

In practice innovations are not so neatly categorized and maybe aberrations of several categories. One could argue for example that the mobile or cellular telephone is a modular innovation since initially it still used the same utility companies and could dial to and from existing landline telephones. However the advent of cheaper mobile telephones, SMS Text messaging, and international roaming facilities would hint that the industry evolution has moved to an architectural innovation where new linkages have been developed and traditional distribution channels are somewhat challenged.

Ulrich (1995) alludes further into types of product architecture and in particular discusses issues with intermixing singular function components to become products with more integration. Figure 2.6 for example shows a design with components that have singular functions, whereas Figure 2.7 demonstrates how a design could potentially utilize components that could support more than one function.

Note for example that “The upper and lower halves of the trailer have slots cut in them. The strip of material remaining between two slots acts as a leaf spring. The cargo is hung by straps from the two springs in the upper half. The axle is attached to the spring in the lower half. Covers, shown shaded, are attached over the slots. The nose piece is the component containing the trailer hitch.” A functional element can also be supported by more than one component.

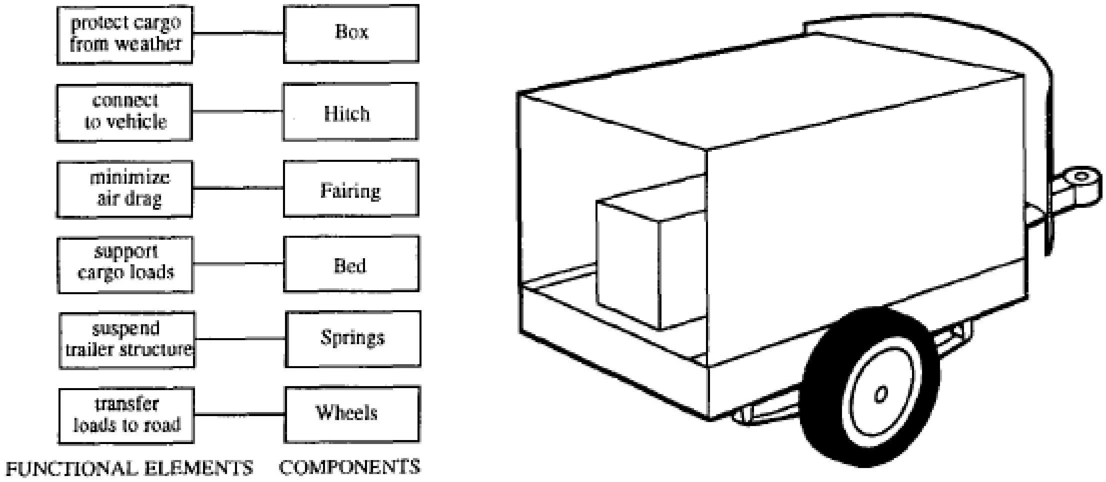


Figure 2.6

A modular trailer architecture exhibiting a one-to-one mapping from functional elements to physical components.

(Ulrich 1995)

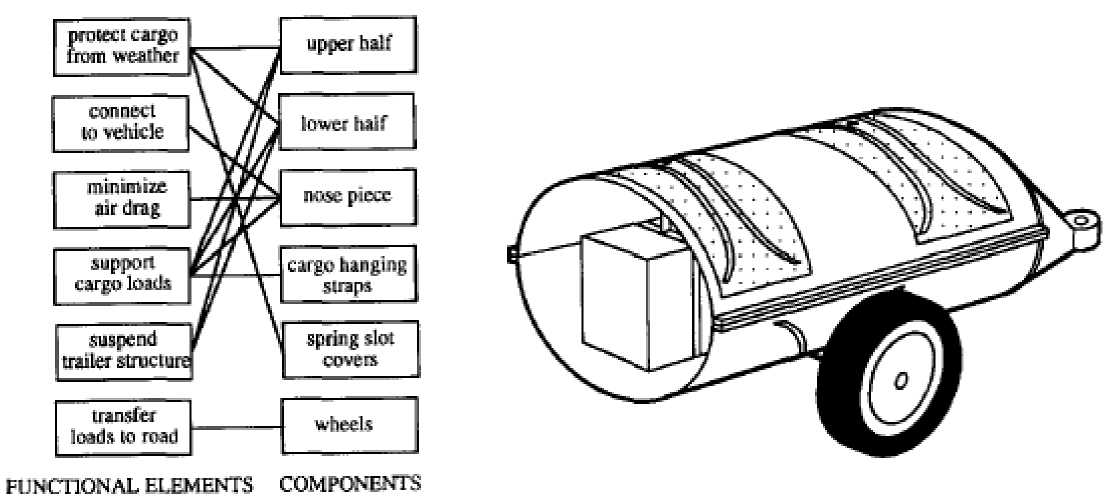


Figure 2.7

An integral trailer architecture exhibiting a complex mapping from functional elements to physical components.

(Ulrich 1995)

Ulrich also illustrates interesting examples of system architecture as per below, between "Integral" and "Sectional" types. In the "Integral" design, all components and functions are combined into one. It makes for a much neater and compact design and can be more efficient in terms of infrastructure (boxes, cables, power supplies etc.). Should a single component should fail or become obsolete however, the risk is that the whole product can be at similar risk.

The "Sectional" design on the other hand may be less tidy but offers more modularity and allows changing or upgrade of any component without requiring a re-design of the whole system. For this particular example, standards such as the USB or Universal Serial Bus connector system accentuate this advantage further.

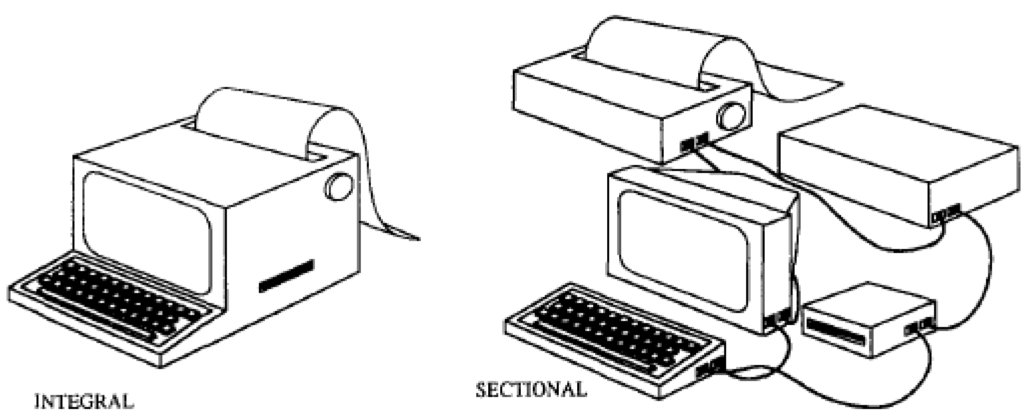


Figure 2.8
Integral vs. Sectional Systems
(Ulrich 1995)

Baldwin and Clark (2006) go even further into this by describing how architectural innovation can be utilized where a smaller technological footprint of the firm of the overall system allows a strategy to outsource the other parts for faster development by specialist firms but development of the key components are maintained by the incumbent firm. That way the firm can maintain its competitive edge as well as develop and bring to market products faster than competitors.

2.3. Product Life Cycle

Complex products may not necessarily follow a simple pattern of innovation. Rothwell and Gardiner (1985a) for example extract the figure below of an innovation model that reflects development, feedback, re-development, and eventual maturity. Rothwell (1986) quotes that innovation should not be mistaken as a clearly bounded process that somehow "terminates once the original new product reaches the marketplace.

In practice, technological innovation is a dynamic, iterative process rather than a one-off event". Carlsson and Stankiewicz (1991) note that innovation tends to be an interactive process, sometimes between producers and users, sometimes between producers, and sometimes amongst organizational networks.

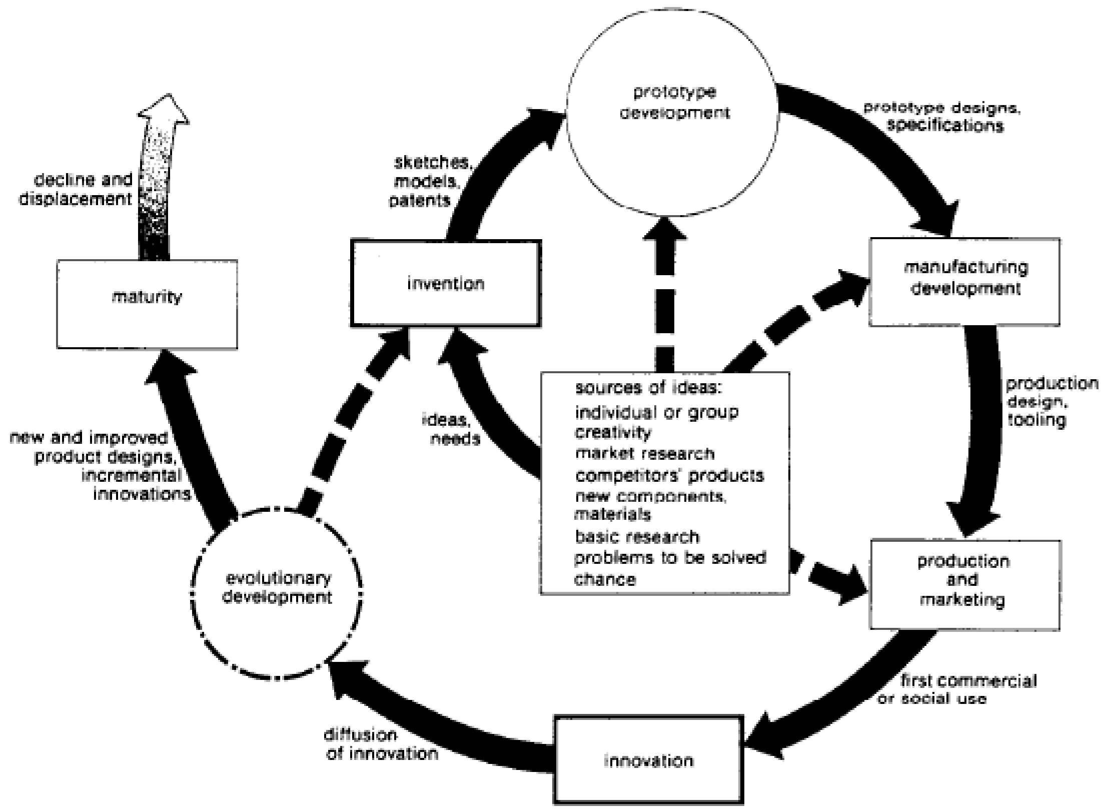


Figure 2.9

Model of the evolution of a successful invention

(Rothwell and Gardiner, 1985a)

What is interesting is the inclusion of *time* (re-development, maturity etc.). Products evolve, and so do markets. Lynn et al (1996) describe how complex products need to go through a "Probe and Learn" process where several market failures can occur before the successful dominant design is established. In the process the company improves the product and tries to match the market. Often the market itself may not be ready for such a product and does not yet know how to adapt.

In the case of Lynn et al's (1996) examples of Motorola's cellular phone, Searle's Nutrasweet, GE's CT scanner, and Corning's optical fiber, the industry beyond manufacturing also changed. The term "architectural" innovation becomes more appropriate as obviously the linkages with suppliers and distributors all had to adapt somewhat.

For a complex product or system, this time factor can be relatively large to the point where perhaps the technologies themselves can be obsolete before the project is completed. Even worse the production quantities may be very small or singular. As a result the linkages with suppliers and manufacturing can also face premature obsolescence and a vicious cycle develops that inevitably drives up technical difficulties and costs up. More importantly the feedback cycle necessary to fully mature a product may not be attained due to the low rate of production.

2.4. Disruptive Innovation

Particularly with respect to technological changes, Utterback and Brown (1972) highlighted the importance of monitoring for changes in the environment. In their study of the supply of silver for the photographic industry, even non-technological "signs" such as the demand being greater than supply of silver in the 1970s can be an indicator for an impetus to improve technology to reduce the consumption or find alternatives altogether. More significantly, the rate of technological change should be monitored just as importantly as technology itself. Combined, these issues can be threats or opportunities for a business.

In their paper "Strategic Responses to Technological Threats", Cooper and Schendel (1976) with a study of several firms faced with new competition with new technologies and innovations describe quite well what could be the foundations of "Disruptive Innovation". They note that the new technologies at first could be quite crude to the point of being ignored but the incumbent firms.

However, often the new technologies would improve at a rate that eventually caught up and supersede the capabilities and costs of the older technologies. Secondly despite being crude, the new technologies would get a beach head by certain submarkets where they might have an advantage such as cost where the existing technologies might never be applied.

In response many of the incumbent firms could reduce their dependence on submarkets and/or try to compete by improving the old technologies. Notably the old technology, such as vacuum tubes used in electronics, “reached its highest stage of technical development *after* the new technology was introduced” (Cooper & Schendel, 1976). Notably the decision to commit resources to new and, or old technology can be difficult, as often the old technology markets indicated significant financial return while new and immature technologies pose a degree of risk and uncertainty.

Cooper and Smith (1992) indicated that even if a firm decided to try the new technology, the likelihood of failure was high and the commitment was very much just a token effort with the company pulling out shortly after. Recognition and possible re-entry was only considered after other firms had succeeded and a ‘dominant design’ was established. The disadvantage of this is that a late entry into the market can mean a loss of profit margin as prices can begin falling with commoditization of the product. The R&D effort will also be behind other firms that have already a head start in the technology.

Timex was an example when despite having entered electronic watch manufacturing early, preferred to concentrate on mechanical watches. By the time it decided to commit to electronic watches, prices for electronic watches had begin to fall and other producers could produce superior models at lower costs.

“While most of the firms examined made substantial commitments over time, these investments were made only after the potential of the new product had become apparent. Such firms seemed to harbor the expectation (initially) that the new product would not penetrate the core markets of the traditional business. In several cases, there were also concerns that the new product's early imperfections could tarnish the firm's reputation; as such, there was a reluctance to make a full commitment until the product was "proven." In virtually every case, however, these companies appeared to underestimate the ability of firms from outside the established industry to overcome important technological obstacles, to gain market acceptance for the new product, and to establish a defensible competitive position. Only after the miscalculation became apparent did these firms begin to mount a more vigorous effort” (Cooper and Smith, 1992).

Finally Cooper and Smith also note that incumbent firms adopting new technologies are also faced with the challenge of integrating supply, manufacturing, distribution and support for the products in organizations designed for the old technologies. Even if separate divisions are created, rivalries and different corporate values can give management headaches in the transition period.

In 1997 Clayton Christensen published his best selling book “The Innovator’s Dilemma”. Using examples of excavators, computer disk drives, and steel mills, the basis of Clayton Christiansen’s disruptive innovation theory is that established companies are often though subtly disrupted by entrants with new types of products that have less performance capabilities than the established products, but which may be cheaper and still meet customers' needs.

In many cases the customers are new ones for which the established companies products are too high end as they develop and improve along a technological rate that is often faster than the customers ability to absorb those technologies. As with Utterback and Brown (1972) the rate of change is a key issue. As the new entrants gain a foothold at the low end of the market, they grow stronger and eventually improve their products so as to compete and threaten the established companies.

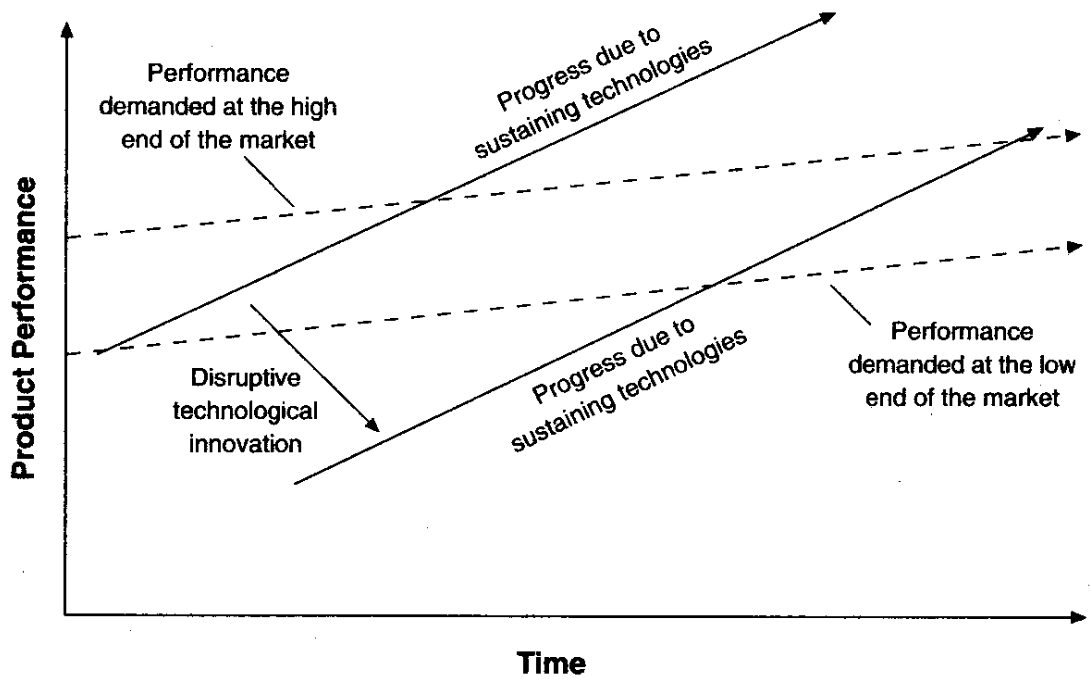


Figure 2.10

The Impact of Sustaining and Disruptive Technological Change

(Christensen, 1997)

Introduced was a concept that "Good Management" is in fact responsible for subsequent failures of otherwise successful firms faced with disruptive competition. This occurs when incumbent firms may choose to give up low end low profit margin markets to the entrants and are rewarded by higher profit margins with the remaining higher end markets. However this cycle keeps going higher and higher end until the incumbent firms run out of high margin markets to sustain their business.

The book encompasses the work of Bower and Christensen (1995) and Bower and Christensen (1996). Bower and Christensen (1996) highlight the difficulty of decision making towards resource allocation between existing proven and new but risky technologies, as did Cooper & Schendel (1976). Bower and Christensen (1995), as with Cooper & Schendel (1976), stresses the possible need to place new disruptive technologies in separate divisions or organizations of an incumbent company that already has a successful operation with the old technology. As an addition Lansiti, McFarlan and Westerman (2003) note that autonomous divisions to promote the new technology should at some point be re-integrated to the main company to realize the long term benefit of the then recognized product.

Aside from cost, new products can also enter via new markets where the different characteristics of the new products may be valued differently to the existing products. But upon entering, eventual improvements can make them better such that they threaten and possibly supersede the existing technologies as in Fig 2.11. This matches Cooper & Schendel's (1976) findings where new products can enter via "sub-markets".

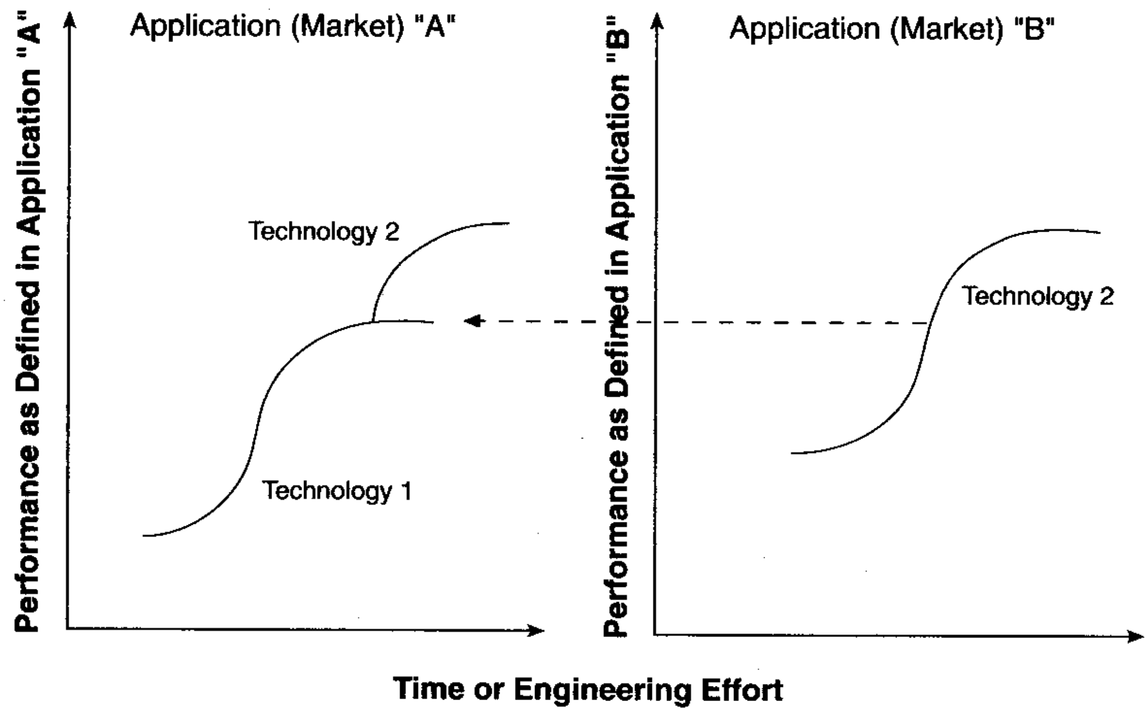


Figure 2.11

Disruptive Technology S-Curve

(Christensen, 1997)

The use of "S-curves" however is somewhat vague as not all products may follow that shape. Christensen and Raynor (2003) clarified the distinction between Low-End and New-Market Disruptions which is better illustrated in Figure 2.12. Daneels (2004) amongst discussing many possible interpretations of aspects of the theory prefer the latter definition of Disruptive Technology using different product attributes as the differentiating measure that makes it attractive for the new market.

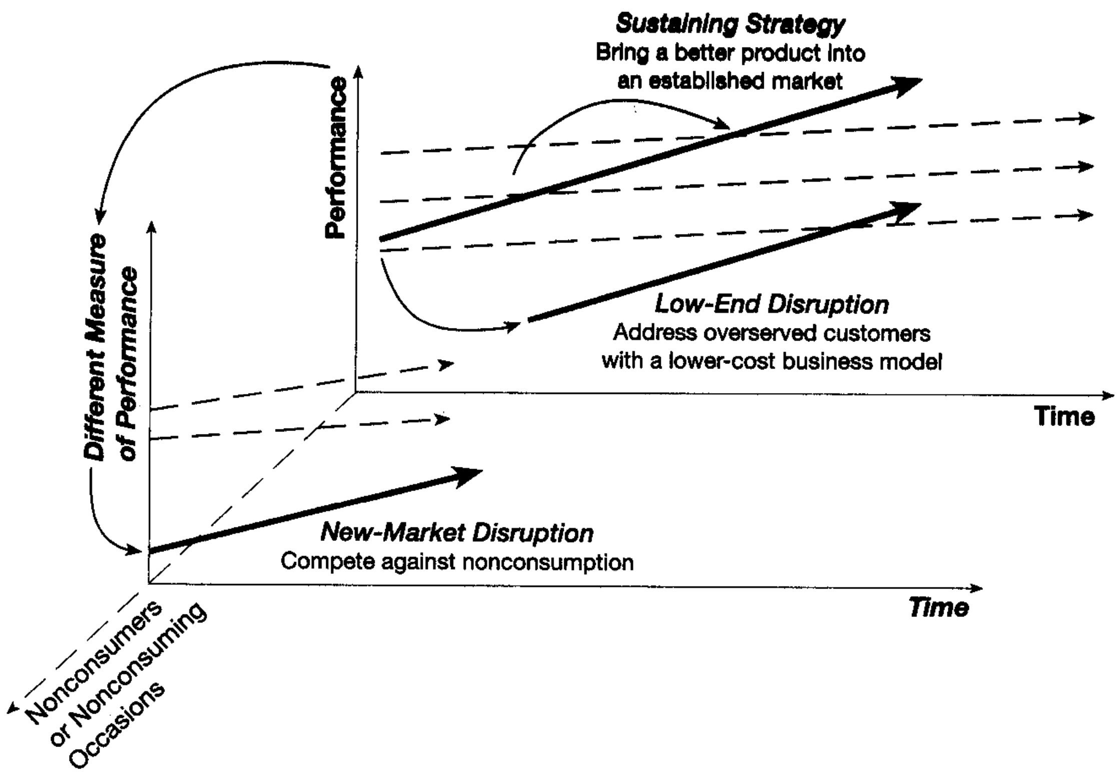


Figure 2.12

The Third Dimension of the Disruptive Innovation Model

(Christensen and Raynor, 2003)

Christensen and Raynor (2003) also begin to use the term "Disruptive Innovation" rather than "Disruptive Technology" as Christensen (2006) notes that he eventually understood that it was the business model and not the technology itself that was the key issue.

> "In 1997 just after The Innovator's Dilemma was published, in a personal conversation Andy Grove surfaced an anomaly that helped me see I had defined it wrong, as he recounted how Digital Equipment Corporation (DEC) was disrupted by makers of microprocessor-based computers. He said, 'It wasn't a technology

> problem. Digital's engineers could design a PC with their eyes shut. It was a business model problem, and that's what made the PC so difficult for DEC.'
>
> He noted that in the early 1980s proposals to make PCs promised 40% gross margins on machines that could be sold for $2,000. What is more, none of DEC's customers could use them. These proposals were competing for resources against proposals to make more powerful computers than DEC had ever made before. These promised gross margins of 60% on machines that could sell for $500,000. It was the attractiveness of the opportunity relative to the company's business model that made the sustaining path attractive and the disruptive path unattractive" (Christensen and Raynor, 2003; Christensen, 2006).

Walsh, Kirchhoff, and Newbert (2002) in their study of time-to-market of disruptive innovations observed significantly that as existing incumbents tended to follow sustaining type product innovations, these equated to "Market-Pull" strategies whereas a new company with disruptive technology would tend towards "Technology-Push" strategy.

The major difference would be that while the Market-Pull would simply mean a replacement or substitute event using existing organizational channels, the Technology-Push scenario meant a destructive type effect requiring new forms of distribution and support. On the other hand, when incumbents tried to perform a Technology-Push, it tended to be sold as an improvement type technology, again emphasizing existing channels. This inflexibility allows new firms to be faster in innovating.

“Surprisingly, the lack of an established customer base is an advantage for the new firms attempting to market their new technology. Unfettered by demands from existing customers for improvements on existing products based upon evolutionary technologies, new firms can be flexible about to whom they chose to sell and what applications can be profitably produced and sold. It is this flexibility that probably underlies the much smaller cycle time in ‘prototype to first sale’ ” (Walsh, et al, 2002)

While Christensen, Suarez, and Utterback (1998) stressed the implications of recognizing the emergence of a dominant design for entry into a new technology arena, Christensen and Raynor (2003) provide an excellence reference for product architecture at which points an integrated or modular design is best optimized.

When the technology is still in its infancy, an integrated design may be best to optimize the performance which is still not up to the expectations of the customer. However once the technology is working and well and subsequent improvements start towards exceeding customer performance requirements, then a modularized architecture allows an organization to compete better with optimized processes such as in sales, marketing and support.

Hence in Figure 2.13, an integrated architecture type design is optimal on the left hand side while a modular architecture type design is optimal on the right hand side. The important parameter for the company is to monitor where the product is relative to customer expectations to assist in deciding when to start switching design architectures.

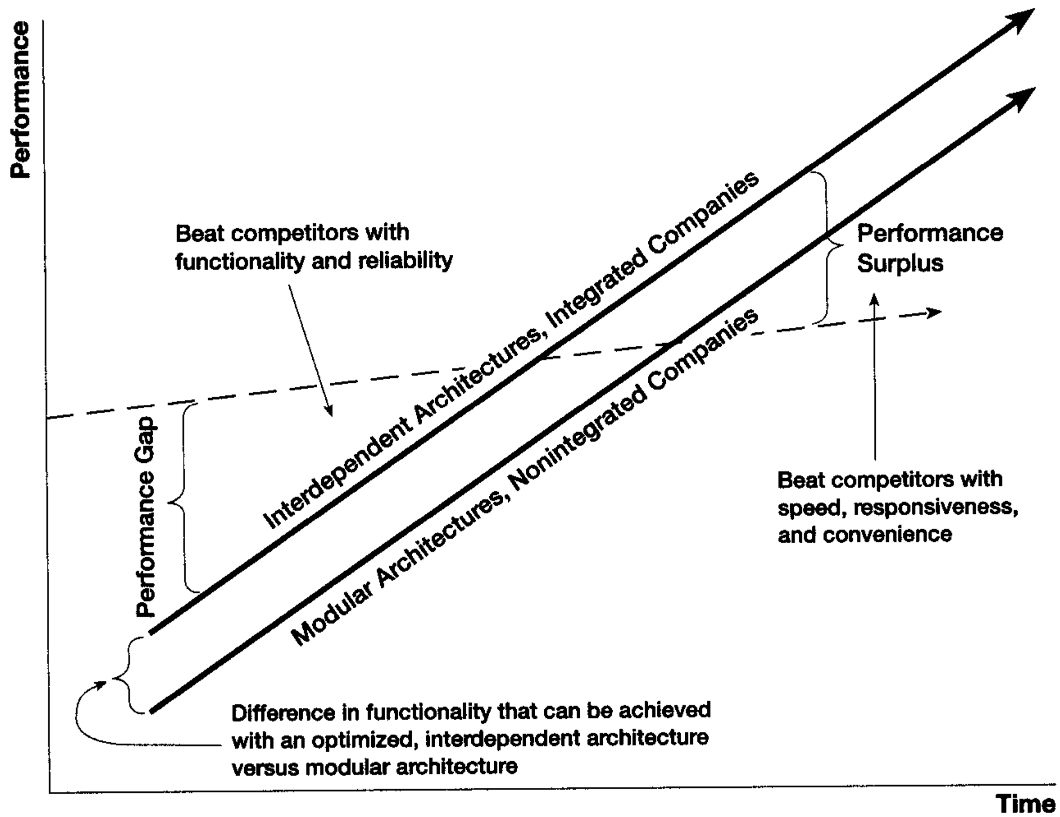


Figure 2.13

Product Architecture and Integration

(Christensen and Raynor 2003)

While Christensen, Johnson, and Rigby (2002) describe how to grow disruptive businesses, what then does one do if one is the incumbent being attacked? Charitou and Markides (2003) offer, though non-conclusive, a variety of response strategies. Perhaps the most interesting strategy is to "develop a third game, attacking the innovators by emphasizing still different product attributes" since that was innovator's strategy in the first place.

Traditional airline Air Canada for example, when confronted by the emergence of low cost carrier Westjet, fought back by emphasizing Aeroplan, its frequent flyer program which Westjet did not have. Furthermore Aeroplan provided the ability to earn free flights on overseas destinations, again an attribute that domestic carrier Westjet could not offer.

Tellis (2006) emphasizes that while case examples such as that used by Christensen and colleagues can illustrate a phenomena, the reaction or pro-action towards a disruptive innovation can be affected by "Visionary Leadership". That is, the strategists of firms can positively and actively try to foresee future events and be part of a new strategy either offensively or defensively. It is not a helpless situation.

No matter which strategy is taken however incumbents often fail to see that a disruptive technology, particularly those that seek entry via new attributes, actually open up new markets. In the event the new technology is successful, that market can grow to a significant size. If the strategy chosen was to take advantage of this new market, then even if the old market is replaced or reduced to a minority by the new market, the incumbent then will be in a strong position long term.

In the defense of its business, incumbents typically have time to strategize and action as new technologies can in fact take years to mature, especially since incumbents would be financially and organizationally stronger than new entrants initially. The key is in recognizing the situation early on (Gilbert, 2003).

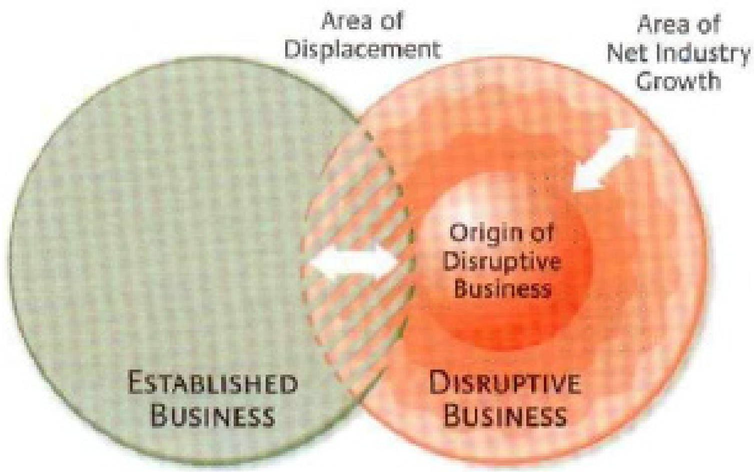


Figure 2,14

Disruption as an Opportunity for Growth

(Gilbert, 2003)

In fact Paap and Katz (2004) endorse a "dualism" whereby incumbents should in fact by focusing on the needs of customers to manage both continuing sustaining actions, while at the same time incorporating potential disruptive innovations to enable future competitiveness. In effect this means a monitoring function of the technological environment as Utterback and Brown (1972) mentioned in 1972.

Danneels (2004) points out an important aspect that Christensen's findings about firms listening too much to major current customers are often miss-interpreted to be against customer orientation. Instead the interpretation is "that firms should not be focused narrowly on serving current customers and should not allocate all their resources to serving current customers". Thus both current and potential future customers should be considered.

Schmidt (2004), Utterback and Acee (2005), Schmidt and Druehl (2008), Sood and Tellis (2011), offer an enlightening twist that disruptive innovations can also occur from products that come in with higher price and higher performance with a similar procession of events where the new technology eventually takes over the old. Utterback and Acee give the example of audio compact discs and digital cameras that subsequently took over the cassette tape/vinyl records and film cameras as their costs and performance improved with time.

Cost	Traditional performance	Ancillary performance	Examples
Lower	Lower	Higher	Christensen case Hard disc drives
Lower	Higher	Higher	Compact disc/ vinyl album
Lower	Lower	Lower	Wafer board/ plywood
Lower	Higher	Lower	Oriented strand board/plywood
Higher	Lower	Higher	Digital/ film camera
Higher	Higher	Higher	Fuel injection/ carburetor
Higher	Lower	Lower	Wartime substitutes
Higher	Higher	Lower	Electronic calculator/ slide rule

Figure 2.15

A Map of Possibilities of Competitive Advantage due to Technological Change (Utterback and Acee, 2005).

Markides (2006) further argues that in the description of Disruptive Innovation, there should be a separate category of Business-Model Innovations which are quite different from Technological Innovations. As the name suggests, Business-Model Innovations are those that do not discover new products or services, but redefine the existing product or service and how it is provided to the customer. Such innovations, such as Low-Cost airlines or internet book sellers, are different from technological innovations in that they can be largely successful in attaining market share, but only in the sense that it is just a segment of the market. They never replace the old business model completely as would a technological innovation such as audio compact discs versus cassette tapes.

However one could argue the converse also. Some new technologies might never replace old technologies entirely either if the old value attribute is still in demand by certain sectors of the market. For example electronic laser measurement devices could replace plain old rulers and tape measures but the market for the latter products still exists for e.g. students and carpenters. Similarly there may be cases where business model innovations are winning a complete market takeover such as electronic airline tickets which are making paper tickets obsolete. Perhaps the important issue is to simply recognize the existence of different markets as per Gilbert (2003).

Using 'good tasting' chocolate bars ("conventional confectionery") versus 'healthy' energy bars as an example, Henderson (2006) offers an illustration of this as shown in Figure 2.16 where the different performance attribute dimensions are used as axes on a chart. This helps to differentiation of the target markets and provides a decision tool if the manufacturers wished to use one product to attack the market of the other, e.g. by making the energy bars taste better, or creating at least a perceived healthier content of conventional confectionery.

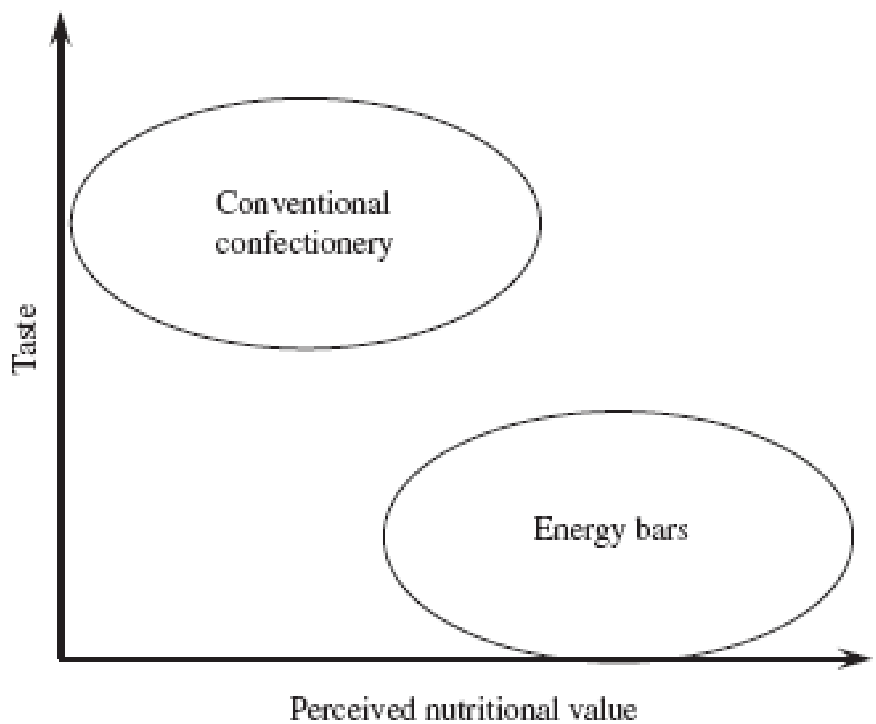


Figure 2.16

A Simple Market Map for Chocolate Confectionary

Henderson (2006)

A similar chart is offered by Sood and Tellis (2011) as in Figure 2.17 where the "Niche" product eventually improves to participate in the "Mainstream Customers" market at a later time (t_2), whereas the dominant technology ($T_{dominant}$) by that time has improved to a point beyond customers needs.

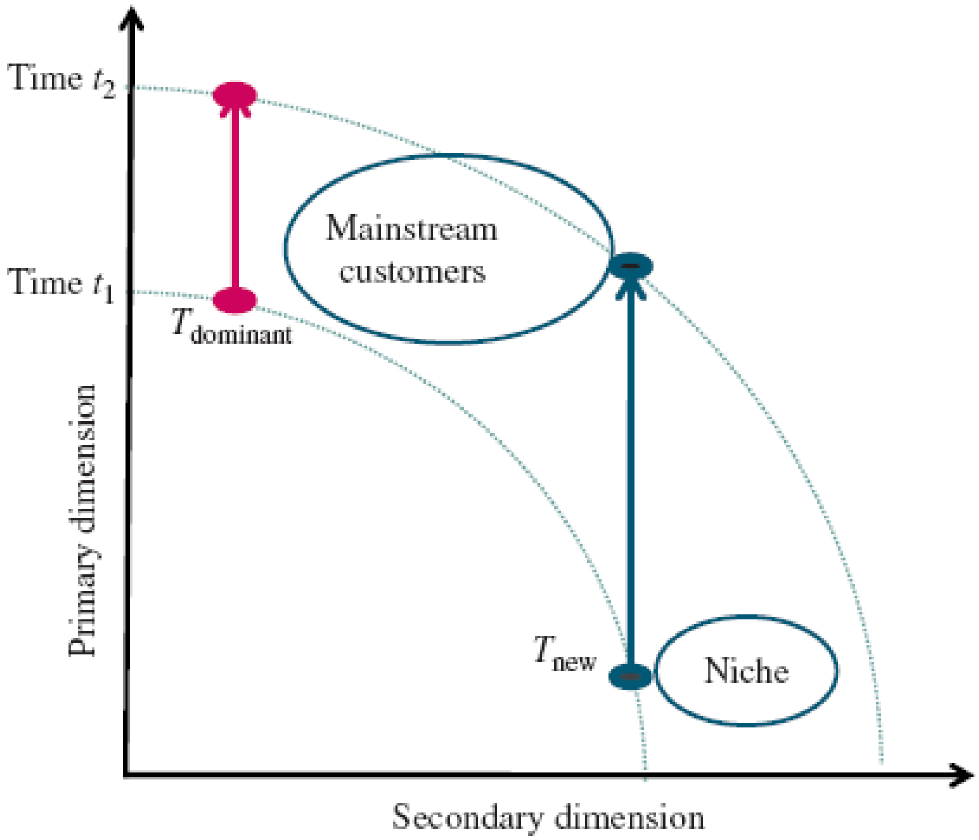


Figure 2,17

Dynamics of Competition

(Sood and Tellis, 2011)

Sood and Tellis (2011) attempt to develop a model for predicting Disruptive Technologies and their findings indicate that technologies that attack from a lower performance point are frequently introduced by incumbents as new entrants rather than from completely new entrants, and are not necessarily cheaper than old technologies.

They claim that their results apply to platform technologies but offer little evidence why. However they do admit limitations due to the size of the study.

As a good reference, Christensen (2002) quotes four rules of innovation:

- Take Root in Disruption

  Disruptive companies aim at low end market segments with products that are not as good but the incumbent companies are motivated not to compete and may even exit those markets as the low end markets have low margins. The new entrant products may not have all the functionality of the incumbent's more developed product but with a lower price point they offer a convenient alternative to consumers who might otherwise not be able to afford the incumbent's product.

- Pick the Scope Needed to Succeed

  The scope of success depends on the stage at which the product development is at. If further improvements are still needed to meet customers' basic needs, then an integrated company could effect those improvements to stay ahead with proprietary type product architectures across different components that are difficult to imitate. However if those basic needs are already met then modularity with standardized interfaces would be the environment and the focus should then be on improving the components of the product as well as the processes of sourcing, manufacturing, and distribution (e.g. Dell).

- Leverage the Right Capabilities

  Perhaps a fallacy is that good entities with proven track records of production would be good at introducing new products. Christensen argues that a free-standing value network may be better, i.e. with a separate entity free of existing process that could motivate imitation of existing processes within a company. The motivation of the new entity should be impatience for profits rather than company size as a new successful entity, given the corporate freedom, could be quite different to what existing or incumbent entities would be. Hence these processes include everything from resource planning, sales, marketing, distribution, and even the supplier chain.

- Disrupt Competitors, Not Customers

  The emphasis should be on improving customers' lives or work processes. If it is more difficult, then obviously the chances of success are much less. A fair amount of good judgment is hence needed to ensure that a new product will actually do that and be appreciated by the customer, keeping in mind the previous points that a low end customer may be in a position of having the alternative of no product at all. Hence using consumer reviews of existing products or copying other companies with already successful products can be quite misleading. A disruptive product target market and application could be quite specific and different to be successful.

These four rules are particularly relevant here since in the B737's case it went through several product life cycles as the models and derivatives were developed over time. The question to be asked would be if these rules were met at each re-incarnation of the product with revised models. An oddity in the case of the B737, is that it is actually the incumbent product and the A320 is the new entrant as the A320 is actually the more up-to-date modern design with more bells and whistles than the B737. Thus it will be interesting to see if Boeing used the B737 as a "basic" design and improved it just marginally enough to compete with the A320.

2.5. Complex Products and Systems (CoPS), Have Blue, and the Model T

The subject of Complex Products and Systems or "CoPS" is a relatively new classification in the study of innovation. In their study of flight simulators, electro-mechanical machines that can reproduce the cockpit, feel and motion of flying an airplane for training purposes, Miller et al (1995) observed that CoPS appear to go through a different process of innovation that are quite different to the "'conventional', market contest Schumpeterian model" typified by mass consumer products. "Typically, CSs (Complex Systems) industries are bilateral oligopolies with a few large buyers facing a few large users. Buyers are not single individuals or families, as in the case of mass market durables, but large organizations with their own complex technical needs, as in the aircraft, military systems, telecommunications and FS (Flight Simulator) industries" Miller et al (1995).

Because CoPS may be high cost, low rate or even one-off productions, involve long lead times, and significant amount of customization, they may not necessarily ever have a chance to mature in the "normal" product life cycle. This normal life cycle is well described by Miller et al (1995) as "the standardization process whereby a particular product configuration (or dominant design) emerges to galvanize an entire market and to give direction to subsequent evolutionary trajectories (Utterback and Abernathy, 1975). At the early stage, the rate of product innovation is high, stimulated by market needs and a wave of new competing entrants. Product markets are ill defined, products are unstandardized, processes are uncoordinated and user-supplier interactions shape the pattern of innovation.

Eventually a dominant design is selected by the market, signaling an industrial shakeout. Small uncompetitive firms exit or are acquired by large companies. Eventually, a small number of firms come to dominate the industry by exploiting scale-intensive, incremental process improvements. As Utterback and Suarez (1993, pp. 2-3) put it, 'Eventually, we believe that the market reaches a point of stability in which there are only a few large firms having standardized or slightly differentiated products and relatively stable sales and market shares, until a major technological discontinuity occurs and starts a new cycle again' “ (Miller et al,1995).

While Miller et al (1995) use the term Complex Systems or CS, Hobday (1998) eventually coins the term CoPS. Other than flight simulators, examples of CoPS can be nuclear power stations, aircraft engines, telecommunication exchanges, air traffic control systems, etc. Military programs such as in dedicated mission type aircraft, submarines, weapon systems, are good examples.

Notably high cost projects such as roadworks which may involve large costs are not necessarily classed as CoPS “as they involve a narrow range of knowledge and skills and utilise mostly standard components and materials” (Hobday, 1998). Development and production of CoPS on the other hand usually involves a high degree of advanced technology linked with risk and uncertainty requiring wide ranging specialist skills and tacit knowledge of the industry.

Characteristics of CoPS described, including Hansen & Rush's (1998) case studies and Hobday et al (2000), can be determined as:

- High cost and complexity involving hierarchical and multiple layers of interacting systems and sub-systems (and hence potentially multiple projects and related organizations).
- Low production rates (Learning is not necessarily at a low rate but is mostly at an early product stage type and less on refining the product).
- High involvement of the customer in selecting the design before the order and accordingly a high degree of customization which may slow the process towards a dominant design.
- High degree of risk and uncertainty due to the low production rate and learning cycle.
- High product life longevity. An aircraft model may last 20-40 years, compared to a cellular phone that may not even last one year.
- CoPS industries tend to be oligopolies with high barriers to entry.
- Dependence upon suppliers and difficulties with procurement systems

	CoPs project organisation	Commodity products, functional organisation*
Product characteristics	Complex component interfaces	Simple interfaces
	Multi-functional	Single function
	High unit cost	Low unit cost
	Product cycles last decades	Short product life cycles
	Many skill/knowledge inputs	Fewer skill/knowledge inputs
	(Many) tailored components	Standardised components
	Upstream, capital goods	Downstream consumption goods
	Hierarchical/systemic	Simple architectures
Production characteristics	Project/small batch	High volume, large batch
	Systems integration	Design for manufacture
	Scale-intensive, mass production not relevant	Incremental process, cost control central
Innovation processes	User–producer driven	Supplier-driven
	Highly flexible, craft based	Formalised, codified
	Innovation and diffusion collapsed	Innovation and diffusion separate
	Innovation paths agreed ex-ante among suppliers, users etc.	Innovation path mediated by market selection
	People-embodied knowledge	Machinery embodied knowhow
Competitive strategies and innovation coordination	Focus on product design and development	Focus on economies of scale/cost minimisation
	Organic	Mechanistic
	Systems integration competencies	Volume production competencies
	Management of multi-firm alliances in temporary projects	Focus on single firm (e.g., lean production, TQM,MRP II)
Industrial coordination and evolution	Elaborate networks	Large firm/supply chain structure
	Project-based multi-firm alliances	Single firm as mass producer
	Temporary multi-firm alliances for innovation and production	Alliances usually for R & D or asset exchange
	Long-term stability at integrator level	Dominant design signals industry shakeout
Market characteristics	Duopolistic structure	Many buyers and sellers
	Few large transactions	Large numbers of transactions
	Business to business	Business to consumer
	Administered markets	Regular market mechanisms
	Institutionalised/politicised	Traded
	Heavily regulated/controlled	Minimal regulation
	Negotiated prices	Market prices
	Partially contested	Highly competitive

Figure 2.18

CoPS vs Mass Production Industries

(Hobday, 1998)

An analysis of the technological profiles of aircraft engine manufacturers by Prencipe (2000) also showed "that engine makers do not focus their technological capabilities only on the architecture of the control system, but they also maintain knowledge related to its components". Tapping often into sub-systems suppliers' knowledge and developing their own technical capabilities, the uncertainty of the technology indicates a motivation to have control and risk reduction on the part of the manufacturer.

Hobday (1998) notes in his implications for management deliberate strategies are needed for innovation with CoPS including a capability to coordinate amongst producers, suppliers, users, and regulators. Hobday et al (2000) provides a good reference and summary of CoPS characteristics and joins Miller et al (1995) to argue that CoPS need to be treated as a different category with respect to the "conventional" Schumpeterian model, particularly in the sense that radical discontinuities in the CoPS world do not usually mean the end of incumbent firms, as illustrated by Bonaccorsi and Giuri (2000).

Magnusson et al (2005) provide an interesting case study where manufacturers of large power plants are faced by a disruptive innovation type scenario of being challenged by smaller mass produced distributed generators. Hardstone (2004), similar to Bonaccorsi and Giuri (2000), discovered in a range of case studies that when faced with technological and competition challenges, incumbent CoPS firms tended to have a diversity of response strategies. This replicates the notion that a deliberate strategy can be considered rather than an automatic typical reaction.

Hence while subsequent CoPS papers constantly repeat these previously mentioned characteristics, one has to wonder if these characteristics are simply a result of a lack of strategy which by chance permeates the majority of the industry. Or is it simply the early stage of innovation where multitudes of varying designs exist before the dominant design emerges? That is the seeming so endless early stage being exaggerated by high product life longevity and low production rates caused by high costs of a complex project. This seems quite plausible and the relative differences to say a mass produced consumer product causes these “unique” characterizations, which in fact may not be so unique.

“While repeatable mass production learning processes are not so important to CoPS, there may well be scope for learning economies between product generations and at the component level, where demand may be very high e.g. in aircraft and high technology buildings. CoPS suppliers often gain strategic advantage by modifying design architectures to increase the scope for using high volume components” (Hobday et al, 2000). This has interesting connotations. Quite simply, just because a product is complex, it does not mean that every component has to be complex or novel. “Complexity” is a relative term. Proven parts or sub-systems from other products can be employed in the design of a new complex part.

This strategy can be seen in some prototype efforts which particularly under budget constraints will beg, borrow, and steal from other designs. Probably the most famous prototype house in aviation history is the Lockheed “Skunk Works”. Led by the infamous aircraft designer Clarence “Kelly” L. Johnson, the Skunk Works was established in 1943 in response to U.S. Army Air Forces (USAAF) interest in obtaining a jet fighter (Aronstein and Piccirillo, 1997). The XP-80 was designed and built in only 143 days, an incredible feat considering jet airplane technology was very new at the time.

“What allowed Kelly to operate the Skunk Works so effectively and efficiently was his unconventional organizational approach. He broke the rules, challenging the current bureaucratic system that stifled innovation and hindered progress” (http://www.lockheedmartin.com/aeronautics/skunkworks/). Other often secret but successful projects followed. “The XF-104, U-2, and Agena are all examples of Skunk Works projects that were successful because they were simple, elegant designs that deliberately did not push every aspect of technology” (Aronstein and Piccirillo, 1997).

One notable Skunk Works project was the “Have Blue” project which was the prototyping of what was to become the radar avoiding F-117 Nighthawk (or Stealth fighter as more commonly known), used in the Gulf War. In 1977 the US government recognized breakthroughs in VLO or Very Low Observable technology and commissioned development of an aircraft to take advantage of this technology.

“To reduce time, costs, and risk in this revolutionary project, a Tactical Air Command major named Jack Twigg was cleared into the program and became the system program officer (SPO) whose remit was to procure wherever possible "tried and tested," "off-the-shelf" pieces of equipment that would then be delivered into Building 82, via circuitous, covert routes in order to retain tight security.

The two Have Blue aircraft were single-seat, subsonic machines, each powered by two 2,950-pound-thrust, General Electric J85-GE-4A nonafterburning engines. the power units were government-furnished equipment (GFE), and Twigg acquired six for the program from the U.S. Navy's North American T-2B Buckeye trainer stores. The only engine modification made was a coating applied to the spinners.

Have Blue was 47.25 feet long, 7.54 feet high, and had a span of 22.5 feet. Its modified delta wing planform, with a sweep of 72.5 degrees, created a wing area of 386 square feet. No flap, speed brakes, or high lift devices were incorporated into the structure, which was built mainly from an aluminium alloy, using steel and titanium in the hot areas. Aerodynamic control was achieved by ailerons, located inboard on the wings, and by two all-moveable fins at the tail. The fins had a leading-edge sweepback of some 35 degrees and were canted inboard about 30 degrees. Flight control actuators were the same as those used on the F-111. A small side stick controller (YF-16 stock) and conventional rudder pedals enabled the pilot to operate the control surfaces.

The external shape evolved from VLO and controllability considerations, the fallout from which is a relaxed static stability (RSS) aircraft that required a quadruple redundant fly-by-wire (FBW) flight control system to provide normal handling qualities throughout the flight envelope. The FBW system provided stability augmentation and was made by Lear-Seigler (also F-16 stock). Indeed the aircraft was so dependent on this system that mechanical backup was not possible" (Crickmore and Crickmore, 2003).

Hence we see that despite the novel stealth features of this aircraft, many of the components were taken from existing aircraft such as the F-111, F-16, and T-2B. Even the landing gear was borrowed from existing aircraft (Different references quote the

Northrop F-5 Freedom Fighter per Crickmore and Crickmore [2003] or the A-10 per Goodall [1991] but the important point is that an existing design was used.).

Figure 2.19
Have Blue
(http://www.afa.org/_private/Magazine/Oct2006/1006black.asp)

Using the F-16 FBW system was genius since the computerized flight control system could be re-programmed for the new aircraft's unique flying characteristics due to the unusual shape designed to deflect radar waves. Two Have Blue prototypes were known to have been built and flew in 1977 or 1978. As per Figures 2.19 and 2.20, it can be seen that except for the tailplanes, the F-117 which was larger than the Have Blue aircraft, inherited much of the latter external shape characteristics. The program ultimately was successful and provided Lockheed the basis to develop the F-117 Stealth fighter.

Figure 2.20

F-117 Nighthawk "Stealth Fighter"

(http://en.wikipedia.org/wiki/Lockheed_F-117_Nighthawk)

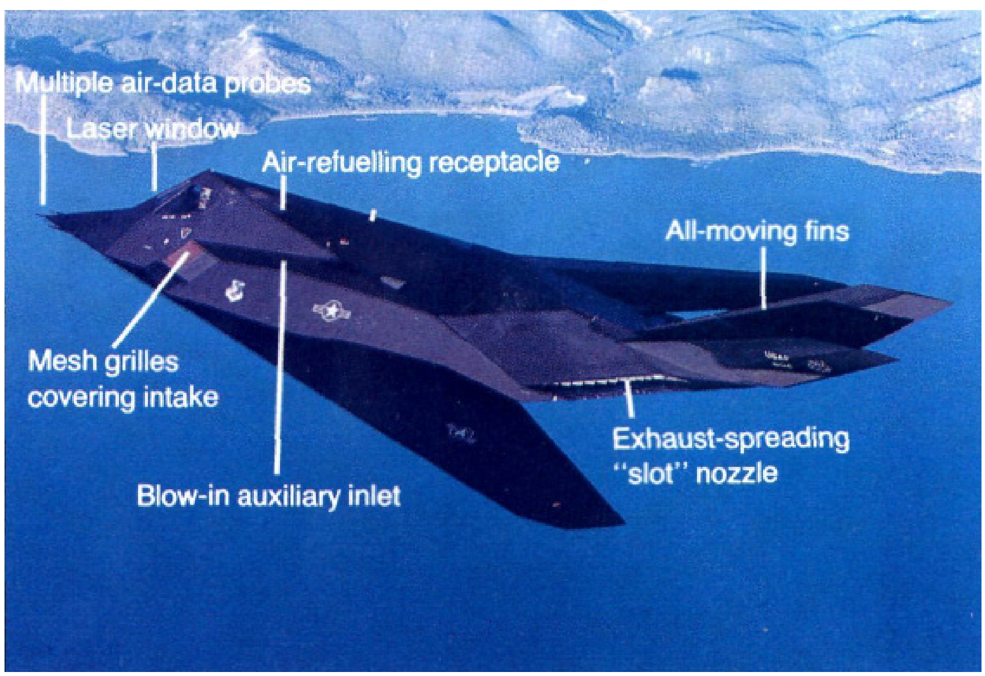


Figure 2.21

F-117 Nighthawk "Stealth Fighter" Features

(Bailey & Richardson, 1990)

This echoes many of the features that Brian Arthur writes about in his 2009 book “The Nature of Technology”. Arthur questions literally the nature of technology, how it evolves, and the origins of so-called innovative processes. An important foundation is the idea of a central concept or principle. The concept for example, to use a laser to print images for a laser printer, is the key that drives the building of these technologies.

Once the concept is established, technologies are developed or grouped together to provide function for the objective. These technologies are inevitable structured by layers or functionalities. Hence a layer or sub-component technology could in fact be changed, improved, or replaced, provided the overall concept is maintained to provide the overall functionality and output that is desired.

By looking at other products that could in fact be characterized as CoPS, there are obvious examples that do not fit the typical CoPS mould. For example cars are mass produced today. They have a dominant design layout. Cars may not seem complicated today as they are almost accepted as a mass produced consumer good. However in the 1900s, surely they would be considered an extremely complex product worthy of CoPS classification.

In 1908 Ford launched the now famous Model T. The production run lasted 19 years until 1927 during which 15 million Model T cars were produced (Alizon et al, 2009). Definitely this was not a low production rate. But does that mean that the Model T should not be classified as a CoPS product or is it in fact a CoPS product that defied the odds due to Henry Ford's outside-the-box thinking? For sure, while the fame of the Model T may be the moving assembly line and this would have reduced unit costs to assist sales, prices alone cannot have been the only factor for consumers to buy what was then a fairly complex product.

At first glance 15 million cars reeks of a mass produced product with very little customization, a non-characteristic of CoPS. Yet any car enthusiast magazine and papers including Alizon et al (2009) show that the car was in fact refined over several years. Furthermore many different versions as shown in Figure 2.22 were produced with an average of five different models a year. Even highly customized models were developed as can be seen in Figure 2.23. Ford even offered up to around 5000 gadgets that the customer could buy as options to customize as their own.

What was interesting was that the highly customized models were outsourced to other specialized companies. That way Ford could maintain focus on their core production models. What was provided to the specialist companies was essentially a basic car without the external body. This basic car was a platform that had the basic underbody consisting of the wheels, engine, chassis, drive-trains and steering mechanisms.

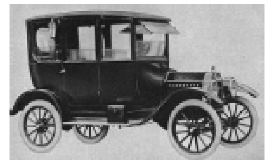
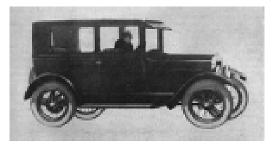
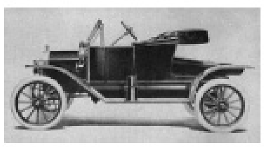
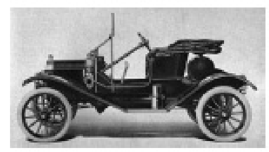
Model T – Type	*Picture*	*Year of Production*	*Model T – Type*	*Picture*	*Year of Production*
Touring		1909–1927	Sedan		1915–1923
Touring Fore-door		1912–1916	Sedan Fordor		1924–1927
Coupé		1909–1911, 1914, 1919–1927	Tudor		1925–1927
Runabout		1909–1927	Torpedo		1910–1912
Town		1909–1917	Coupélet		1915–1918

Figure 2.22

Types of Model Ts in Ford's catalogue built and produced from 1908 to 1927

(Alizon et al, 2009)


White snowmobile (Burdick, 2006)


Chemical/Hose Car (CLAFMA, 2006)


Woody wagon (Filiss, 2006)


Racer (Michael, 2001)


Truck w/chain hoist (Ritter, 2006)


'Business Body' (Oldwoodies magazine, 1959)


Tractor with a Model T platform (Anonymous, 2006a)


Tractor coupled to semitrailer (Cavette, 2006)


Circus model (Anonymous, 2006b)


Chain drive (Anonymous, 2006c)


Business tops (Quinn, 2006)


Milk wagon (Oldwoodies magazine, 2006)

Figure 2.23

Sample of Customized Model Ts

(Alizon et al, 2009)

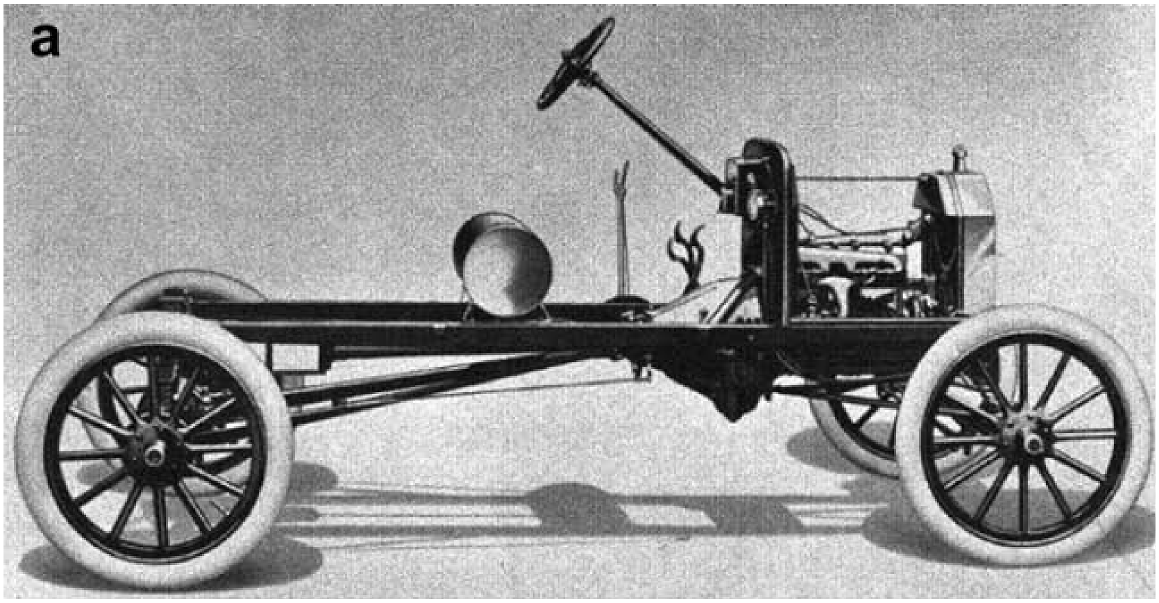


Figure 2.24
Model T Platform
(Alizon et al, 2009)

In retrospect we should consider that with the time factor, many products are, or were in fact CoPS products. A simple pencil was a complicated item to manufacture if we go back several centuries. A laptop or tablet computer encompasses many different technologies such as microprocessors and liquid crystal display screens that we now take for granted but have been developed only recently and would have been an impossibly complex piece of machinery to produce as recently as in the 1930s. The closest thing at the time would have been the computers at Bletchley Park (famous for use in breaking secret military transmission codes) which were enormous by today's standards. Those computers in 1939 would have been classified as CoPS.

2.6. Families and Platforms

It could be argued that by developing a product platform, Ford had developed in essence a part dominant design. The platform allowed Ford to build model derivatives to satisfy different market segments. Hence although externally the products might look a little different, a major part of the product was always the same. This part of the product could then be considered ripe for incremental improvements as per the traditional dominant design life cycle theory.

And in fact this is exactly what happened with the Model T. Small continuous improvements were made to the platform until the end of the Model T's production where other competing cars had performance improvements that the Model T platform could not keep up with.

Until that point however, it is interesting to note the key fact that allows the basic model to be stretched into variants of the first basic model that can satisfy different market segments. With the Model T, the highly customized models (Figure 2.23) only accounted for 5% of the production. Since we are mainly interested in the large production run that seems to contradict CoPS characteristics, we consider the remaining 95% which are shown in Figure 2.22. Just visually we see primarily variants for the application of carrying human passengers, including 2-seat and 4-seat versions.

The latter is a simple but important observation. Supposedly there were different market segments for 2-seat cars and 4-seat cars respectively. By shrinking or stretching the car body length, Ford could accommodate both markets. But by doing so the structure would decrease or increase respectively. Obviously a heavier car would have relatively less power to weight ratio and for the same engine and drive-train, perhaps go not as fast as a lighter 2-seat car. It would also use more gasoline per kilometer although cost of gasoline was probably not a significant factor in that era.

Hence variants of a basic model involve simple modifications of some basic part of an initial model that can satisfy a different market, but usually at the expense of some other performance factor. Other than cosmetic type modifications, the implication is a significant trade-off where the customer is willing to pay for more of one factor than another to suit the particular market requirement.

Meyer (1997) and Simpson (2004) both discuss this factor and the figure below is a good illustration of the various ways a platform can be derived. In this study it is perhaps important to make some definitions to prevent confusion amongst terms that may seem similar. In Alizon et al (2009)'s paper they refer to the platform (under-body) requiring common mating interfaces to the upper-body. This refers to *modularity* which is not necessarily a requirement of a product platform, especially when we discuss an integrated type design as in Figure 2.8.

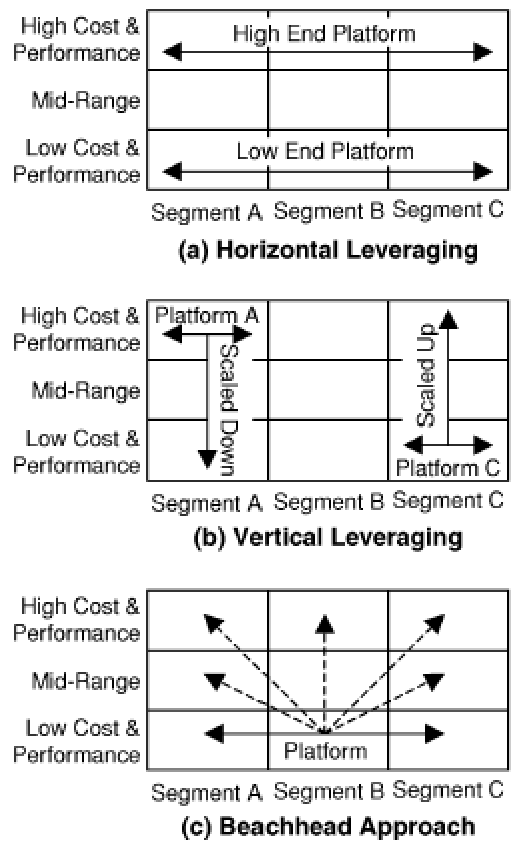


Figure 2.25

Platform Leveraging Strategies

(Simpson, 2004, adapted from Meyer, 1997)

However this is just the physical aspect of it. The architecture itself can lend itself to be somewhat modular even if the physical interfaces may not be standardized and engineering work is required to incorporate pre-designed sub-assemblies. The engineering incorporation capability of the company in effect creates the "standardized mating interfaces" required for modularity and hence increases the capability of the company to create combinations using pre-existing designs.

A distinct advantage of modular type architectural thinking is the ability to group work teams to work concurrently and hence learn as well as develop faster as in Figure 2.27, compared to a sequential type work process as in Figure 2.26.

Having this capability gives the company an important source of strategic flexibility for 'mixing and matching' of components to develop large variations of products to meet different requirements and market segments (Sanchez and Mahoney, 1996). Kogut and Zander (1992) describe this ability to leverage product variations from existing designs as the company's "combinative capability". They even describe this capability and knowledge as the *platform* with which a company can enter new markets.

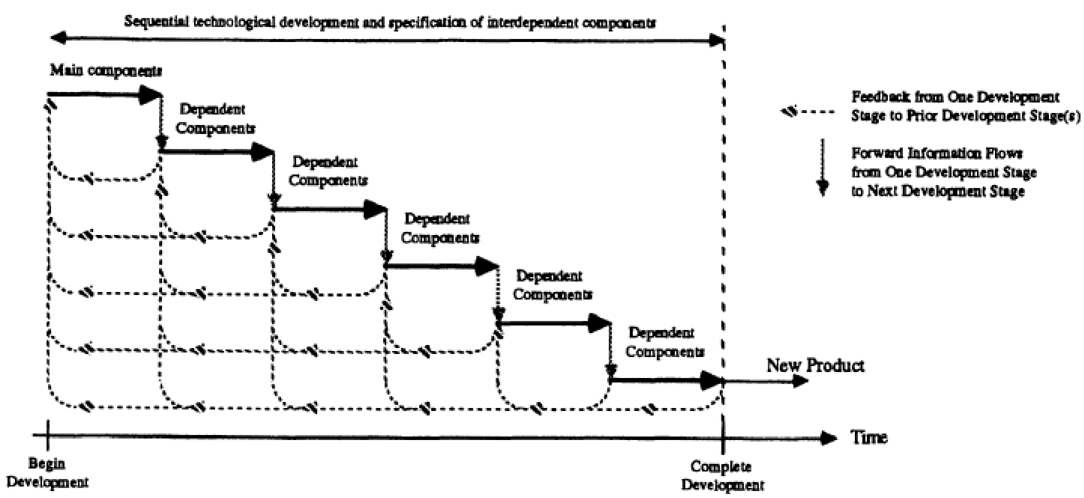


Figure 2.26

Sequential Organization of Product Development Processes

(Sanchez and Mahoney, 1996)

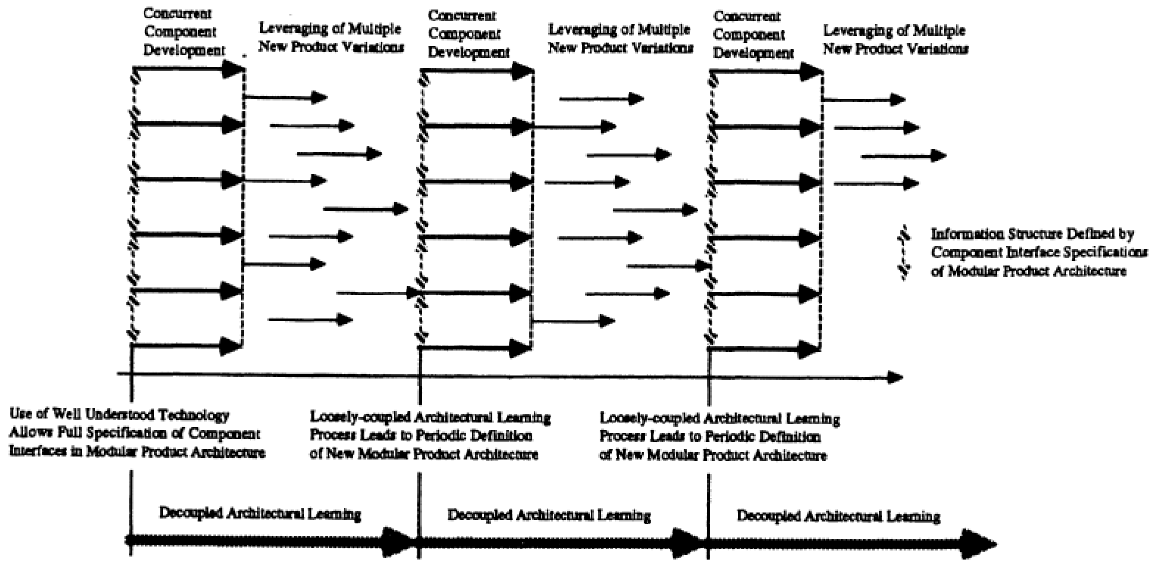


Figure 2.27

Modular Organization of Product Development Processes

(Sanchez and Mahoney, 1996)

In the same vein it is notable that a platform may be a grouping or collection of components used from the first basic model but they do not necessarily have to be physically connected to each other in a derivative or variant design. Going back to Abernathy and Clark (1985), and Henderson and Clark (1990), it is the product architecture and the knowledge behind it that is the critical factor. Meyer (1997) notes this stating that the platform as a whole does not have to be used in adjacent segments, but rather key sub-systems.

"A product platform is the set of parts, sub-systems, interfaces, and manufacturing processes that are shared among a set of products, and allow the development of derivative products with cost and time savings" (Meyer and Lehnard, 1997). To achieve "mass customization" (Pine, 1992), the platform approach allows higher volumes as well as permitting "highly differentiated products to be delivered to the market without consuming excessive resources" (Robertson and Ulrich, 1998).

Conversely, each part of this platform can also be viewed and utilized independently as a product of its own. In doing so it can be freely applied by a firm to different product lines and hence creates its own market without having to allocate different resources for that sub-component function each time a new product is developed. Meyer (2008) proposes that a fast way to develop new products is to leverage a firm's current capabilities to produce new products or services for new users and new uses. Furthermore these "solutions are proven, working technologies applied creatively to new purposes."

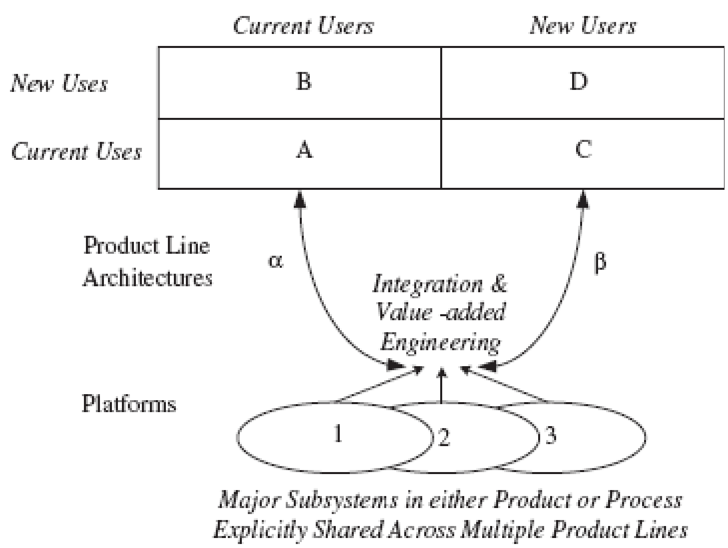


Figure 2.28

Leveraging Platforms to New Market Applications

(Meyer, 2008)

In the aircraft world, the major manufacturers such as Airbus and Boeing have typically developed "different" models of different lengths and passenger/freight capacities by simply changing the fuselage lengths (Sabbagh, 1996). "Stretching" using additional fuselage plugs, or "shrinking" by removal of fuselage sections, but at the same time using common wing, nose, and tail components as well as interiors and other sub-systems (Sanchez and Mahoney, 1996).

Simpson (2004) describes this method as a "scale-based product platform", "…wherein one or more scaling variables are used to "stretch" or "shrink" the platform in one or more dimensions to satisfy a variety of market niches." Fujita (2002) describes such aircraft design strategy similarly as "stretch-based design deployment".

Aircraft jet engines tend to follow this pattern as well using improved parts of the engines to either increase or lower thrust (such as adapting new fans to the same hot section core), and reduce fuel burn with new technologies.

One of the subtle advantages of a product platform is that the company enjoys a better concentration of efforts and resources. "Large savings can be made in design costs and in the tooling of equipment" (Bonaccorsi and Giuri, 2000). As Rothwell and Gardiner (1984) show in Figure 2.30, over a span of more than twenty years, Ford consistently had an advantage over the resident car company in the United Kingdom, British Leyland, by simply having half the number of basic models (Cortina, Capri, Escort) but twice as many variants and derivatives as its competitor.

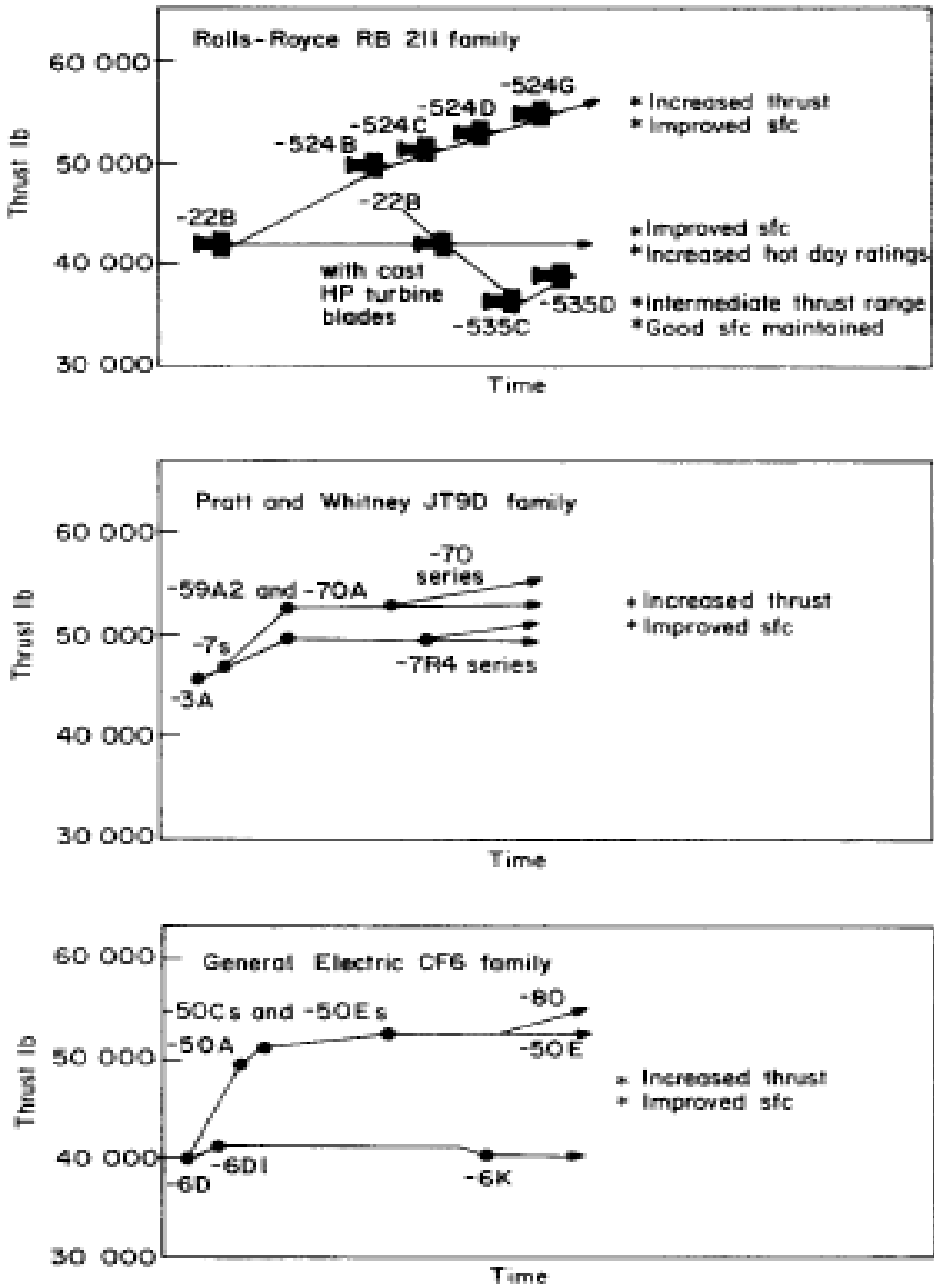


Figure 2.29

Design families: High powered aero engines RB211, JT9D and CF6

(Rothwell and Gardiner, 1983)

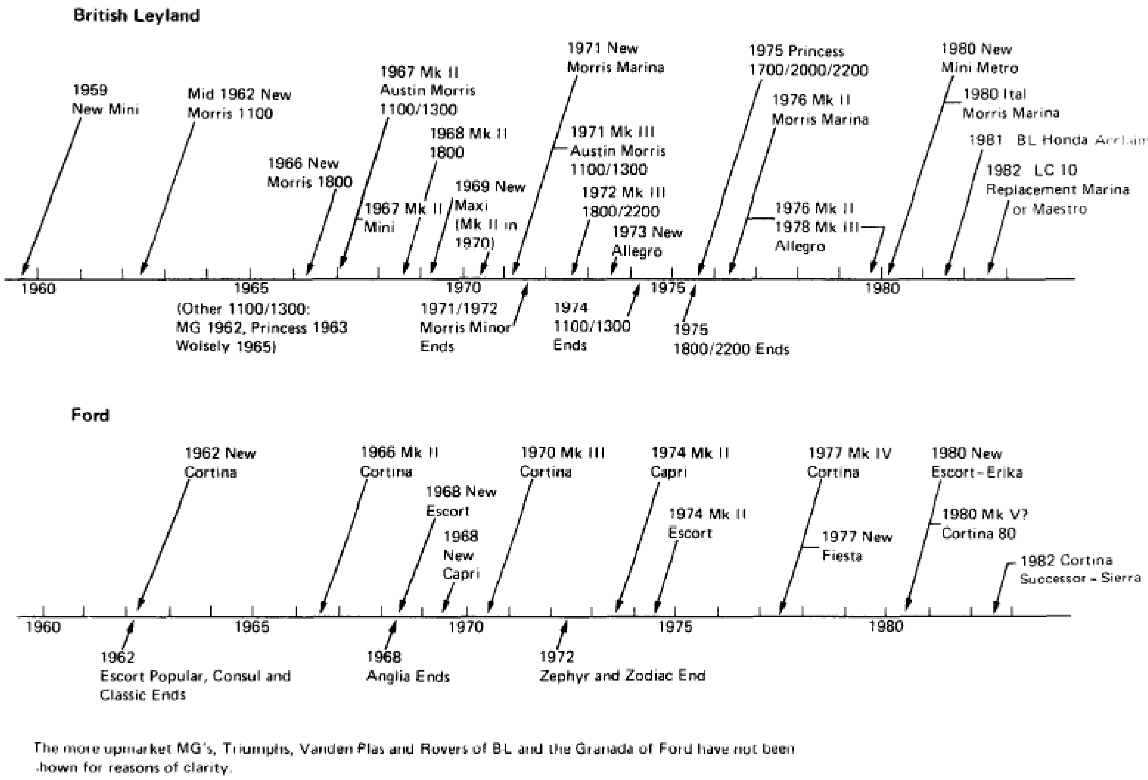


Figure 2.30

Ford and British Leyland Family Cars

(Rothwell and Gardiner, 1984)

"As a consequence, Ford was able to achieve considerably wider market coverage while maintaining a highly disciplined production base. With half the number of basic models, Ford almost halved its production problems while at the same time greatly simplifying its parts and servicing operations." (Rothwell and Gardiner, 1984).

Sanderson and Uzumeri (1995) likewise demonstrate this with their case study of the Sony Walkman. The Sony Walkman enjoyed fantastic product longevity but accomplished it with just a few product platforms. The large variety of models marketed consisted in fact of minor and cosmetic changes to a few otherwise standard mechanism platforms.

One of Sony's strategies was to study lifestyles in different parts of the world so that they could customize the products accordingly but it would have been difficult to individually develop all these different models without using the basic product platform concept. "85% of Sony's models were produced from minor rearrangements of existing features and cosmetic redesigns of the external case. Sony generated these designs much as a child would build with Lego." (Sanderson and Uzumeri, 1995)

Probably the product most famous for ultimate modularity is the Lego brick toy. Lego in itself is not a complex product or toy. However its feature is that the Lego bricks can be combined in an endless variety of ways to make further more complex configurations. Hence it is useful to review the Lego "system" as an introduction to product families and platforms.

Six eight-stud Lego bricks can be combined in 915,103,765 ways (Lipkowitz, 2009). But while the eight-stud brick is almost the front line representative of the Lego toy range, there are many variations of the theme as in Figure 2.31. The common part is the interlocking feature that allows Lego to develop multiple different types of bricks that can match each other as per Figure 2.32.

Godtfred Kirk Christiansen's favorite solution, the three-tube clutching system devised in 1957, became the final model for the new and improved LEGO brick.

All 2 x 4 LEGO bricks manufactured since 1958 have been produced to the exact same measurements as the three-tube version described in the original patent.

BRICK VARIATIONS

Godtfred Kirk Christiansen's stud-and-tube solution continues to form the cornerstone of LEGO building. Today, LEGO elements are produced in thousands of different shapes, colors, and sizes, but each and every one of them is precisely designed to connect with the original brick, two studs wide and four studs long, that was patented on that famous day in 1958.

UNLIMITED POSSIBILITIES

The patented clutching ability of the LEGO brick gives builders of all ages an almost infinite variety of ways to express their imagination and creativity through construction. Each brick in the system can be connected to every other brick in multiple configurations, and as more bricks are added, the possibilities grow exponentially.

Two eight-stud LEGO bricks can be combined in 24 ways.

Three eight-stud LEGO bricks can be combined in 1,060 ways.

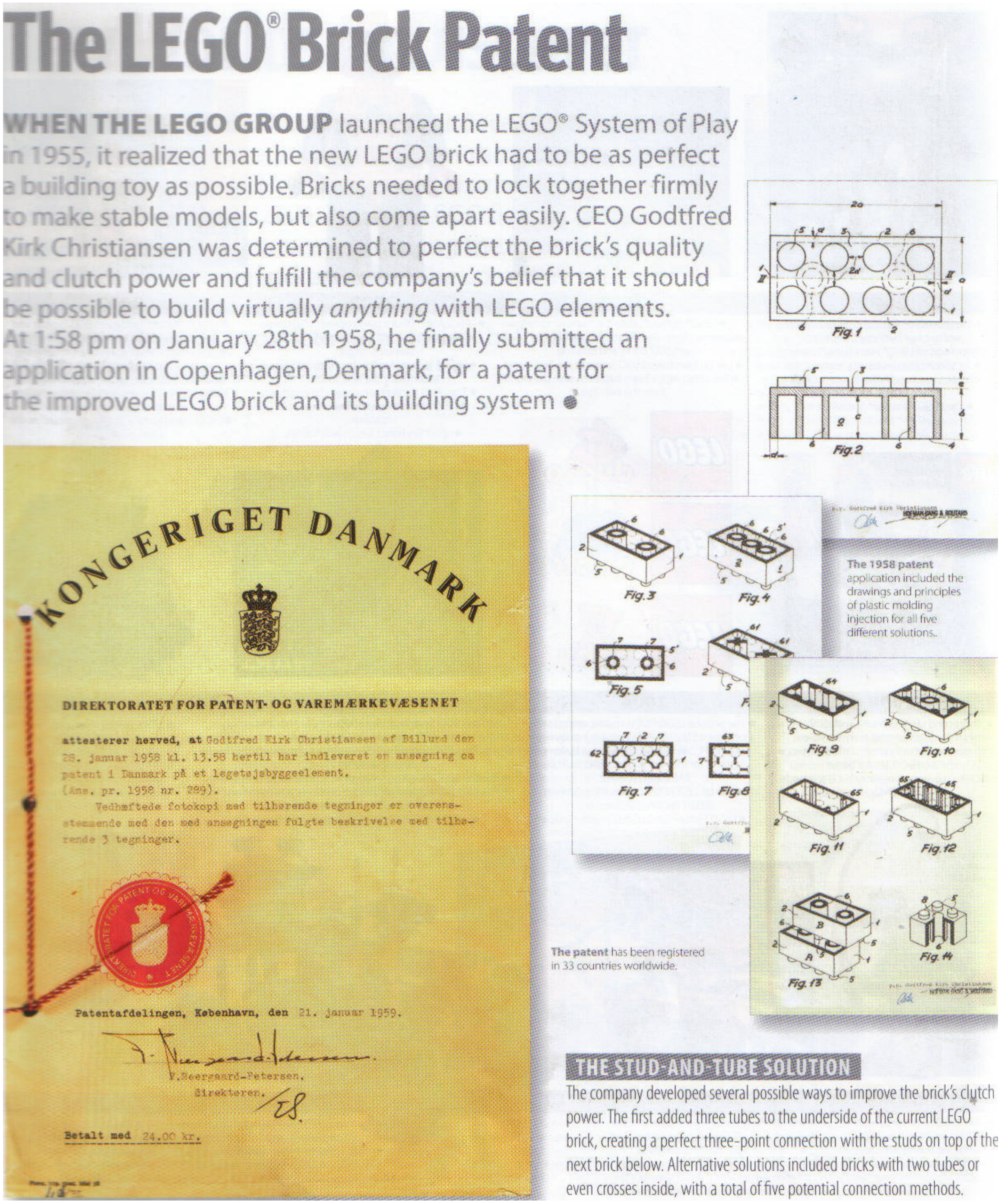
Six eight-stud LEGO bricks can be combined in 915,103,765 ways.

With eight bricks, the possibilities are virtually endless.

Figure 2.31

Lego Brick Combination and Parts Variety

(Lipkowitz, 2009)



The LEGO® Brick Patent

WHEN THE LEGO GROUP launched the LEGO® System of Play in 1955, it realized that the new LEGO brick had to be as perfect a building toy as possible. Bricks needed to lock together firmly to make stable models, but also come apart easily. CEO Godtfred Kirk Christiansen was determined to perfect the brick's quality and clutch power and fulfill the company's belief that it should be possible to build virtually *anything* with LEGO elements. At 1:58 pm on January 28th 1958, he finally submitted an application in Copenhagen, Denmark, for a patent for the improved LEGO brick and its building system

KONGERIGET DANMARK

DIREKTORATET FOR PATENT- OG VAREMÆRKEVÆSENET

attesterer herved, at Godtfred Kirk Christiansen af Billund den 28. januar 1958 kl. 13.58 hertil har indleveret en ansøgning om patent i Danmark på et legetøjsbyggeelement.
(Ans. pr. 1958 nr. 289).

Vedhæftede fotokopi med tilhørende tegninger er overensstemmende med den med ansøgningen fulgte beskrivelse med tilhørende 3 tegninger.

Patentafdelingen, København, den 21. januar 1959.

V.Neergaard-Petersen,
Direktøren.

Betalt med 24.00 kr.

The 1958 patent application included the drawings and principles of plastic molding injection for all five different solutions.

The patent has been registered in 33 countries worldwide.

THE STUD-AND-TUBE SOLUTION

The company developed several possible ways to improve the brick's clutch power. The first added three tubes to the underside of the current LEGO brick, creating a perfect three-point connection with the studs on top of the next brick below. Alternative solutions included bricks with two tubes or even crosses inside, with a total of five potential connection methods.

Figure 2.32

Lego Brick Patent & Interlocking System

(Lipkowitz, 2009)

One well-known Lego product line is the Minifigure series that is a series of miniature toy people but deploying different themes such as Star Wars or Indiana Jones. While there are infinite variations, the basic *platform* is always the same as in Figure 2.33 employing just one stud of the Lego interlocking system in each part. For the user, any part can be intermixed, for example the hat of a policeman could be fitted to the head of a nurse and a hand accessory for a mechanic could be fitted to a cowboy. Yet the basic "platform" is recognizable. They may be aesthetically different parts, but having enough common design features to indicate a *family* of products.

Figure 2.33

Lego Minifigures Sample

(Martell, 2009)

Once a variant of a basic model is developed, a *family* is born since there are now more than one model. However what if the platform is improved or changed significantly? Perhaps just a sub-assembly of the platform is used to develop a new line of products. Engines of cars are common candidates of such sub-assemblies. Hence to differentiate, a family can be termed to belong to one basic model and its relative variants, and separate families would be termed as *derivatives* of the platform.

The term "derivative" could be easily used to term a variant or a change in platform, so for simplicity and to differentiate against a *variant*, it will be used only to define a *new basic model* that has a significant platform change.

While some may define a platform as a physical major sub-assembly of a product, it is perhaps more useful to consider that the platform is a combination of a *concept* and a design or collection of designs that is or are somewhat proven. Obviously if the platform is based on a somewhat proven design that is used over and over again to develop new iterations of a product, then the platform tends to fall into a category of where only incremental innovations would apply to it, as long as that generation of product family exists.

Should the platform be changed radically due to some major part or component being redesign or replaced by newer technology, then a convenient thought would be that a new generation or families of product then develop.

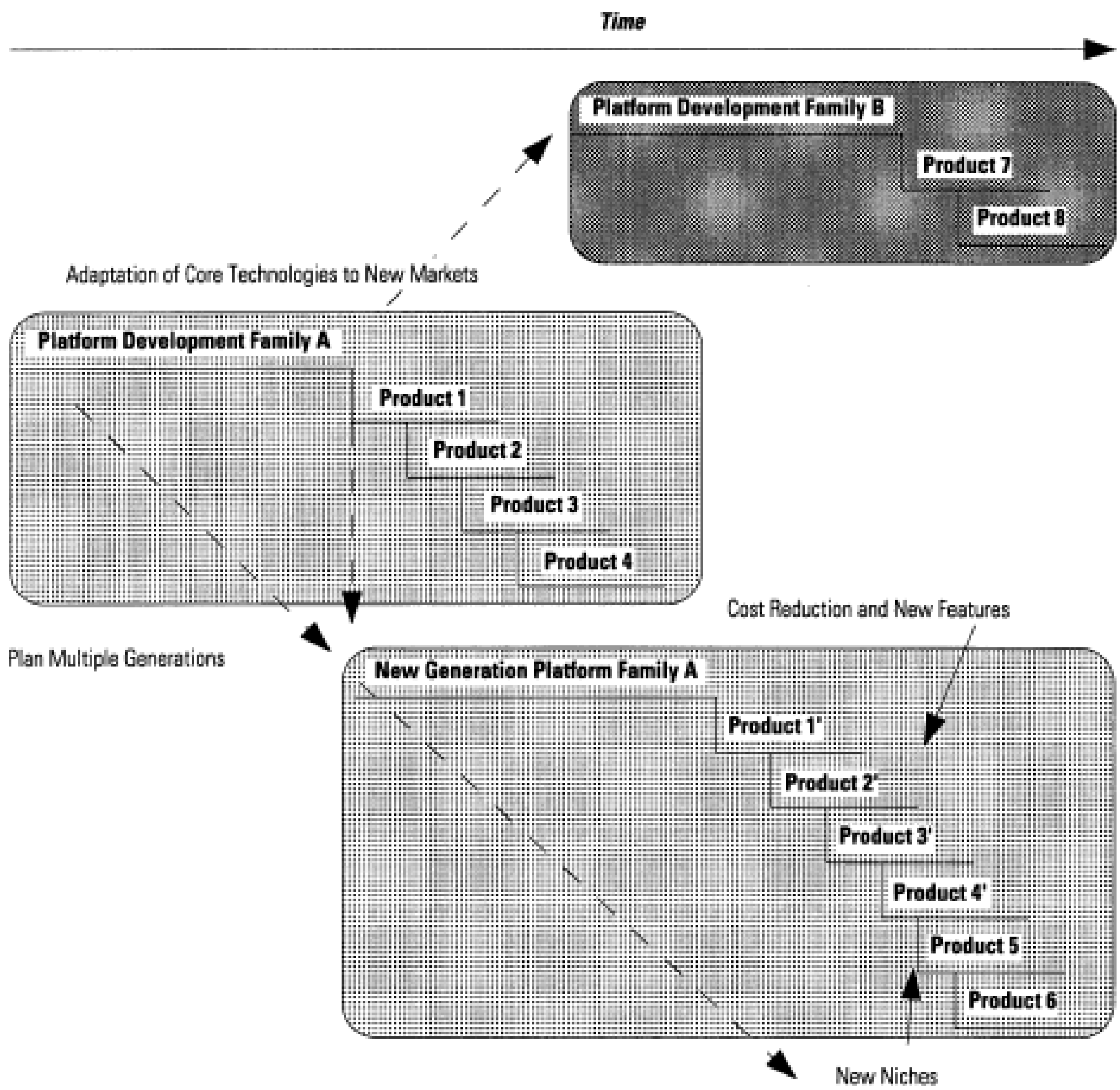


Figure 2.34

The Product Family Approach to New Product Development

(Meyer and Utterback, 1993)

If the concept is maintained, then one could argue that the product architecture is not changed. However it is probably more useful to debate that a concept can be used to steer re-designs towards the desired path of improvement. The concept could also be used to design other products to maintain compatibility with the original product.

To illustrate this point, we first consider three other product lines that are similar to the original Lego brick.

Megabloks is a Lego copy and it has a range larger than Duplo for young children. Duplo was developed also by Lego in 1969 for children 1-1/2 to 6 years old. The shape is essentially the same, with the main difference being the size, a Duplo brick being twice as tall, twice as long, and twice as wide as a normal Lego brick (Lipkowitz, 2009).

Nanoblock is a Japanese product that looks like Lego and works in a similar way except the bricks are smaller than Lego. The attachment system is similar to Lego using studs, but the under part is slightly different, lacking the Lego tubes which allows variation in positioning (www.diablock.co.jp/nanoblock). Nanoblock is in fact designed for adults to create desktop type displays.

Hence between four product lines of Megabloks, Duplo, Lego, and Nanoblock, the physical designs are different, and even the target market segments are different (age of consumers), but the platform concept of interlocking bricks is the same. Even the product material basis of ABS (Acrylonitrile Butadiene Styrene) plastic is the same for all four product lines.

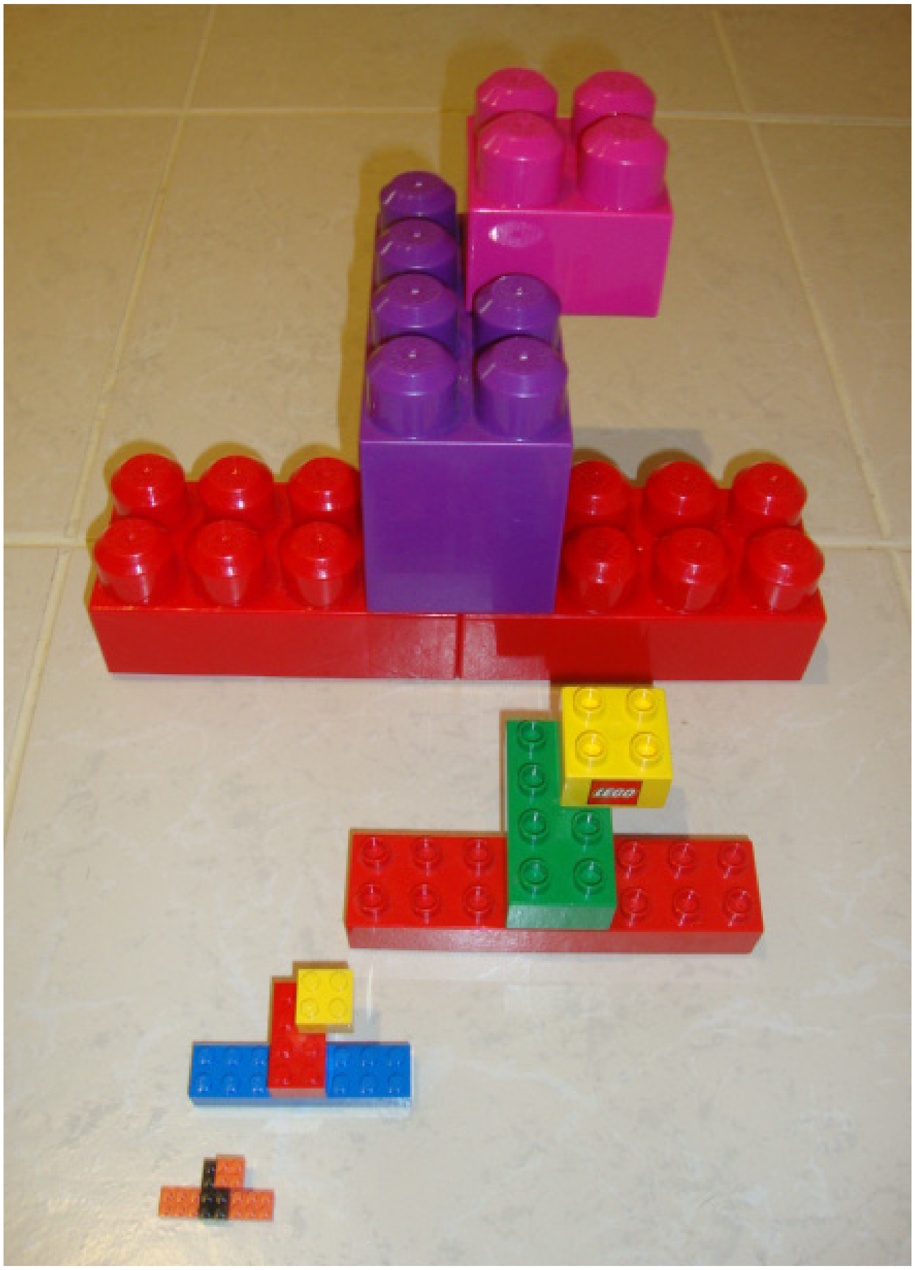


Figure 2.35

Megablok, Duplo, Lego, Nanoblock bricks (Largest to smallest)

In Lego the concept part goes even further. Lego bricks were designed so that the strength of a 3-year old could put them together as well as pull them apart. This same concept is applied to other Lego non-brick parts and accessories such as wheels, tires, propellers, doors, hinges, etc. In doing so, these other parts can be included in the same category of toys as Lego bricks and be marketed together accordingly.

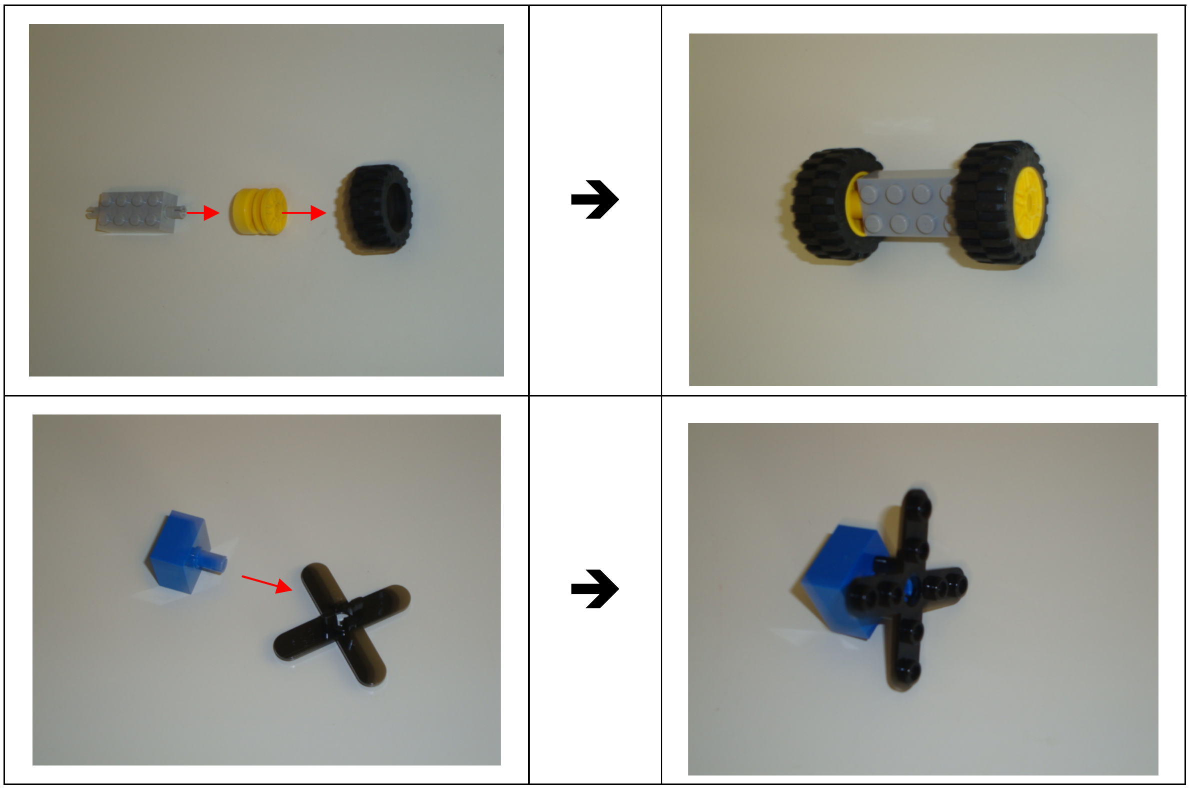


Figure 2.36

Lego non-brick parts that can be put together or pulled apart

As a recap, it is perhaps useful to use the following convention for the rest of the thesis.

Term	Description
Basic Model	The first model of a product *Family* – where the platform is derived from.
Platform	A common concept using a collection of the components of the basic model which are used to develop variants of the *Basic Model*. Design changes to platform components are kept minimal.
Variant	A new product model developed using a *Platform*, where one or more performance factors can be traded off against others to meet particular market segment requirements.
Family	The group of Variants derived from one Basic Model.
Derivative	A *new Basic Model* having high commonality with the *original Basic Model*, but with design and component changes that improve performance for a majority of factors. The *Platform* is thus significantly improved and hence the tradeoff performance factors of the *Variants* of this *Derivative* can all gain. *Variants* of a new Basic Model belong to a new *Family*.

Figure 2.37

Product Platform Convention Terms

With Rothwell and Gardiner (1989), they discuss even non-physical variants or derivatives using the performance of aircraft engines that can be rated at different levels of thrust. Hence an airframe manufacturer or aircraft customer can select different "models" of what would be essentially the same physical engine to suit their needs. The pricing presumably would also reflect the thrust level chosen, but the cost savings to the engine manufacturer of not having to develop physically different engines is obvious.

This is shown in the figure below where after the designs are composed (merging of different component designs) and consolidated, a convenient option (Phase III) would be to "stretch" the design by rating or minor adjustments to meet different market segment requirements.

Today these artificial thrust ratings are done via electronic controls for commercial aircraft jet engines. By doing so it may be that "up-rated" or "de-rated" engines are not as optimized as would be the nominal basic model, but at the same time the product line would enjoy maintenance and spares commonality. The basic platform design meanwhile would enjoy the benefit of continuous incremental improvements over its basic life that would be more concentrated than where the engine manufacturer would have to split its research and development budget over different engine basic models.

There is also a marketing advantage should the engine be redeployed on a different aircraft model (e.g. the engines of the B747-400 and B767-300 can be interchangeable) or operator that wants to utilize a different thrust level.

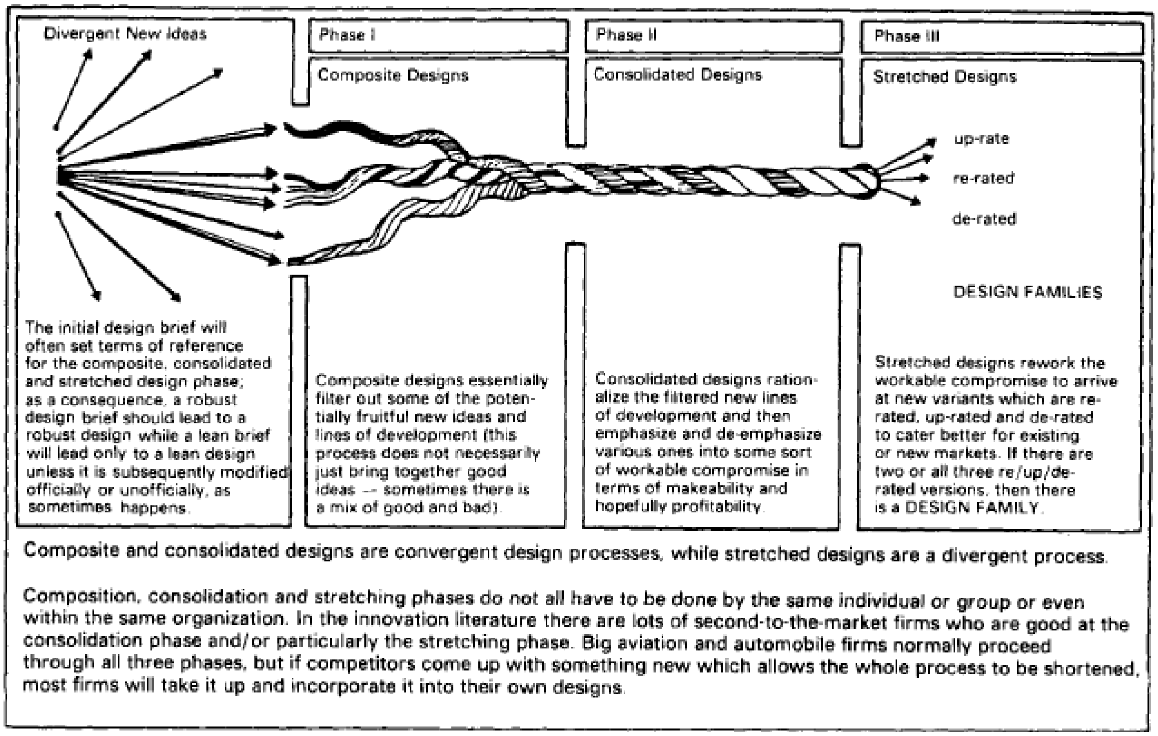


Figure 2.38

The Evolution of Robust Designs

(Rothwell and Gardiner, 1989).

Hence we see that product platforms are a strategic way of subverting the CoPS stereotype inhibited by low production volumes and high costs. Obviously the higher the production volume, the lower the costs would be. Hence it appears that deliberate strategies can be developed to manage this desirable outcome.

"Product families do not have to emerge one product at a time. In fact, they are planned so that a number of derivative products can be efficiently created from the foundation of common core technology. This foundation of core technology is called the 'product platform.’ It is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced. A platform approach to product development dramatically reduces manufacturing costs and provides significant economics in the procurement of components and materials because so many of these are shared between individual products. Perhaps as important, the building blocks of product platforms can be integrated with new components to rapidly address new market opportunities” (Meyer, 1997).

What of derivatives, i.e. development of the product platform itself? Is it acceptable just to depend on variants of a basic model? It would appear that once new designs or configurations or technologies that appear that could significantly affect the performance of product platforms as a whole (rather than trade-offs that are a characteristic of variants), then this would be the time to develop derivatives.

“Product families must be managed.... if a platform is not rejuvenated, its derivative products will become dated and will fail customers in terms of function and value; however if a company's platforms are renewed periodically - re-designed to incorporate new functions, components and materials - the product family will remain robust through successive generation…..Robust platforms do not appear by accident. They are the result of methods and strategies for designing, developing and revitalizing them over time as an essential element of business strategy to dominate markets” (Meyer, 1997).

Gonzalez-Zugasti et al (2000) for example note that with the known advantages of product platforms, a company may choose to do this as a strategy to lower developments costs as in the example of developing spacecraft in Figure 2.39.

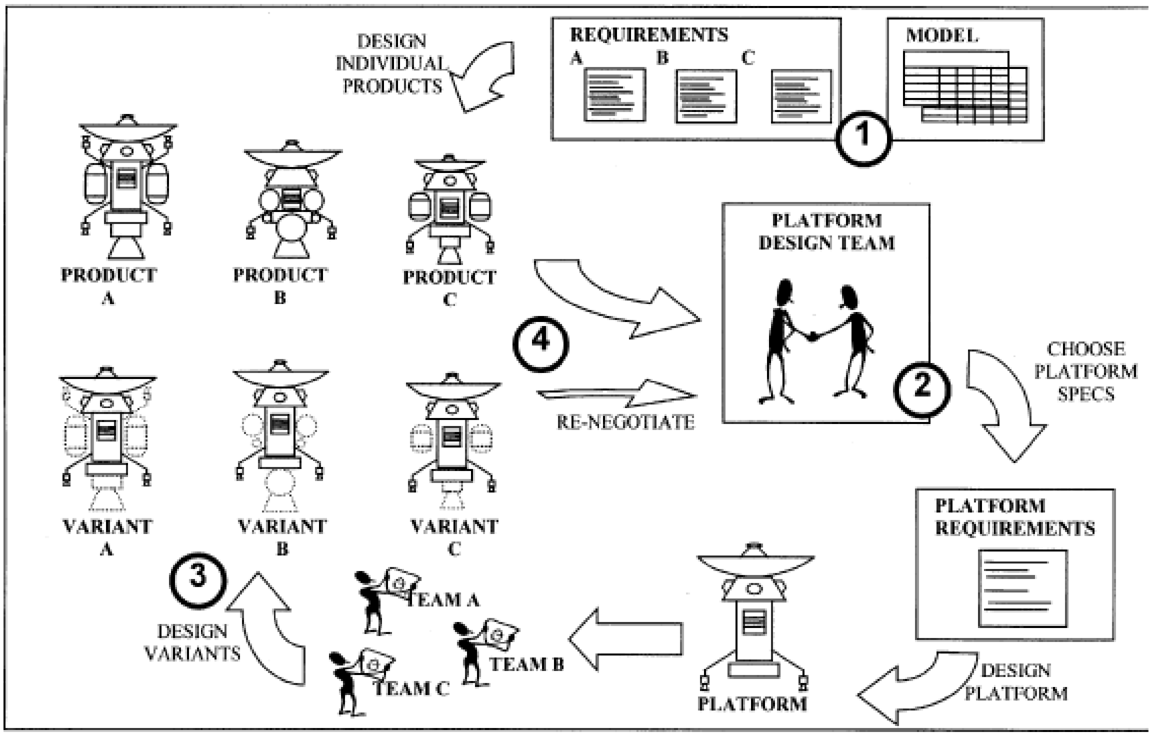


Figure 2.39

Platform-Based Product Family Design Implementation Approach

(Gonzalez-Zugasti et al, 2000)

Krishnan and Gupta (2001) note that product platforms have another disadvantage particularly when the market range is diverse such that the variant designated for the low end may have parts common to the product platform that are overdesigned for the high end. In other words the end product is under-optimized or has too much product for the low end.

Hence if there is a time lag between developments of models, it may be advantageous to leave development of the high end models last so that they can absorb the maximum benefits of experience with the basic design. Once a basic model is in service surely the manufacturer would gain experience as to which parts of the design can be refined to for example save structural weight (in the case of aircraft) or reduce the size, number, or complexity of components and systems that may have excessive performance or be even redundant. The resultant increase in performance would assist development of the high end model without penalizing the low end model.

For the aircraft scenario, if a larger variant is developed after the basic model and a shrunk model, it would have the benefit of a re-analysis of the structural and aerodynamic loads on the smaller variants, further improving the manufacturer's knowledge of the design.

As an alternative, Suh et al (2007) suggest that product platforms have an effective bandwidth beyond which the ability to maintain a common product platform becomes undesirable to meet different markets. Fujita (2002) also demonstrates this as in Figure 2.40 where new combinations would be required past certain ranges to maintain optimality.

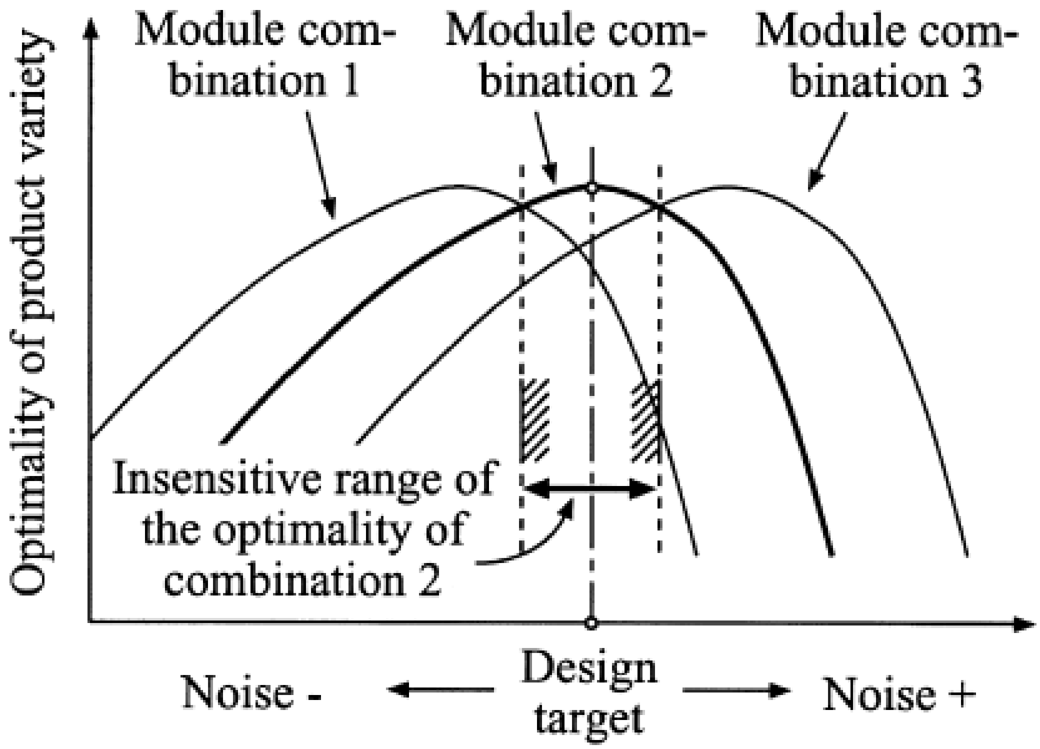


Figure 2.40

Sensitivity and Robustness in Product Variety Optimality

(Fujita, 2002)

Hence an option could be to stretch the platform into separate basic platforms to ensure efficient performance coverage.

With the Model T car series, Ford in fact effectively did this when the Model T platform chassis was stretched into the Model TT chassis to obtain a 1-ton light truck at the same time re-using many components from the Model T (Alizon et al, 2009).

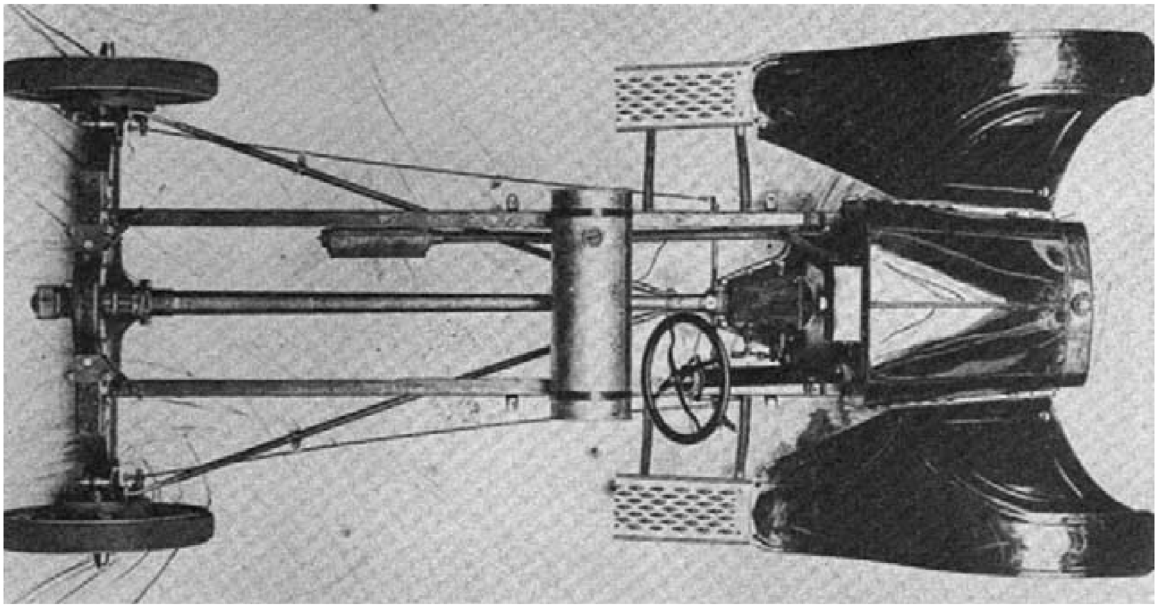


Figure 2.41

Ford Model TT Platform

(Alizon et al 2009)

In the aviation world at least one aircraft manufacturer has done that. Embraer's E-Jet family is actually made of two platforms. The E170, E175, E190, and E195 (the model number indicating roughly the passenger capacity of each model), like the B737 families, all share common cockpits, fuselages.

But the family has two different sets of wings and engines, one set being shared by the E170 and E175, and the other by the E190 and E195. That way the degree of optimization loss by having a family of variants is minimized, albeit at the expense of loss of commonality in spares and maintenance should an operator select models from the two sub-families.

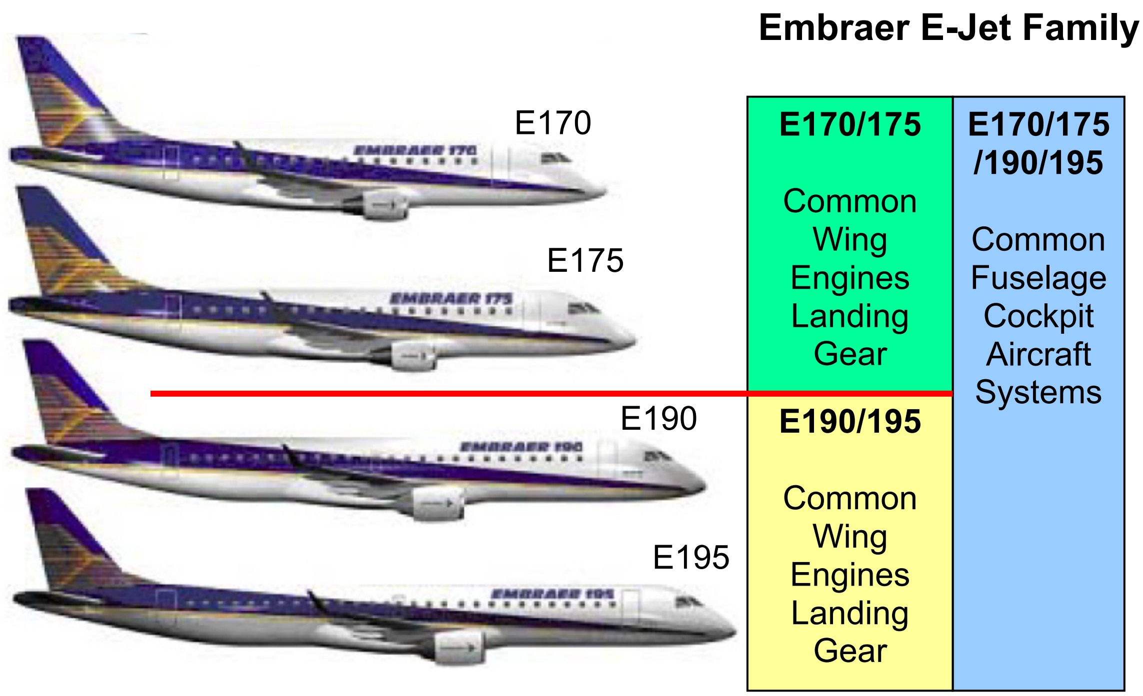


Figure 2.42

Embraer E-Jet Family

We also keep in mind that the product platform itself need not necessarily be static in design, and can be the subject of continuous development. Meyer (1997) advocates that product lines should be revitalized through continuous platform renewal. As an option he suggests that vertical scaling particularly from the low end side. While it is rare to see a deliberate strategy by a company to build the basic model at the low end and then develop other variants based on only stretches and no shrinks, if we consider the case of the B737, successive generations have grown larger and larger to get close to its former larger cousins the B707, B727 and B757.

On the B787, Boeing has chosen to develop first the smallest model, the B787-8 with the larger B787-9 following later. What is interesting is that Boeing now indicates that the entry into service B787-9 airframes may have relatively better range performance than the initial B787-8 airframes despite being larger, due to planned product improvements from development and design experience on the B787-8.

What is more important than the design itself is the product architecture as per Henderson and Clark (1990). Christensen et al (1998), note that firms that focus more on architectural innovations rather than component innovations tend to survive longer. Simply put a component is just part of a product's architecture. No matter how new a component may be, if the architecture becomes obsolete, then the component would also become obsolete. The architecture itself however has the possibility of being ahead even if the components being used are not new in technology.

Hofer and Halman (2004) also note that "the striking advantage of layout platforms is that for a complex product it is comparably easier to standardize the *arrangement* of its subsystems than to standardize these subsystems. A layout platform seems especially suitable for *redesigning* product architectures of *existing* products by supporting the reuse of developed elements within a clearly structured framework (layout)."

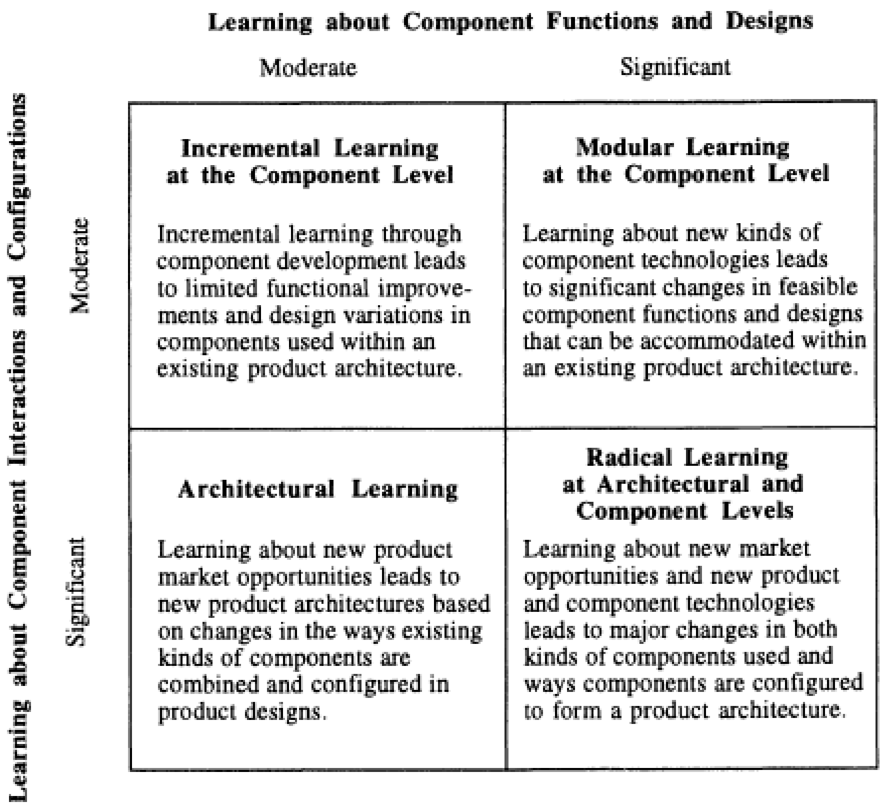


Figure 2.43

Modes of Learning in Product Creation Processes

(Sanchez and Mahoney, 1996)

Sanchez and Mahoney (1996) for example speak of the concept of an "evolving product architecture" and this would seem an extremely healthy way to maintain competitiveness of products. The focus is less of the product components themselves but more to do with a higher level focus that can only serve the overall needs of the company's different customers better.

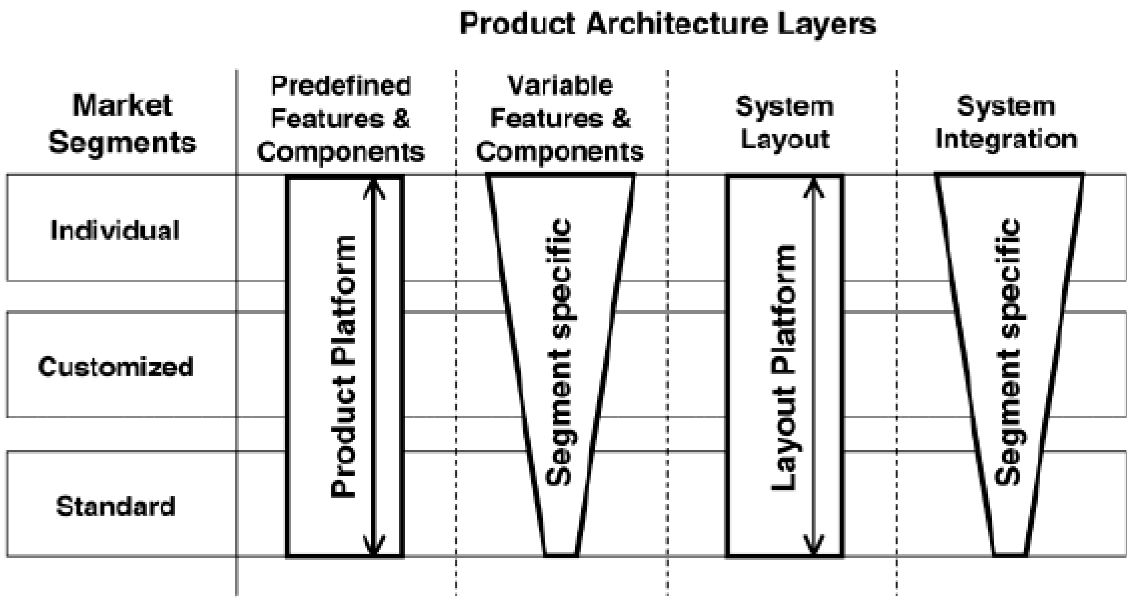


Figure 2.44

The Segment-Specific Variety of Product Architecture Layers

(Hofer and Halman, 2004)

Hofer and Halman (2004) in fact argue similarly that the adoption of Product Platforms, though more a layout platform of sub-systems catering to different segments of individual, customized or standard markets, is an effective strategic solution to the CoPS problem of low production rates. Other than enabling market segmentation, it also enforces at least a proportion of commonality in sub-systems that offer scope towards a dominant design (Hofer and Halman 2005). This in turn accelerates the transition from CoPS to a traditional product innovation cycle as per Abernathy and Clark (1985).

Investing in shared sub-systems hence can assist in improvements across several product lines as with Honda's VTEC Power Train which is shared across multiple product lines as shown below. Honda's sports utility vehicle (SUV), the Element, utilized many common systems and parts from other Honda products not only saving costs, but also improving development time as well as ensuring proven reliabilities from proven sub-systems (Meyer, 2008).

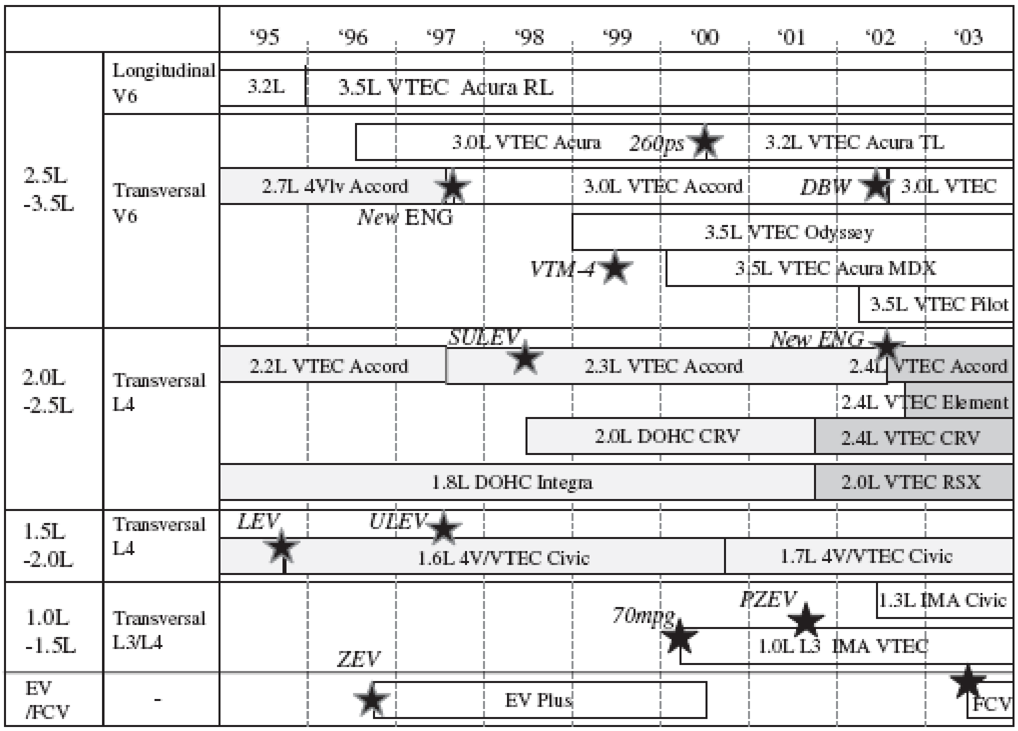


Fig 2.45

Honda VTEC Power Train Roadmap

(Meyer, 2008)

Alizon et al (2007) also propose methods of balancing between commonality and diversity when re-designing, i.e. a way of determining which parts could remain different or benefit from re-design to have commonality or vice versa. In practice as we see from the B737 example, it may be development and production costs as well as customer preferences that drive the manufacturer to adopt minimal and only significantly beneficial changes for derivatives and variants.

Interestingly while many papers discuss the ability of product platforms to differentiate, e.g. Robertson and Ulrich (1998), the B737 example is one where the manufacturer strives to maintain commonality. Perhaps the difference is in that the purpose of differentiation in the prior type of cases (e.g. cars) was largely for cosmetic and marketing reasons such as with Sanderson and Uzumeri's (1995) Sony Walkman study.

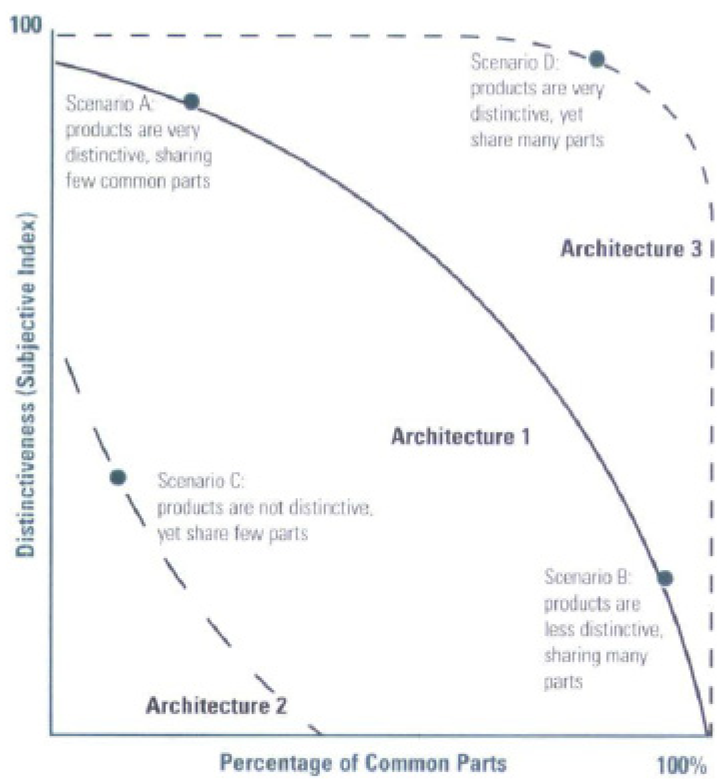


Figure 2.46

Trade-off between Distinctiveness and Commonality

(Robertson and Ulrich, 1998)

Certainly the platform approach allows large variations of "soft" cosmetic type changes while the "hard" engineering parts remain constant. However in the case of aircraft, and perhaps many CoPS cases since these would typically be non-consumer type extremely high cost items, the prevailing requirement would be cost reduction in operability that could be gained by use of common parts, training, and operating crews and procedures.

Hence we see that the objective is different, albeit with the same platform idea. The consumer type product chases differentiation, whereas the CoPS scenario chases commonality. In the former, the objective is to create mass models with minimum engineering effort with little performance implications, while in the latter the objective is to maintain maximum commonality while creating new models, which in turn are created to minimize de-optimization of performance at different ends of a market.

Conversely, the hint is that a CoPS product could be expanded into a family by simply stretching or shrinking a few key component parts (such as the fuselage on the B737) to alter its performance to serve different market segments and hence enjoy the benefits of a product platform.

In the case of Boeing, it is interesting to note that while wartime refined the design of the extremely successful B-17 Flying Fortress bomber aircraft, it was in a catch-up position to develop civilian transport aircraft during that time as Douglas had produced the 21-passenger DC-3 that was more popular than Boeing's 10-passenger B-247. Boeing's response was the 33-passenger B-307 Stratoliner.

While this was not a huge commercial success, what is interesting of the design is that it used the wings, engines, and undercarriage (landing gear) from the B-17 (Hill, 2002; Yenne 2005). Had the B-307 been more of a success with later versions, then the B-17 components would have been seen as a platform with which Boeing saved design and development costs using wartime proven designs.

The concept however was repeated when Boeing postwar developed the Model 367/KC-97 military transport and the Model 377 Stratocruiser commercial transport aircraft. The two airframes were primarily the same, but used the wartime developed B-29 Superfortress bomber aircraft wing and other components. The similarities between the KC-97 and B-50 (a postwar re-engined version of the B-29) can be seen in Figure 2.49 (Yenne, 2005).

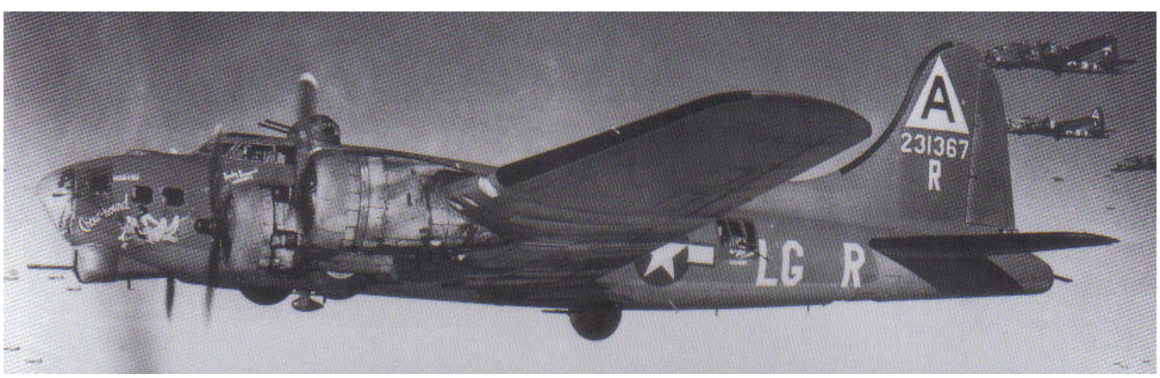


Figure 2.47

B-17 Flying Fortress

(Yenne, 2005)

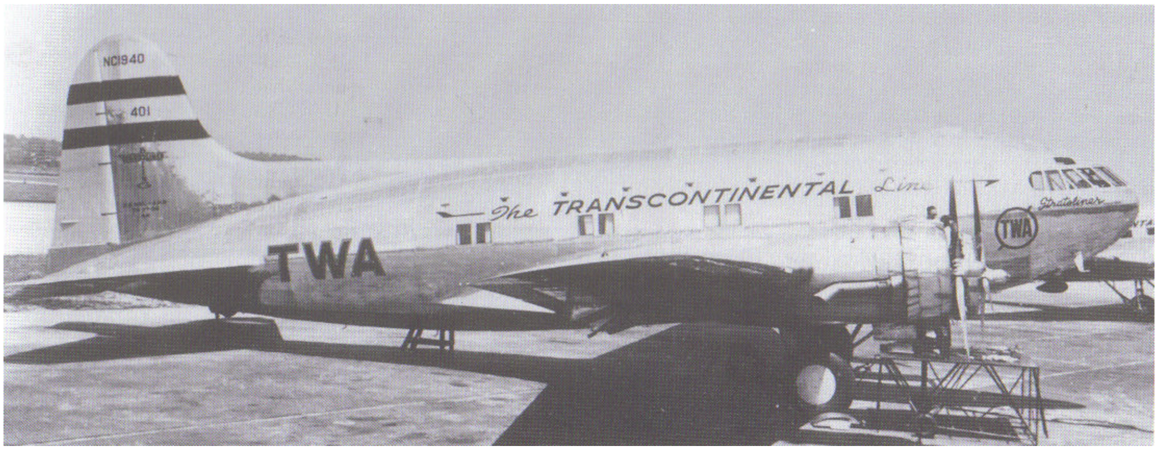


Figure 2.48

B-307 Stratocruiser

(Hill, 2002)

Figure 2.49

KC-97 (left and above) refueling a B-50 (right and below)

(Yenne, 2005)

We will see later that Boeing’s ability to transpose designs from one product line to another is a common theme.

“Since the entry into service of Boeing’s first jet airliner design, the medium/long-range Boeing 707 in 1958, the company had been working towards offering a ‘family’ of designs. Each different member of the ‘family’ was to be able to serve the airline’s needs in different operational markets, but with enough of a degree of commonality in design so as to reduce production costs to the maker and significantly decrease operating costs to the customer” (Hill, 2002).

Further, a flight simulator for example may need the cockpit dimensions and controls to be close to identical to the aircraft type it is simulating and hence be quite customized. But the visual display systems, motion mechanisms, hydraulic and/or electrical systems, air conditioning systems, fire extinguishing systems, and computer systems that drive the motion and simulation imagery do not necessarily have to be different for simulators that simulate different aircraft types. The computer hardware in particular can be the same, the difference only being in the software and databases that are loaded.

With the CoPS scenario, a purposely driven strategy to use a product platform can have drawbacks if the drive to maintain commonality is too rigid. Halman, Hofer and van Vuuren (2003) note four types of platform related effects – Process Platform, Customer

Platform, Brand Platform, and Global Platform. The names speak for themselves and the depths to which the platforms can be created can be quite deep.

For example the Process Platform can lock in how products are produced, the Customer Platform as to which market segments are targeted, the Brand Platform as to what type of sub-brands can be created, and the Global Platform as to how the offerings of a globally-rolled out product has to be standardized. This lock-in of a multitude of different aspects can create rigidity when the product platform reaches a point when in fact it should be updated.

2.7. *Emergent Strategy and the AH-1/UH-1*

One definition by Mintzberg (1978, 1987) of strategy is that it can be a “pattern in a stream of decisions”. He notes that “emergent strategies” can occur depending on circumstances as in the figure below. Changes in the environment elicit reactions that can form new strategies.

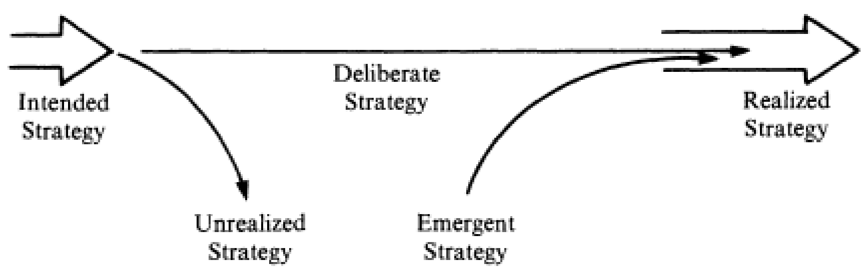


Figure 2.50
Types of Strategies
(Mintzberg, 1978)

With respect to CoPS, the aspects of time and learning can be utilized for improvement. “While normal production process learning may be difficult in CoPS, there may well be scope for learning economies between product generations and at the components level, where demand may be very high. From a strategic viewpoint, CoPS suppliers may be able to gain advantage by altering design architectures to increase the scope for high volume component use in CoPS.

For efficiency in CoPS projects, it is likely that a responsive, step-by-step, crafted management is needed to deal with uncertainty and feedback loops" (Hobday, 1998).

As in Figure 2.51, Mintzberg and Waters (1985) suggest that through feedback learning, the emergent strategy in fact can eventually become a deliberate strategy.

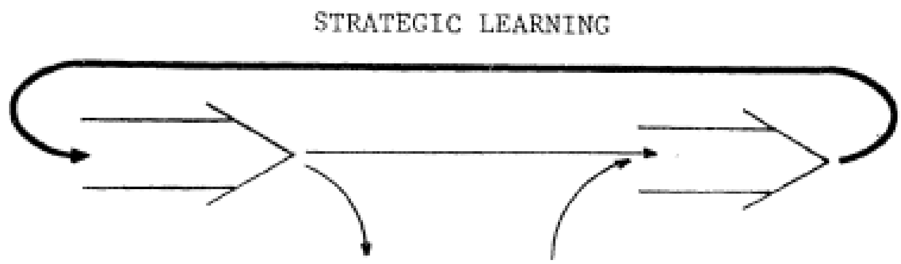


Figure 2.51
Feedback Loop
(Mintzberg & Waters, 1985)

An interesting example of this is the Bell AH-1 Cobra attack helicopter developed by Bell in the 1960s for the Vietnam War. Using the engines, rotor blades and transmission dynamic systems of the UH-1 "Huey", it represented a marked improvement as a dedicated gunship over the Huey that was much slower as the less aerodynamic fuselage was designed for carrying troops (Lambert, 1967). With the obvious advantage in commonality in spare parts and training for the operator, Bell also saved considerably in development costs by using major components from the Huey.

Over the years however the AH-1 Cobra and UH-1 Huey were improved but on separate programs. For example the AH-l's original Lycoming T53 turboshaft powerplant was replaced by dual General Electric T700s, while the UH-l's T53 was replaced by Pratt & Whitney Canada's twin-turbine T400. As a result much of the commonality advantage was lost. This was particularly felt on missions where both types were operated together in joint light/attack helicopter squadrons.

In 1995 the USMC (United States Marine Corps) received US Department of Defense approval to upgrade its AH-1s and UH-1s with four-blade rotors and other improvements. Interestingly the upgrade was approved as an alternative to buying more modern McDonnell Douglas (MDC) AH-64 attack and Sikorsky UH-60 assault helicopters.

"Capt Steven Fahrenkrog, head of the Marine H-1 upgrade programme, emphasises the commonality benefits within the HMLAs (Marine Light Attack Helicopter squadron) which will result from the 4BW/4BN (4 bladed rotor, the "W" and "N" refer to the latest AH-1 and UH-1 models) upgrade. Not since the 1960s, he says, have Marine Corps Cobras and Hueys shared the same dynamic system … Using the same dynamic system - rotors, engines and transmission - on AH-1 s and UH-ls flown by the same squadrons will reduce spares, maintenance and training, Fahrenkrog says. Few HMLA pilots are now cleared to fly both types, but similar handling qualities resulting from common dynamics should make cross-training easier, he believes.

The 4BW/4BN upgrade is centered on a derivative of Bell's Model 480 four-blade bearingless, hingeless main rotor. This all-composite rotor is used on Bell's latest Model 430 commercial helicopter, and features a flexible composite hub which allows pitch, flap and lead-lag motion of the blade without the bearings and hinges of conventional rotor-heads.

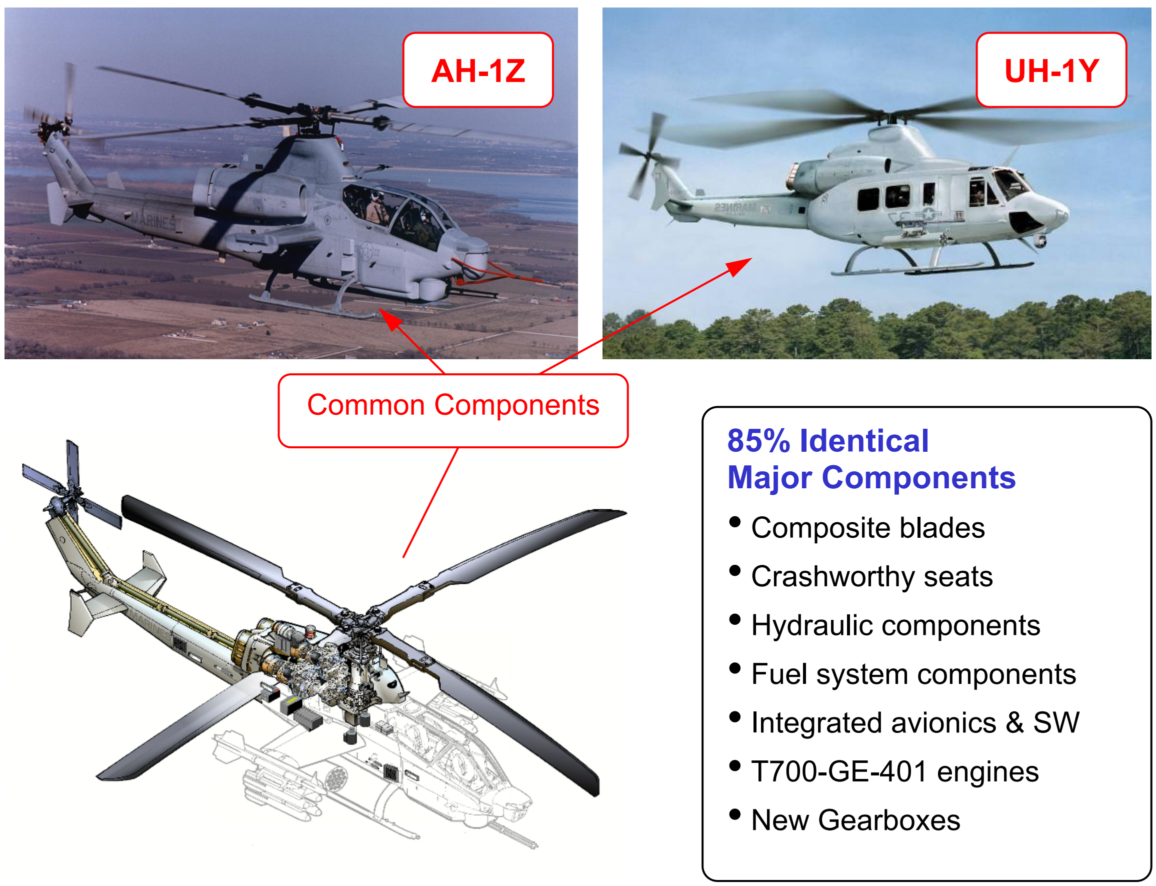


Figure 2.52

Bell AH-1Z & UH-1Y Systems & Components Commonality

(Birkholz, 2001)

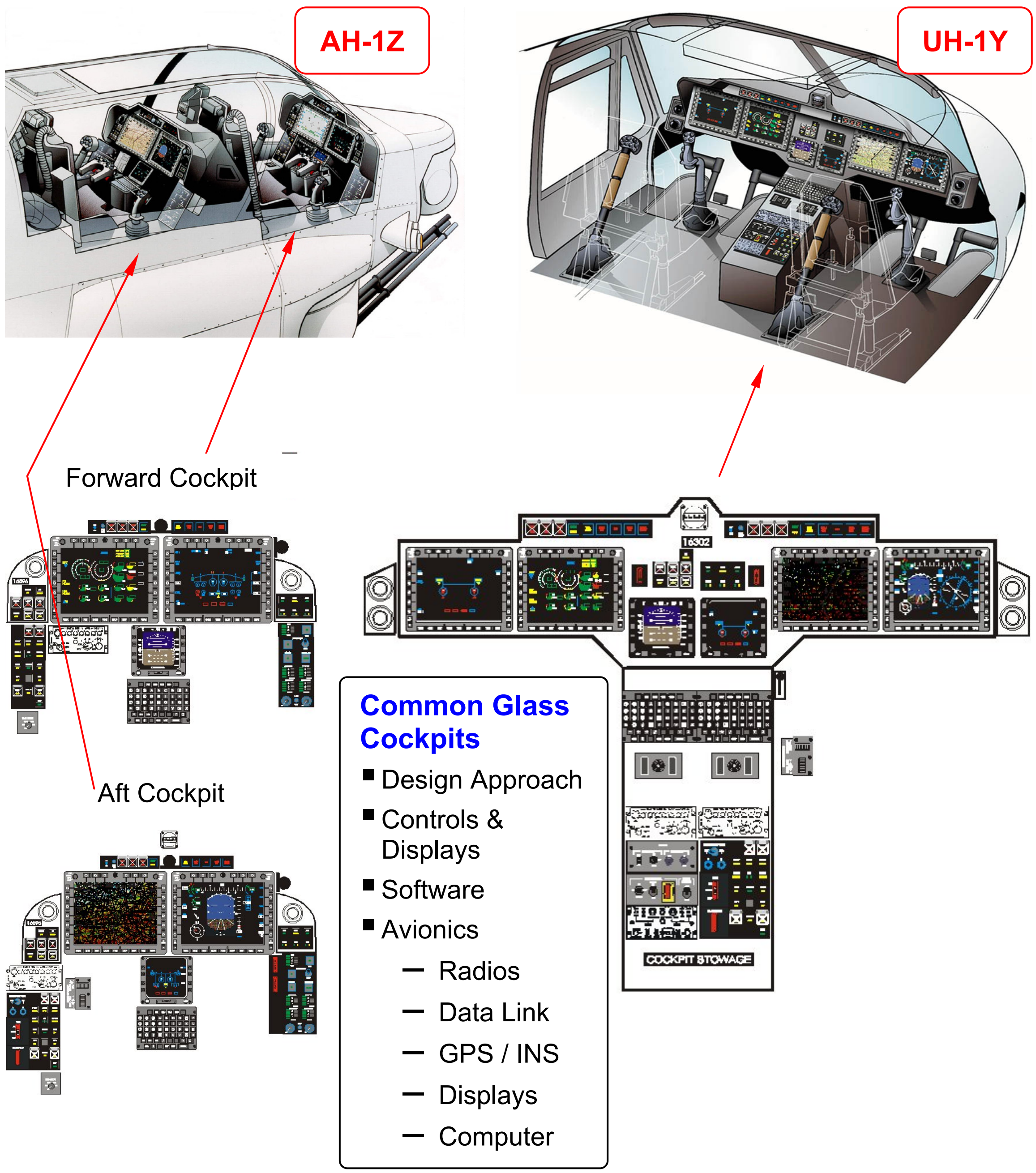


Figure 2.53

Bell AH-1Z & UH-1Y Cockpit Commonality

(Birkholz, 2001)

The upgraded dynamic system for both aircraft consists of the four-blade main rotor, a l,960kW (2,625shp)-capacity transmission, T700 engines with infra-red suppressors, a new 90° gearbox in the tail and a four-blade pusher tail-rotor (replacing the present two-blade tractor tail-rotor). Both aircraft will receive auxiliary power units, and the uprated tail-rotor will be mounted on a strengthened tailboom with a more-effective elevator" (Warwick, 1996).

The final product is the AH-1"Z" and UH-1"Y" with 85% identical major components as seen in Figure 2.52. Even though the cockpits feature different seating arrangements, tandem (forward and aft) in the AH-1 and side--by-side in the UH-1, even the displays and controls are common by simply re-arranging their locations as seen in Figure 2.53.

"Col Harry Hewson, H-1 upgrades programme manager for the US Naval Air Systems Command, argues that the USMC, in nine separate studies - some as recent as 2006 - had concluded the UH-1Y/AH-1Z combination is the most cost-effective means to meet the service's unique operational requirements.

Because a single squadron type operates both machines, commonality between the two airframes during USMC expeditionary operations is far more important than usually across the Department of Defense.

‘Eighty-four percent of the components are identical. The same part number can be used on one or the other. That's really one of the strong selling points for this programme,’ Hewson says. "The Marine Corps exists to operate in an expeditionary environment, being able to pack up and go some place and operate without a lot of support machines for extended periods. So getting your logistics footprint down to as small as possible is critical.’

Increased commonality means that personnel costs can also be reduced, he argues. ‘Now you only have to train one flavour of avionics guy, or one flavour of rotor and powerplant guy. The skills sets focus down much more, which means when you go on some extended operation at some remote site, you can take fewer people.’

The reduced number of support troops and associated facilities helps to lower the operating cost of the aircraft over the course of its service life” (Majumdar, 2010).

The program has not been trouble free. However despite delays and cost overruns, the USMC still expects to save $3 billion in operating and support costs as the result of the increased commonality between the upgraded helicopters (Warwick, 2002).

Hence in the face of more modern alternatives such as the McDonnell Douglas (MDC) AH-64 attack and Sikorsky UH-60 assault helicopters, Bell managed to review old designs from the 1950s-60s (the AH-1 first flew on in 1965 as the Model 209, while the UH-1 first flew in 1956), by developing commonality advantages and in essence using the those common parts as a *platform*. Having a common platform allowed Bell to add other improvements such as the auxiliary power units and tail rotor and booms to both types. Training and logistics support are also powerful but positive side effects of this theme. This platform strategy had its origins from when the AH-1 was first developed using parts from the UH-1, but after both types had experienced a history of divergent upgrades, re-emerged as a sound strategy for upgrading both helicopter types.

3. Research Methodology

3.1. The Need for Context

The research questions that have been posed in the previous chapter indicate a need for a research methodology that can deal with contextual complexity. In searching for an innovation process, the search is towards determining longitudinal processes that can occur not necessarily as general phenomena but in specific cases that could be affected by deliberate human intervention.

Hence in each of this type of specific phenomenon, it is important that the context behind these decisions should be understood, particularly with the technical detail of changes of complex products and systems that happen over time. Some of this context may be the background behind why changes are made, for example due to competition or technology obsolescence. With the B737, a real mix of old, new, and old modified to new, designs are evident and it is of interest to review the features of these as each new generation of B737 is developed.

The CoPS general theory assumes that the innovation process follows a similar general trend for all CoPS products but this very assumption is that which is being debated. Hence the specificity of the research tends to dictate one towards a case study qualitative type approach rather than a quantitative one with statistical surveys that can show trends from general observations.

Mintzberg (1979) argues effectively with his comment "What, for example, is wrong with samples of one?", that in-depth study of a few cases can be far more effective than superficial data on many thousands of cases. Theory building he argues comes from a richness of description that is derived largely from anecdotal data. Miles (1979) indicates similarly so highlighting the contextually rich nature of specific case studies versus generalizing across a large number of studies by saying "Must we trade close-up descriptive validity for accurate but "thin" generalization?" He notes that "qualitative data are attractive for many reasons: they are rich, full, earthy, holistic, "real"; their face validity seems unimpeachable; they preserve chronological flow where that is important, and suffer minimally from retrospective distortion…". (Christensen, 2006) notes "researchers who derive a theory from statistics about a population still need to establish external validity through *circumstance-based* categorization"

Hence it is this type of context that is pursued and is followed for the study to preserve the reasons why and how decisions were made in the product development process.

"Theorists are lost because they are blind to what words in context can teach them . . .

Formal rationality, when carried into theory, is the idea that we can define decisively all relevant terms, allow for all conceivable possibilities and bundle up our understandings such that our meaning will be perfectly clear. *Practical rationality emphasizes context* and, when carried into theory, suggests that ambiguity is always and necessarily present." (Van Maanen, 1995)

3.2. The Case for the Case Study

Based on the previous chapters, the nature for an exploratory type research is obvious. "Scientific" methods using conventional equations, hypotheses or constructs may not seem appropriate as in this case we are looking to see why in certain conditions CoPS type products can better succeed with higher production lives in an evolutionary manner than other. The understanding of these phenomena surely lies in the stories behind the decision making rather than just from performing a mathematical analysis of collectable data.

The fact that CoPS stands for *Complex* Products and Systems makes it even more difficult in terms of trying to measure these sorts of issues in a codified way. Quite simply the variables would be too numerous and the relationships too complex to model and present in an appropriate way without oversimplification and loss of context. Hence it would appear to be more wholesome and realistic to investigate the issue via a case study of where such a CoPS product succeeded where traditional CoPS theory says it should not and then investigate the reasons of why.

Yin (2002) particularly notes that “who”, “what, “where” type questions are more appropriately answered by survey type strategies or analysis of archival records. As such these often statistical type analysis forms a predictive type nature when the analysis results are confirmed. “How” and “why” type questions on the other hand are more explanatory in form and this is where case studies are preferred research strategies. This is particularly so when relationships between factors occur over different periods of time and the conditions could be different each time. This variance in conditions would make a statistical type study difficult as the assumptions could not be held constant.

In this study the answers to the research questions being asked would assist in creating a management or business strategy going forward rather than a predictive theory based on past activities. Hence in part it is the theory from why things were done well (or not) in a particular case or cases and if well, then how to do it for future projects.

Developing such theory through case study is reinforced by Meredith (1998) and Sutton and Staw (1995). Sutton and Staw (1995) note that common academic paper categories such as references, data, variables, constructs, diagrams, or hypotheses are not by themselves pure representations of theory. While these may be helpful and supportive, they instead say “ … theory is the answer to queries of why. Theory is about the connections among phenomena, a story about why acts, events, structure, and thoughts occur. Theory emphasizes the nature of causal relationships, identifying what comes first as well as the timing of such events. Strong theory, in our view, delves into underlying processes so as to understand the systematic reasons for a particular occurrence or nonoccurrence."

Weick (1995) argues that "data, variables, constructs, diagrams etc." should be at least considered supportive but condones Sutton and Staw's basic view that there should be a "why" to explain relationships. Dimaggio (1995) goes further in proposing theory as "enlightenment" and/or "narrative". In theory as enlightenment, Dimaggio proposes an important point that theory should not be to generalize, but to clear away "conventional notions to make room for artful and exciting insights." In theory as narrative, he highlights the actions of humans that theory could describe. He also notes "Theories are not just constructed, they are socially constructed after they are written. Theoretical ideas take on a life of their own. In some cases, sophisticated ideas are degraded. In other cases, half-baked ideas go back into the oven, coming out in more satisfactory form. To some extent, the quality of a theory is a function of the quality of the people who employ it."

These issues can be debated at length, but the important recognition is the human aspect to it all. To describe human intervention, decisions, the "how" and "why" cannot be simply reduced to a set of numbers. A suitably descriptive narration to a case study may be more appropriate in this case.

Eisenhardt (1989) notes that some researchers have converted theory-testing research into theory-building research by taking advantage of serendipitous findings and quotes ". . .

most importantly, theory-building research is begun as close as possible to the ideal of no theory under consideration and no hypotheses to test. Admittedly, it is impossible to achieve this ideal of a clean theoretical slate. Nonetheless, attempting to approach this ideal is important because preordained theoretical perspectives or propositions may bias and limit the findings. Thus, investigators should formulate a research problem and possibly specify some potentially important variables, with some reference to extant literature. However, they should avoid thinking about specific relationships between variables and theories as much as possible, especially at the outset of the process."

This is an important statement as it hints that in the type if research intended, i.e. to explore and determine new theory, one should be careful not to pre-empt that theory finding by pre-building theoretical models of what is expected. Rather an open mind should be kept open.

Meredith (1998) is particularly helpful as he highlights how case studies can assist in understanding phenomena rather than simply explaining what happens. Again the emphasis is on "why". "Rationalism, an epistemological paradigm that includes the beliefs of positivism and some forms of empiricism, generally employs quantitative methodologies to describe or explain phenomena and here specifically includes optimization models, simulation modeling, survey methodology, and (less frequently in operations management) laboratory experiments.

Rationalism is concerned with *explaining* what happens and how, so as to achieve some goal or end such as predicting production system characteristics, or perhaps the effect of some change in managerial policy on plant measures. Case/field study is one example of an alternative research paradigm known as interpretivism and uses both quantitative and qualitative methodologies to help *understand* phenomena. It is more process- or means-oriented and helps the researcher comprehend why certain characteristics or effects occur, or do not occur." (Meredith, 1998)

Like Yin (2002), Meredith also emphasizes the advantages of the case study when it comes to exploratory type research investigating the "why" type questions. In his arguments he notes that to develop theory, a rationalist must still make the "leap" from just an ability to tell what a phenomenon entails to actual understanding. Hence he suggests that rationalist methods may be more appropriate for testing or verifying existing theory, while methods such as case studies are best for generating or extending theory.

	Theory building	Theory testing	Theory modification
What	Case	Rationalist (Case)	Rationalist (±) Case (±)
How	Case	Rationalist (Case)	Rationalist (±) Case (±)
Why	Case	(not relevant)	Case

Figure 3.1

Theory development under rationalist and case research methods.

(Meredith, 1998)

One advantage of the case study for exploratory type research is its flexibility. "… the research scope can be expanded as necessary, the focus shifted, or other sources sought as the study progresses" (McCutcheon and Meredith, 1993). This way while research questions should be kept in focus, the findings don't have to follow a rigid structure which may not necessarily be appropriate as the research progresses. Instead an iterative approach can be used.

An issue against a quantitative type study which is of a specialist industry may be that the understanding of the numbers are really only understood by specialists in the field and the assumption is that the readers understand in a qualitative sense. This is particularly so in Complex Products and Systems and more so in the aviation field where this case study is performed.

A non-specialist may not understand for example that aircraft weight is often traded for range or the distance it can fly and these factors are also affected by complicated relationships to other variables such as cruising speed and altitude. Hence a descriptive narrative highlighting the main points of the research may be more helpful than presenting a multitude of aerodynamics data that can only be confusing.

3.3. *Single versus Multiple Case Studies*

Beyond agreement to do a case study in search of theory building, there comes the inevitable question of whether to perform a study on a single case or a multiple cases, and with the latter, how many cases would actually be the suitable number?

Yin (2002) illustrates this below in describing different possibilities, depending if there are single (holistic) or multiple (embedded) units of analysis. For the single case study, Yin justifies this if the case is a critical type case, an extreme or unique case, a representative or typical case, a revelatory case, or a longitudinal one. The revelatory case is described as one where the researcher may have unique access to the subject of study where others may not.

In the study of CoPS innovation, cases are complex by definition and correspondingly rare. A study of the Boeing 737 would reveal several generations of product families and decision making. Hence the longitudinal case is certainly true, while the rarity of CoPS suitable cases would match the unique case. The revelatory case is partially true in this case as the author has an aeronautical engineering background, work experience in the aviation business, and has knowledge of access means to potential data sources. Though not exclusive it is an advantage that perhaps the general researcher may not have. Hence while it would be vague to justify the extreme/unique or representative/typical cases, the other classifications certainly provide strong argument for a single case study.

If a CoPS case of suitable longitudinal study (say over a few decades) and there are generations of product families, derivatives, and variants, then the "embedded" case is inevitable as each derivative or variant can also become a subject of analysis (This is certainly true of the Boeing 737 history since it has many model derivatives and variants). This assists in supporting reliability and validity (at least internally) desires. External reliability needs are somewhat questionable in this particular case since it would be a largely exploratory research and the nature of CoPS does not lend itself to simple verification for any case.

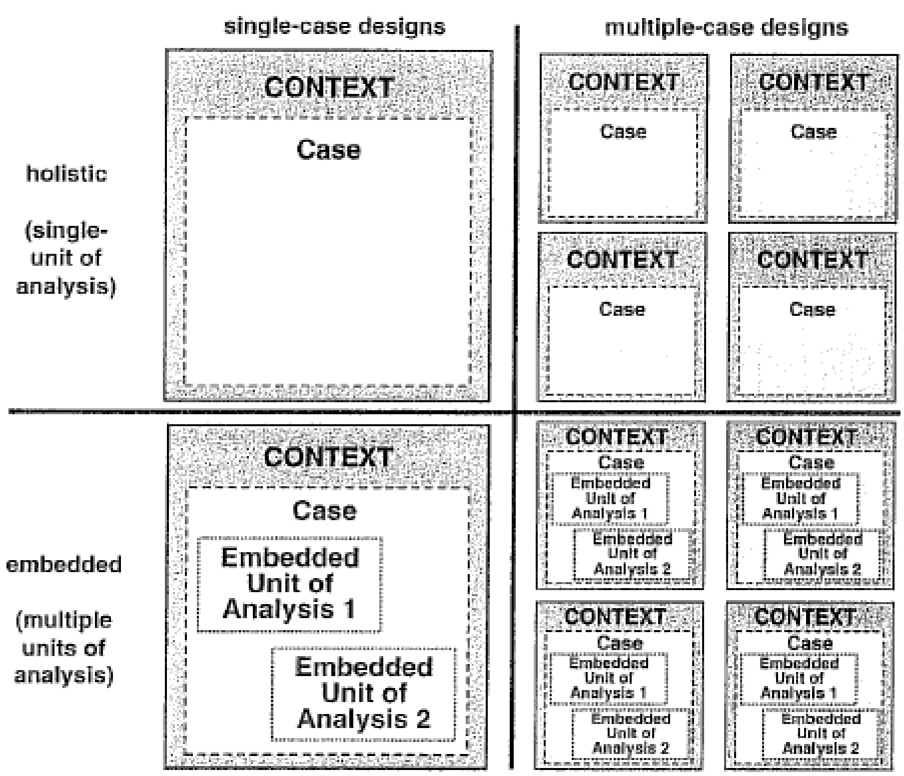


Figure 3.2

Basic Types of Designs for Case Studies

(Yin, 2002)

Replication needs as would be assisted by a multiple case study is somewhat mitigated if the single case was an embedded one. In fact an advantage would be the similar settings of context, whereas it would be difficult to compare apples to apples if the multiple case settings were all different which would be highly likely with CoPS scenarios. Texier (2000) for example provides a rich source of multiple cases of aircraft development projects in France (Dassault Falcon), Sweden (Saab 340), and Korea (Daewoo KTX-1 “Woong-Bee”). However Texier also describes quite clearly that in each case the political, economic, and technical conditions and motivations were quite different.

A valuable point that March et al (1991) point in their paper on “Learning from Samples of One or Fewer” is that organizations can also be learning as they go along events. Hence multiple events within the same case may see an effect on the later cases following learning from the earlier cases. That learning could be negative after bad experiences or positive after a positive experience. March et al quote a case where a firm may not even wait for the outcome of an event because the experience from just actioning the event gave them a positive experience and the confidence to repeat. Even “near-histories” i.e. events that may had a different outcome pending a minor factor offer learning experiences.

Hence just the act of doing or trying to do something creates a foundation for future decisions in terms of understanding capabilities and developing confidence in possible outcomes. In the case of aircraft development which is often a long expensive drawn out process over many years, these are fairly significant factors to take into account and exploit. It would be much more difficult to extract this kind of analysis from lesser events spread across multiple cases that may not even have the same institution involved.

Admittedly Yin (2002) also notes that a two-case study could be selected to show contrasting cases, i.e. where the cases selected would be deliberately different. However again in the CoPS scenario this is almost impossible to select exactly. A "different" case is not necessarily an "opposite" case. Perhaps this may be so with certain parameters but near impossible for all parameters in a complex case.

No pairs in the very different cases in Texier's study could be considered "opposite" or easily contrasting. They were just different. The Dassault Falcon was a business jet, the Saab 340 was a commercial turboprop, and the Daewoo KTX-1 a military trainer. Probably more theory building possibilities could be gained from multiple different cases and contexts, but the fear would be that one loses the focus of the stated "why" research question in the first place.

While Eisenhardt (1989) confirms that novel theory building is a strength of case studies, she complicates the issue by saying ". . . while there is no ideal number of cases, a number between 4 and 10 cases usually works well. With fewer than 4 cases, it is often difficult to generate theory with much complexity, and its empirical grounding is likely to be unconvincing, unless the case has several mini-cases within it . . ." Just as context has been explained to be important to a case study, one should probably interpret the context of Eisenhardt's comments that it was a general comment and not specifically referring to special cases such as CoPS.

This view is similar to Dyer and Wilkins's (1991) critique that Eisenhardt considered only general constructs to amplify the case for multiple cases, whilst ignoring the opportunities to go deep in context for single case studies. They stress the narrative or story telling part to develop theory by saying ". . . we hope that many scholars will continue to try to tell good stories that have theoretical import. If researchers apply the paradigm of hypothesis testing to case study work without the goal of telling good stories, they are likely to miss both the caliber and the quantity of theory we have seen result from classic story- telling through case studies of the past."

It should be noted that this paper incited a response by Eisenhardt (1991) to re-stress the main points she was trying to make on developing theory (". . . if we take the advice too seriously, then we will end up writing interesting stories, but creating little in the way of *generalizable* theory."). However the case study in this research is specific and exploratory.

This applies to her comment also about generalization which can be a common theme on case study papers for reliability and validity or even why one should use multiple case studies. With the CoPS study, generalization is not the main objective. A specific theory is sufficient, especially in an exploratory context. It is not expected that a theory that could be applicable to a nuclear submarine project would be similarly applicable to a mass consumer good such as a portable MP3 music player. Even if we compare complex products with complex products, the best the theory could be is potentially useful as it is impossible to consider all contexts of a complex scenario.

Finally Meredith (1998) provides and interesting trade-off in the figure below between the rationalist statistical methodology and the interpretivist case/field research method. Interestingly he notes that the curves “are convex for the two types of studies for different reasons. For case and field studies, the mental confusion as more sites are added grows exponentially rather than linearly. For statistical studies, the use of small sample statistics and the acceptability of higher levels of the significance criterion for studies of ‘new’ phenomena provide what is generally considered to be ‘acceptable’ evidence.” There is no particular wrong or right, but it offers a guideline towards the choices to make depending on what is desired.

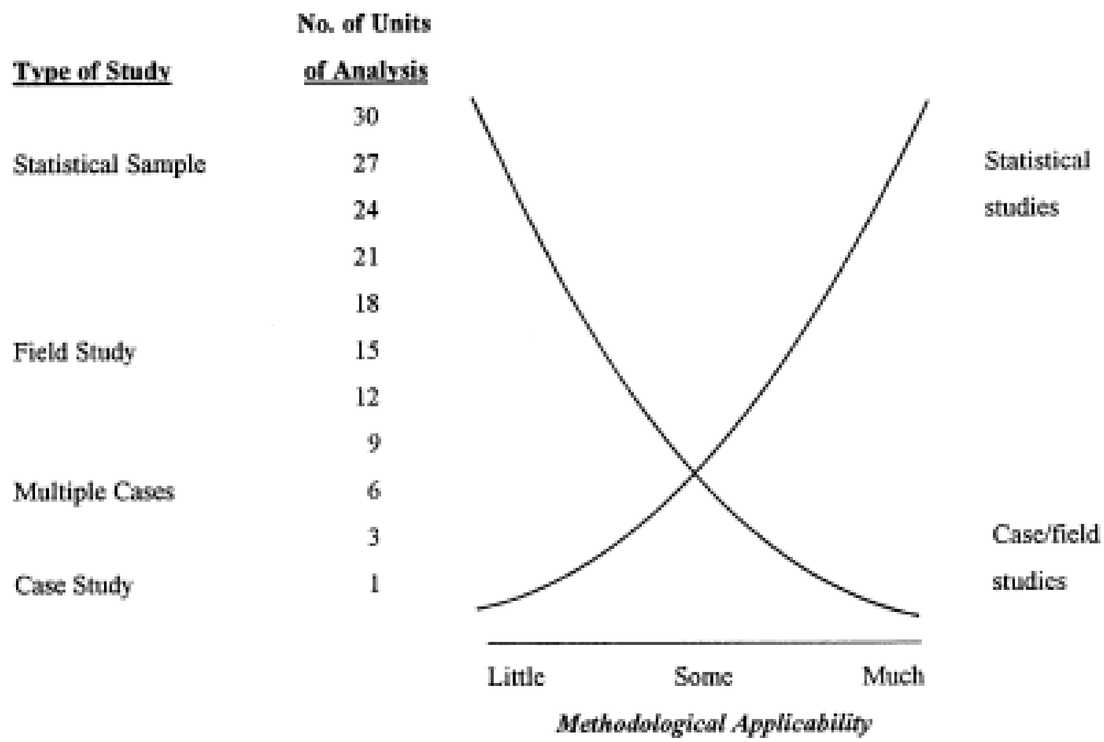


Figure 3.3

Methodological applicability relative to number of units

(Meredith, 1998)

Obviously at the bottom the single case study may be deemed the least appropriate for a statistical methodology approach but offers the most applicable method for "extensive qualitative description and contextual and temporal analysis" in exploratory type investigations.

3.4. Research Structure

Yin (1981) quotes "The typical case study report is a lengthy narrative that follows no predictable structure and is hard to write and hard to read. This pitfall may be avoided if a study is built on a clear conceptual framework. Furthermore, a case study narrative may be replaced by a series of answers to a set of open-ended questions. . ."

Loosely this is the model that this research paper follows. The previous chapter provides the theoretical grounding, framework and most importantly the research questions for case study. While this thesis is largely a "single" case study the case itself is rather large and offers a longitudinal depth of span that provides some replication of events. In the prior development of the theoretical grounding, other cases are also referred to support, such as the Have Blue Stealth Fighter prototype aircraft, the Ford Model 'T' car, and Bell AH-1/UH-1 helicopter programs and history.

In the development of the case study of the Boeing 737, it was recognized early on that it would be easy to get lost in heavy technical discussions and jargon. Much effort was hence put into attempting to simplify the final reporting so that the essence (on innovation processes) is still evident without confusing a non-aviation specialist. However the narratives on "why" decisions were made were given high priority while keeping the sequence of events in the first part (the history of the Boeing 737) in a sequential structure as per Pentland (1999).

Thus development of each generation of the Boeing 737 is described in time ordered sequence. However and in keeping with the theme for an exploratory type case study to possibly generate theory, the analysis parts were left open until the respective histories were completed. This kept open the door for new discussions on topics that might be discovered in the research.

In keeping with the original research objective, a strategy formulation proposal is provided only at the end after the analysis is completed.

3.5. Selecting the Case Subject (The Boeing 737)

The Boeing B737 airplane is a particularly suitable candidate for a number of reasons. As outlined before, it is a CoPS candidate but also conversely as an anomaly to the CoPS stereotype, has enjoyed a huge amount of success commercially.

As case subjects, CoPS do not typically have the advantage of mass consumer goods, such as the Sony Walkman, where much has been written and a multitude of literature abounds available for research. A case study with a desire for narration also typically demands time consuming and difficult to get personal interviews. Again for a CoPS project that may have been done several years ago and possibly in a far away location, resources would be stretched to achieve all this and possibly it may be difficult to track down the designers or engineers behind such a project that may have occurred many years ago.

The B737 however, because of its commercial success has plenty of material in books, magazines and journals with which to research. Being the smallest aircraft in the Boeing lineup, it however does suffer from a less glamorous image and historical narrative of its development generally needs to be sourced from more specialized books as its larger cousins get more detail in books that cover Boeing and its competition in general. Fortunately although it was first produced in the 1960s, the latest models are actually still in production. Hence the Boeing Company and current employees are still available as resources of data.

Advantageous also is the availability of data on its competitors such as the Airbus A320 series of aircraft, which are also still in production.

Though it is still in production, today's B737 however sports many changes since the first model was introduced. It has gone through many generations of development and many different versions including specialty use ones were produced. These variations in the product line offer richness in data for the research questions being asked. That the B737 also thrives in a commercial environment is helpful compared to say a military or state enforced product, where political motives to maintain production over-ride commercial reasons.

In the B737 versus A320 battle, one could also argue why not also make a case study of the A320, or even make it the case study. The A320 was developed under perhaps more political motivations than the B737 with a conglomeration of European nations trying to provide some competition to an otherwise American producer (McIntyre, 1992; Thornton, 1995; McGuire, 1997; Aris, 2002). The existence of possible government subsidies in the development of the A320 and political intervention of sales could potentially interfere with the type of case study here since it is the commercial success of a product and how it stayed commercially successful in the long term which is being explored. Aside from this, the B737 is the product with the longer and richer history. Hence for the purpose of this study the A320 is used mainly as a reference to its status as a competitor to the B737.

3.6. Research Practice

The research process was very much an iterative one collecting technical and historical data on the innovation literature and case study subjects. On innovation, particular journals such as the Journal of Product Innovation Management and Research Policy were a treasure trove of relevant articles. For product related historical data, Aircraft Commerce and Flight International magazines were very good references, particularly since many articles are now accessible via the internet. Aviation history books were helpful and data was cross-checked between various sources for validity.

It was more difficult to obtain product related technical data, not only for the Boeing 737 families, but also on the Airbus A320 family and their respective manufacturers. Boeing personnel however were particularly helpful and assisted in providing interviews as well as providing material on the various Boeing products. Some data is available publicly such as sales figures, but some available only though manufacturer links or aircraft operator/airline access.

Much time was spent collecting hard to find out-of-print documents for out-of production aircraft. Surprisingly a good data source was student material obtained from airline personnel that had attended aviation courses, some from many years ago. Documents such as the “Boeing Advanced 737-200 Systems” D6-24014A-R2 and aircraft-specific training material were extremely helpful in explaining aircraft features, systems and their functions.

4. History of the Boeing 737

4.1. Background of Boeing prior to the B737

Boeing was founded in 1916 by William "Bill" Edward Boeing, a lumber company owner in Seattle, Washington, U.S.A. Together with a George Conrad Westervelt, a naval officer and engineer who had studied aeronautics at the Massachusetts Institute of Technology (MIT), they developed the first Boeing Model 1, a two seat floatplane powered by a 125 hp engine. Also known as the "B&W" for "Boeing and Westervelt", this aircraft's first customer was a New Zealand flying school which bought two of the airplanes. Later model designs were also fitted for land use and Boeing enjoyed contracts with the U. S. military until the war ended in late 1918 (Yenne, 2005).

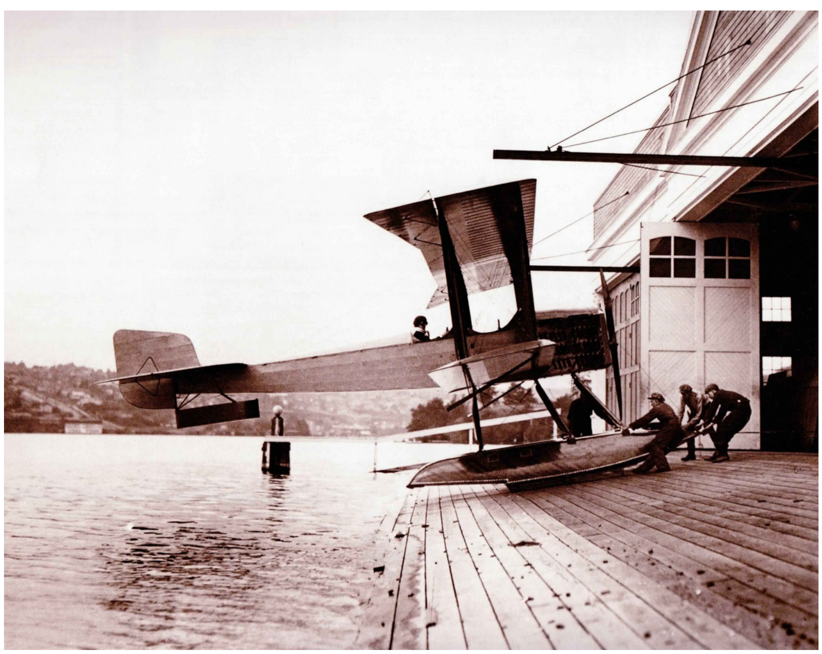


Figure 4.1

Boeing Model 1 "B&W"

(Yenne, 2005)

While developing the next design after the B&W, the "Model C", one of Boeing's engineers T. Wong, also a graduate of MIT, applied ideas from Gustave Eiffel, builder of the Eiffel tower in Paris, about the effect of wind forces on surfaces. Wong subsequently figured out how to make aircraft laterally stable by using dihedral or titling the wings up towards the tips. He also figured out how to improve horizontal stability by positioning the top wing forward of the lower wing on a biplane (Mansfield, 1966).

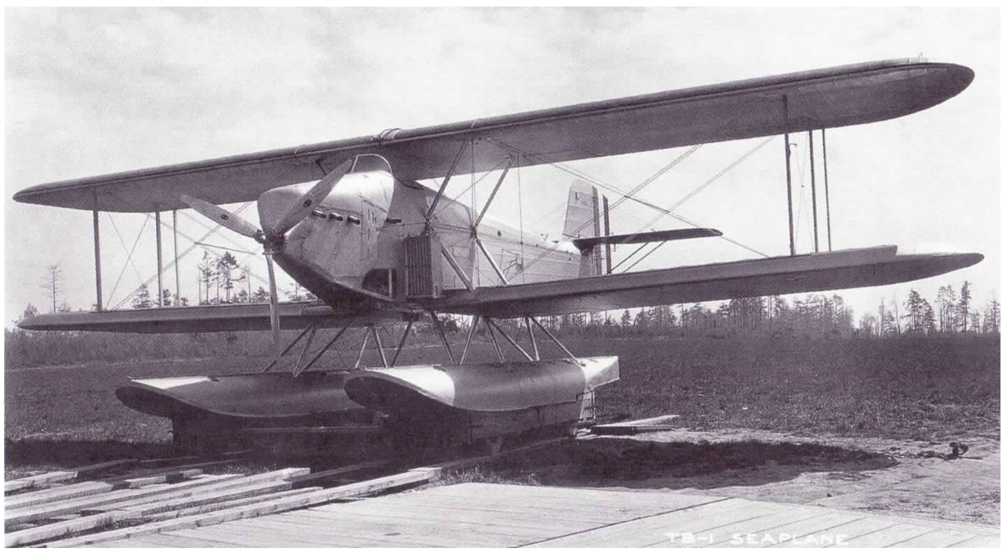


Figure 4.2
Boeing TB-1 Torpedo Bomber
(Yenne, 2005)

In-between the two World Wars, Boeing went on to develop military aircraft including trainers, fighters and bombers, some of which could operate on aircraft carriers. The US Post Office department gave impetus via mail contracts for commercial transports which Boeing competed for using the single engine Model 40. Boeing in the process eventually created a new airline, Boeing Air Transport (BAT), using Boeing airplanes. Later designs such as the trimotor (three engine) Model 80 offered an enclosed heated cabin with individual reading lamps, leather seats, and running water. Nurses were employed as flight attendants and served boxed meals (Yenne, 2005).

Figure 4.3

Boeing Model 40

(Yenne, 2005)

Figure 4.4

Boeing Model 80

(Yenne, 2005)

United Aircraft & Transport Corporation (UATC) was the holding company that eventually held in its portfolio BAT, the Boeing Airplane Company and other companies including Pratt & Whitney, an aircraft engine manufacturer. On 12 June 1934 however the Airmail Act of 1934 forbade the same company from both owning airlines and manufacturing companies which resulted in UATC being broken up. The airline portions became United Air Lines, and the Boeing Airplane Company was on its own again. Unhappy with this event, at this time Bill Boeing left the company permanently.

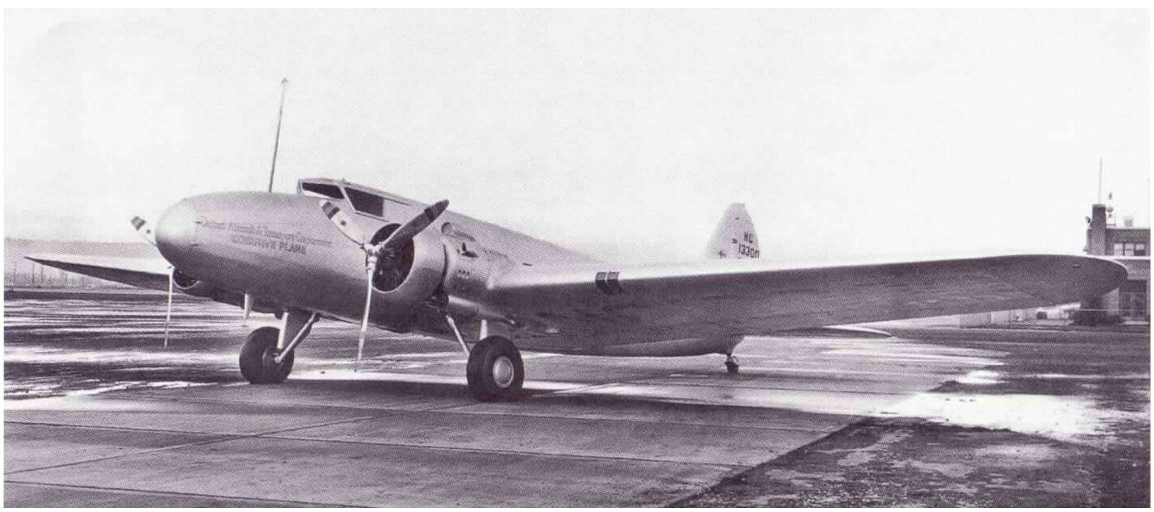


Figure 4.5

Boeing Model 247A

(Yenne, 2005)

While Boeing designed and built a large variety of aircraft, three models developed by Boeing in this era are worthy of mention. The Model 247 was the first all-metal twin engine airliner that preceded the famous Douglas DC-3. Four engine all-metal designs followed in the form of the Model 307 Stratoliner (Wingspan 107 feet 3 inches) with a pressurized cabin allowing the aircraft to fly at 20,000 feet (faster and above turbulence), and the Model 314 Clipper (Wingspan 152 feet), a flying boat. Both were known as comfortable airliners and gave Boeing valuable experience in designing large multi-engine transport aircraft.

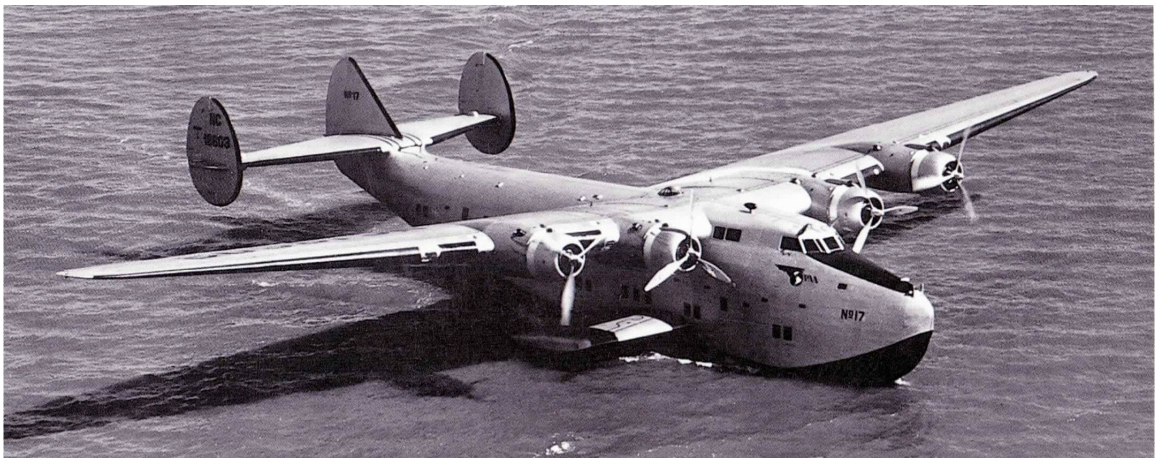


Figure 4.6
Boeing Model 314 Clipper
(Yenne, 2005)

The two most famous Boeing aircraft of World War II were the B-17 Flying Fortress (or Model 299, with a wingspan of 103 feet 9 inches), and the B-29 Superfortress (or Model 345, with a wingspan of 141 feet 3 inches). Both were all metal four engine heavy bombers. 12,731 B-17s and 3,627 B-29s were built. Another 5,000 B-29s were ordered but cancelled at the end of the war.

The first B-17 first flew on 28 July 1935. Interestingly as the war went on, the aircraft was upgraded continuously resulting in the several models from the original B-17*A* to the B-17*G*. Performance of the aircraft nearly doubled in the process, the B-17A having a bomb load 0f 4,880 pounds and a range of 3,101 miles, while the B-17G had a bomb load of 9,600 pounds and a range of 3,750 miles. Engine power increased from 750 hp in the B-17A to 1,200 hp in the B-17G. Gross weight and cruising ceiling also increased dramatically from 32,432 pounds and 24,620 feet in the B-17A to 65,000 pounds and 35,600 feet in the B-17G. These improvements over 8 years (The B-17G was introduced in 1943) indicate Boeing's growing capability to develop aircraft performance using a basic model.

Figure 4.7
Boeing B-29A Superfortress
(Yenne, 2005)

Unlike the B-17, the B-29 had pressurized cabins for its crew and could fly higher than 30,000 feet with a range of 5,830 miles. First flown in 1942, its bomb load of 20,000 pounds was double that of the B-17 and represented a quantum leap in capability. After the war the B-29 was kept as maintained as a bomber with nuclear strike capability, while 200 were converted into aerial refueling tankers with a Boeing designed "flying boom" which is still a method used today. The B-29 design was subsequently evolved into the B-

50 *Super* Superfortress bomber (which kept the Boeing designation of Model 345), of which 370 were built with a larger vertical fin and engines some thirty percent more powerful than those on the B-29.

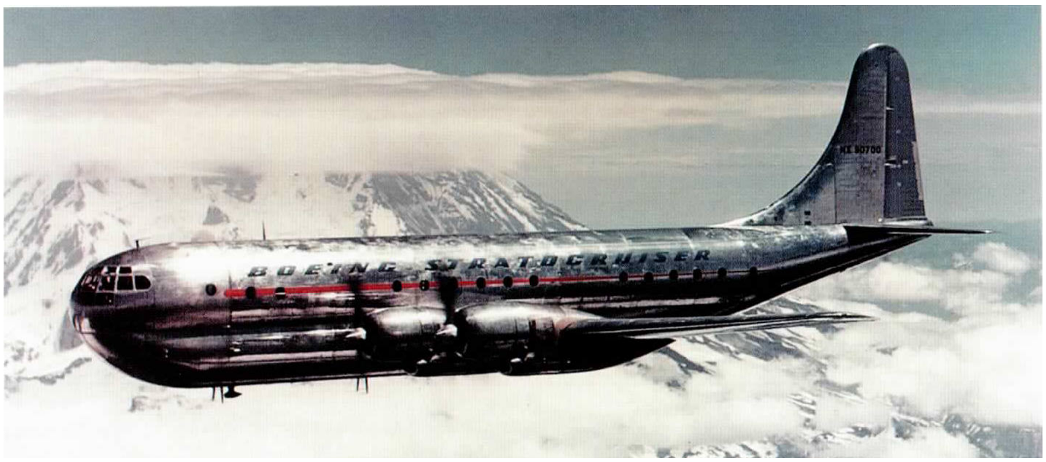


Figure 4.8

Boeing Model 377 Stratocruiser

(Yenne, 2005)

Passing the end of the war Boeing developed Model 367 KC-97 Stratofreighter military transport and Model 377 Stratocruiser commercial airliner. What was unique was that these aircraft used the Model 345 (B-50) wings and engines. The two airframes were similar excepting features for their different uses.

A distinctive design feature was the double bubble pressurized fuselage cross-section to provision for passenger in the upper deck, and a cargo hold below. This configuration has since been used on most Boeing commercial jet airplanes to date. The Model 377 was Boeing's last piston-engine airliner and production ended in 1950. As a result of the

Korean War, KC-97s were still ordered from 1951-1953 and these were a combination of military tankers and transports with later models able to do both (Yenne, 2005).

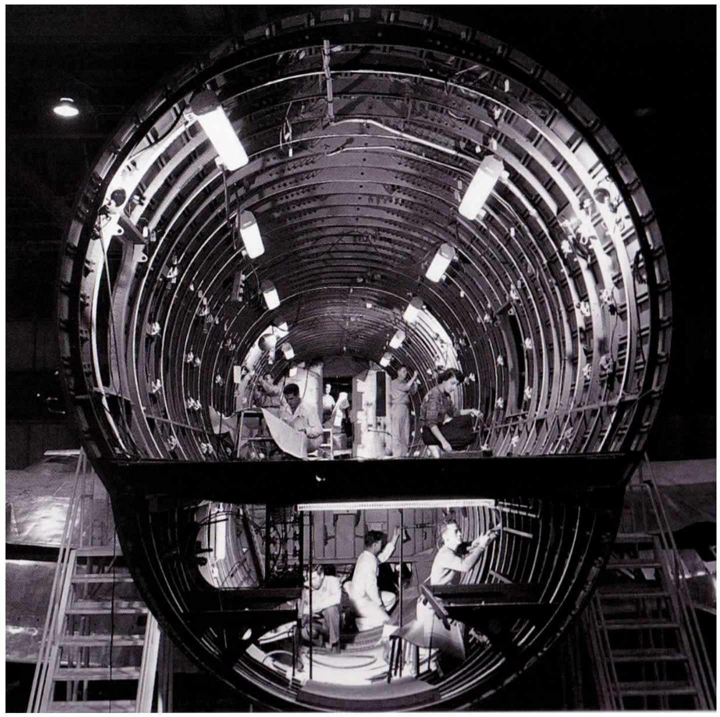


Figure 4.9
Boeing Model 367/377 Double-Bubble Fuselage Cross-Section
(Yenne, 2005)

Boeing's entry to the jet era came with the Model 450 or B-47 Stratojet bomber. The B-47 featured six jet engines and a swept wing using ideas taken from the World War II German Messerschmitt ME262 fighter bomber, to increase speed capability (von Karman & Edson, 1967). The first flight was on 17 December 1947 and orders from the US Air Force increased dramatically due to the onset of the Korean War. The last B-47 was delivered in 1957 with over 2,000 examples built (Yenne, 2005).

Figure 4.10
Boeing B-47 Stratojet
(Yenne, 2005)

In 1952, Boeing flew yet another swept wing bomber, the B-52 or Model 462, powered by eight jet engines. Like the B-29 and the B-17 before, the B-52's capabilities eclipsed the B-47 with the latest versions having a range of 10,000 miles compared to the B-47's 4,000 miles. The last was delivered in 1963 with the model like the B-17, enjoying design improvements from the B52*A* to the B52*H*.

Importantly with the B-47 and B-52, Boeing learnt how to design swept wings with engines mounted under the wings which provided for a very complex combination of structures, aerodynamics, and aero-elastic dynamics. These would provide the foundations of future commercial jet aircraft designs that essentially used this configuration in twin (B737, B757, B767, B777, B787) and four engine aircraft (B707, B747).

Figure 4.11
Boeing B-52 Stratofortress
(Yenne, 2005)

From 1952 onwards until present day, Boeing' main commercial jet developments would focus on the Model 700 series jet airplanes (model 500 and 600 series model numbers hade been reserved for non-aircraft projects such as missiles). The prelude to these aircraft was the "Dash Eighty", prototype to the B707. To maintain secrecy, Boeing chose to name the jet airplane project as a derivative of the propeller driven Model 367 (KC-97) as Model 367-*80*.

Figure 4.12
Boeing Model 367-80 “Dash Eighty”
(Yenne, 2005)

The Dash Eighty first flew in 1954 and was a jet powered pressurized airplane with four engines mounted under swept wings, with a cargo bay under the main deck. As a jet it could go twice as fast as previous propeller driven transports and became essentially the “dominant design” configuration of current jet airplanes (Yenne, 2005).

Boeing later merged with other aircraft companies, notably McDonnell Douglas, manufacturer of the DC and MD series jet aircraft none of which are in production today. As of writing the Boeing commercial jet transports currently, and still in production are the B737, B767, B747, B777, and B787. Boeing is also the manufacturer of helicopters, missiles, rockets, and other space and military equipment.

4.2. The Arrival of Airbus

Airbus was officially started in 1967 when the British, French, and German (West) governments signed a government memorandum to work together to meet a 200-250 seat airplane for the requirements of Air France, Lufthansa, and BEA (British European Airways). Importantly it was formed with the intent to learn from the lessons of Concorde, the world's first supersonic jetliner, which was a technological success but a commercial failure. Two key failures were the unwillingness to build aircraft with customer needs in mind, and the lack of a product family from which cost reductions could be gained by product commonality.

These points were a significant change in strategy from past efforts of European aircraft development efforts which had largely been driven by nationalistic aspirations rather than commercial. Britain left the cooperation in 1969 while Spain joined in 1971. Hawker Siddeley as a British company however stayed on as a prime contractor to develop and build the wings (Aris, 2002; McGuire, 1997; Kemp, 2006).

Because of the governments' involvement, Airbus would also enjoy a partnership whereby it could concentrate on making a commercial product but with the financial and political support of the governments. While Airbus as an entity marketed and performed the final assembly of the aircraft, the member companies would focus on designing and building major sub-components (McGuire, 1997).

Figure 4.13

Airbus A300 First Flight

(Laming and Hewson, 2000)

Led by technical director Roger Béteille, the first Airbus design was the A300, a 270-320 seat twin jet engine airliner that first flew in 1972. The A300 had subsequent variants such as the short range A300B2 and the medium range A300-B4. In later years Lufthansa and Swissair wanted a somewhat smaller aircraft. The result was the A310 which had a shorter but similar fuselage and new wings and tail. What was significantly new with the A310 which first flew in 1982, was a two-man crew cockpit that did away with the need for a Flight Engineer by using automation in the cockpit with ten cathode ray screens marking the beginning of a digital cockpit (Laming and Hewson, 2000).

This technology was re-applied back to the A300 in the A300-600 variant which had more capacity than the A300. With the A310's shorter fuselage tail, the A300-600 could accommodate 15 more passengers without increasing the overall length of the fuselage (Aris, 2002).

Figure 4.14

Airbus A300-600R

(Laming and Hewson, 2000)

Figure 4.15

Airbus A310

(Laming and Hewson, 2000)

Between the end of the Second World War and 1978, the CAB (Civil Aeronautics Board) in the USA controlled which airline would be allowed to operate which route and importantly even the price of tickets. With fixed prices, the main marketing power that could be employed by the airlines were new types of aircraft, especially jet-engined ones that were seen as glamorous by customers who were typically wealthy to pay the high ticket prices at the time. The CAB controlled ticket prices also encouraged the development of longer range aircraft as the prices were higher with range.

In 1978 however the CAB was abolished and airlines were free to compete on ticket prices. However this meant that long range routes became expensive to operate and the impetus was to develop hub-and-spoke type operations to improve network connections and efficiency rather than point to point routes. Hence the demand for smaller aircraft expanded with the need to service a greater proportion of regional type routes to feed and distribute the hubs (McGuire, 1997).

This factor assisted in the motivation for Airbus's next project, the A320. Following various European studies on a 130-170 seat jet airliner, a Memorandum of Understanding was signed between Airbus participants but this time including British Aerospace, MBB, and VFW-Fokker. This aircraft would be a replacement for older designs in service such as the BAC 1-11, Trident, Caravelle, and be a direct competitor to the Boeing B737 and Douglas DC-9. While these were European designs, some of the design requirements came from Delta, a US airline, who was looking for a 150-seat airliner with half the fuel burn of a Boeing B727.

Figure 4.16
Airbus A320 Cockpit
(Laming and Hewson, 2000)

The narrow body single aisle A320 first flew in 1987 and inherited much of the two man cockpit automation heritage from the A310 with the addition of FBW (fly-by-wire) technology that replaced the pilots control wheels with joysticks. FBW offered the Airbus engineers the ability to program flight handling abilities transparent to the pilot including low speed and high speed stall protection. A side benefit was that later Airbus models with similar cockpits could be programmed to feel the same to the pilots, simplifying training. The advanced wing design owed its origins to the British BAC 3-11 project that never materialized.

Figure 4.17
Airbus A319, A320, A321
(Laming and Hewson, 2000)

From the A320, Airbus further expanded the family into the larger A321 (first flight (1993), smaller A319 (first flight 1995), and even smaller A318 (first flight 2002) (Laming and Hewson, 2000). These models together with Airbus's later wide body developments, the A330, A340, and A380 (the world's largest commercial jetliner), are still in production today. All share similar cockpit and FBW technology.

4.3. *Prelude to the Boeing 737*

The Boeing B737 was developed by Boeing in the early 1960s as the smallest stable mate to the already existing long range 4-engine Boeing B707 and medium range 3-engine Boeing B727 (B707 and B727 respectively).

It was an era when commercial jet aircraft were being introduced and slowly replacing propeller driven aircraft starting with the British built De Havilland Comet in 1952 and then the American built Boeing B707 in 1958. Oddly at this time the introduction of jet aircraft started with larger passenger capacity long range models which then permeated to smaller models as the prospect of quantity replacements for propeller driven aircraft was greater at the lower end.

Figure 4.18

Boeing 707

(Yenne, 2005)

The B707 itself was a derivative of the Dash 80 prototype first flown in 1954 and developed by Boeing with the prospects of not just civilian passenger jetliners but also that for military tankers to refuel long range bomber missions. Jet bombers such as the B-47 were already in operation but the only suitable tankers at the time were propeller driven aircraft such as the KC-97 where the slower cruise speeds did not match during refueling operations.

Boeing eventually developed both the civilian B707 and the military cargo carrying C-135 Stratolifter and refueling tanker KC-135 Stratotanker series with a similar platform of cockpit, wings and engines. The main difference in the airframe was in the fuselage where the B707 had a wider upper fuselage to seat 6 passengers abreast in Economy class.

Figure 4.19

KC-135E Stratotanker (refueling F-18 fighter jets)

(Yenne 2005)

Figure 4.20
KC-135R Stratotanker re-engined with CFM56 engines
(Yenne 2005)

Boeing eventually developed shorter smaller capacity (B707-120) and longer range (B707-320) versions of the B707 using the same basic platform, as well as various military variants of both the C-135/KC-135 and B707 itself. Many of these military variants are still in service today, many of which have been updated with modern avionics and re-engined with the more fuel efficient CFM56 engine (see Figure 4.21).

While the B707 was designed to fly transcontinental and transatlantic, the B727 was designed for shorter range routes to connect intercontinental cities. The B727 had a unique configuration of three Pratt & Whitney JT8D turbofan engines positioned in the rear with a high “T”-Tail. However it had the same cockpit and fuselage cross-sections as the B707 affording savings in design and production costs.

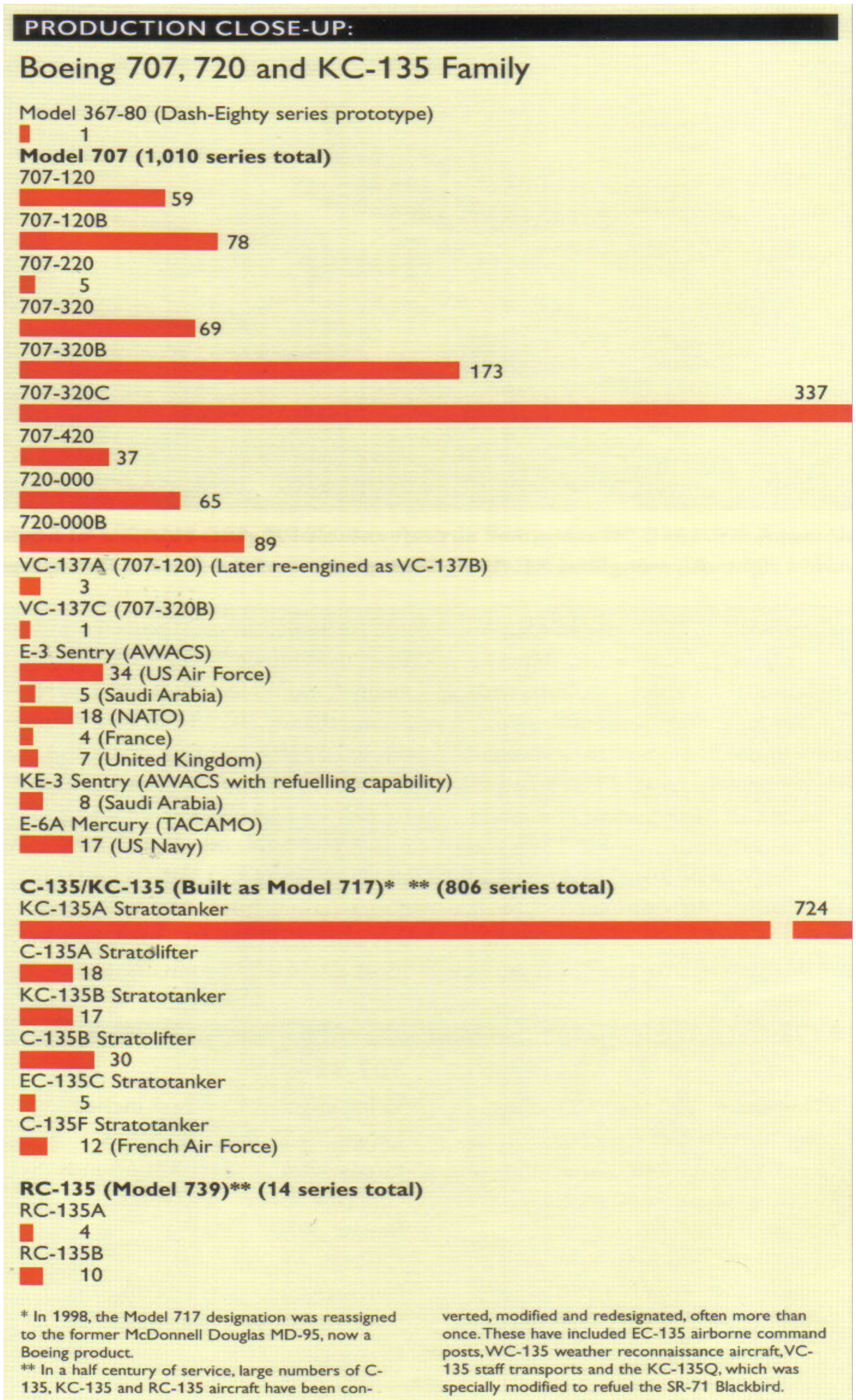


Figure 4.21

Derivatives and variants of the B707/C135/KC135

(Yenne, 2005)

The B727 first flew in 1963 but it had design enhancements that included short field (runway length) capability using new leading edge slats and triple slotted trailing edge flaps. This enabled it to operate from smaller cities that tended to have shorter runways and increased its marketability.

In line with increasing market reach for the operator, it also incorporated built-in airstairs and an Auxiliary Power Unit or APU (Sharpe & Shaw, 2001). The airstairs allowed it to operate into remote airfields where conventional stairs or air bridges might not be available The APU, in essence a small jet engine with a generator and air compressor, allowed it to provide it’s own power to start its engines and provide electrical power and air conditioning independent of any ground support equipment.

Figure 4.22
Boeing 727-200
(Yenne, 2005)

In 1965 Boeing made two major announcements, that it was developing a convertible freighter version 727-100C, as well as a longer fuselage version, the 727-200 that could carry as many as 189 passengers in Economy Class. The 727-100C also later featured a 727-100QC or "Quick Change" version that allowed the interior to be quickly converted between cargo and passenger configuration using pallet mounted seats and galleys. This provided the capability of operators to increase aircraft utilization by for example using the aircraft in passenger mode in the daytime, and cargo mode in the night time when passengers preferred less to travel.

As with the B707, many design iterations followed, but the above features are important to mention as it will be noted that many of these design features would also be implemented on the B737, increasing its marketing potential.

While the B727 helped to service routes that were too small for the larger B707, it was itself too large for many short to medium range routes that were still serviced by propeller driven aircraft.

4.4. Boeing 737 First Generation (B737-100, -200)

Hence Boeing launched the smaller B737 in 1965 amazingly in two versions for two orders that received simultaneous certification in 1967, and were delivered and entered service in the same year 1968. The B737-100 for Lufthansa with 96 seats 6-abreast in Economy Class, and the B737-200 for United Airlines with 124 seats 6-abreast in

Economy Class. The B737-200 was 76 inches longer than the B737-100 through the use of fuselage plugs but was in all other dimensions identical (737 Airplane Characteristics for Airport Planning D6-58325-6, Boeing 2005).

One attractive point of the B737 for Lufthansa was that not only was it able to replace propeller driven Convair 440 Metropolitans, Vickers Viscounts, and Lockheed Super Constellations and go with an all-jet fleet throughout its network, the other jet aircraft already in Lufthansa's fleet were B707s, B720s, and B727s. Hence it enjoyed the benefits of a high degree of commonality and familiarity with the new "family" of Boeing jets.

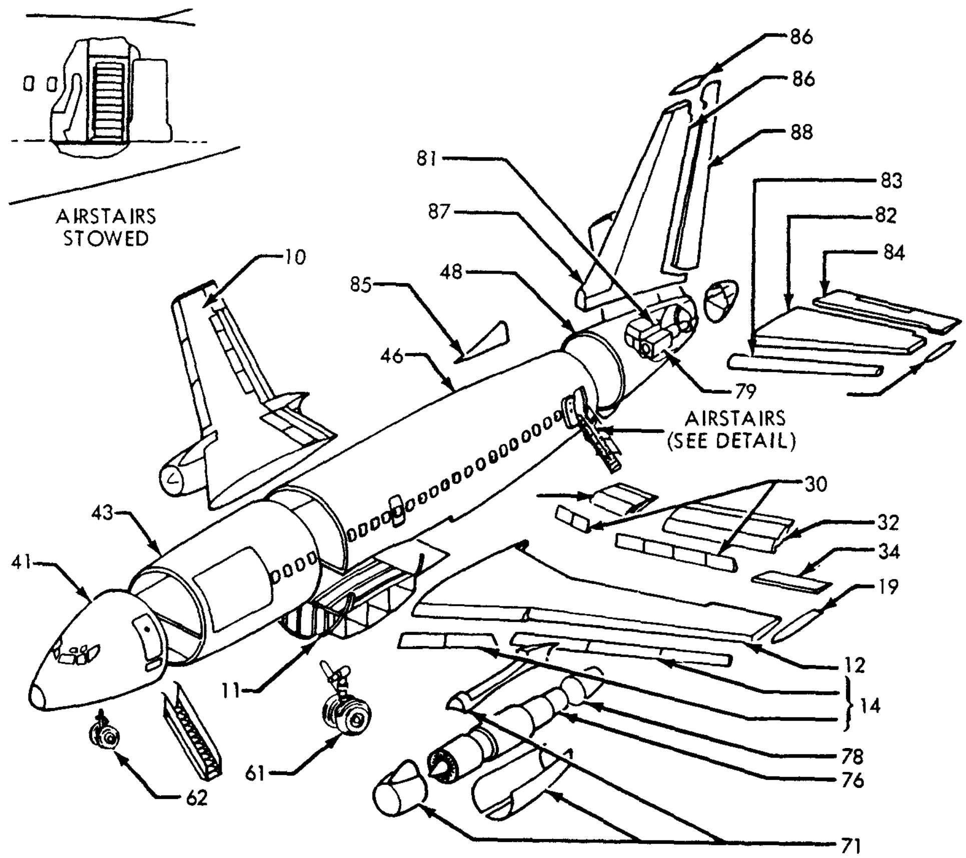
The Boeing 737 had sixty percent commonality in design with the B727 including adaptation of the hydraulically-powered ailerons, elevator and rudder, leading edge slats and Krueger flaps. Even the B707's dual electric motor-driven variable incidence tailplane trim system with a manual backup was adapted (Hill, 2002). Tires for example between the B707 and B737 were interchangeable leading to a reduction in spare parts inventory. Similarly the engine type was the same between B727 and B737.

Meantime other manufacturers' jet aircraft in that smaller size class had been introduced such as the Douglas DC-9, British Aircraft Corporation BAC 1-11, and Sud Aviation Caravelle. These 3 aircraft types had similar features such as twin rear-mounted engines, a high "T"-tail (except the Caravelle), and 5-abreast Economy Class passenger seating. The B737 was different in that it featured 6-abreast Economy Class seating and engines mounted under the wings with a conventional tailplane positioned at the rear of the fuselage.

The 6-abreast seating was result of Boeing's Vice President Jack Steiner insisting that the B737 use the same upper fuselage as earlier jets in the Boeing family to improve marketing and ease of manufacture (Yenne, 2005). While this incurred higher aerodynamic drag and a slight speed cruising penalty compared to it's 5-abreast competitors, it afforded better economics, commonality with the B707 and B727, and was a better configuration for future stretches of the fuselage in later models.

The commonality benefits were not limited to the airframe. Seats and galleys were also interchangeable between B727 and B737, easing maintenance and inventory requirements for the operator and making the aircraft attractive to existing B727 operators (Sharpe & Shaw, 2001).

Using the wider fuselage however meant a relatively shorter and wider fuselage and had the engines been mounted at the rear as with the other competitors, then the engine intakes would have been too close to the wing with potentially disturbed airflow. Mounting the engines under and forward of the wings using conventional pylons like on the B707 was not as easy as the first B737-100 had a much shorter fuselage and the engines would have blocked access for boarding stairs to the front passenger door (Later models did not have this problem as the fuselages were longer).



10. WING
11. WING STUB
12. WING, OUTBOARD
14. SLATS AND FLAPS, L.E.
19. WING TIP
30. SPOILERS
31. FLAP, INBOARD
32. FLAP, OUTBOARD
34. AILERON
35. FLAP, CENTER
40. BODY
41. SECTION
43. SECTION
46. SECTION
48. SECTION
60. LANDING GEAR

61. MAIN GEAR
62. NOSE GEAR
70. POWER PLANT
71. COWLING ENGINE
78. THRUST REVERSER, TAIL PIPE
79. AUXILIARY POWER UNIT
80. EMPENNAGE
81. STABILIZER CENTER SECTION
82. STABILIZER
83. STABILIZER L.E.
84. STABILIZER ELEVATOR
85. DORSAL FIN
86. FIN
86. FIN TIP
87. FIN L.E.
88. RUDDER

Figure 4.23

Model 737-100/200/C/QC Sectional Breakdown

(Boeing Commercial Airplane Company, 1982)

Using pylons would also mean taller landing gear and a subsequent requirement for ladders by maintenance people. Even the cargo hold was considered important to be at standing height level so that airline employees could throw in last minute luggage. So the design iterated to a location directly under the wing, but where the turbine area would be behind the rear spar to meet certification requirements that the wing area used for fuel tanks not be exposed in the event of a turbine explosive type failure (Sutter and Spenser, 2006). Mounting the engines below the wings also permitted an easier center of gravity control especially when longer derivatives and variants were developed compared to its rear-mounted engined and relatively longer 5-abreast fuselage competitors.

As with the B727, the B737 also featured an APU and internal airstairs option, though not of the same design as the B727's ventral airstairs. The airstairs option was available on front and/or rear doors. These airstair units were also removable to save weight should the operator operate where conventional airstairs or air bridges were readily available. Both features again increased the attractiveness of the aircraft for operations into remote airfields where support equipment might not be available. Significantly the B737 also incorporated high lift devices on its wing such as Krueger flaps and triple slotted flaps, to provide high lift & low drag configurations for take-off and high lift & high drag configurations for landing, for operations into short runways. Spoilers that could quickly destroy lift and increase braking also assisted in the operations into short runways. Other aircraft types also incorporated similar features but not to the same degree and sophistication that the Boeing aircraft had, giving the B737 an operating as well as marketing advantage for its class.

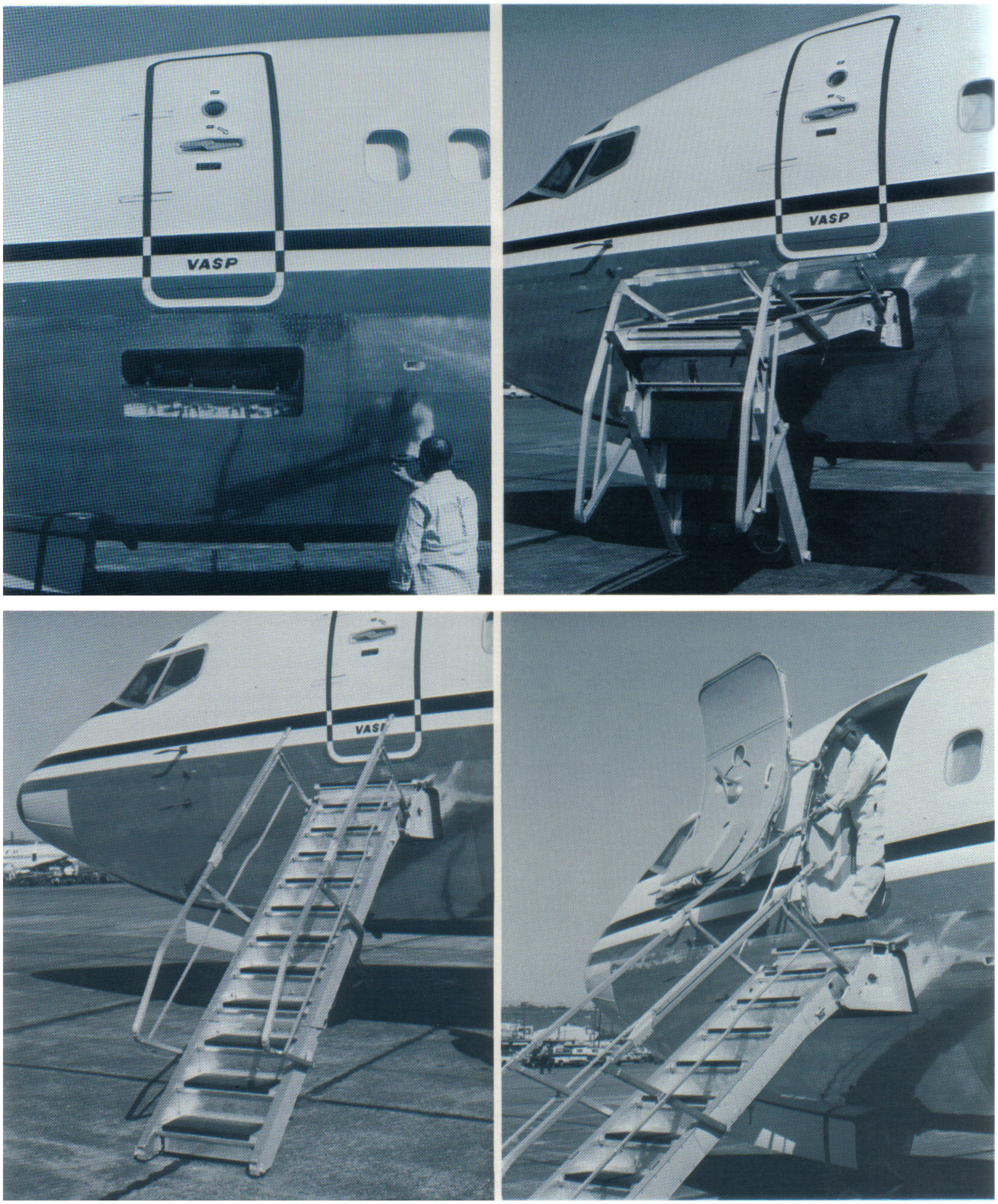


Figure 4.24

B737 Forward Airstairs

(Boeing Commercial Airplane Company, 1984)

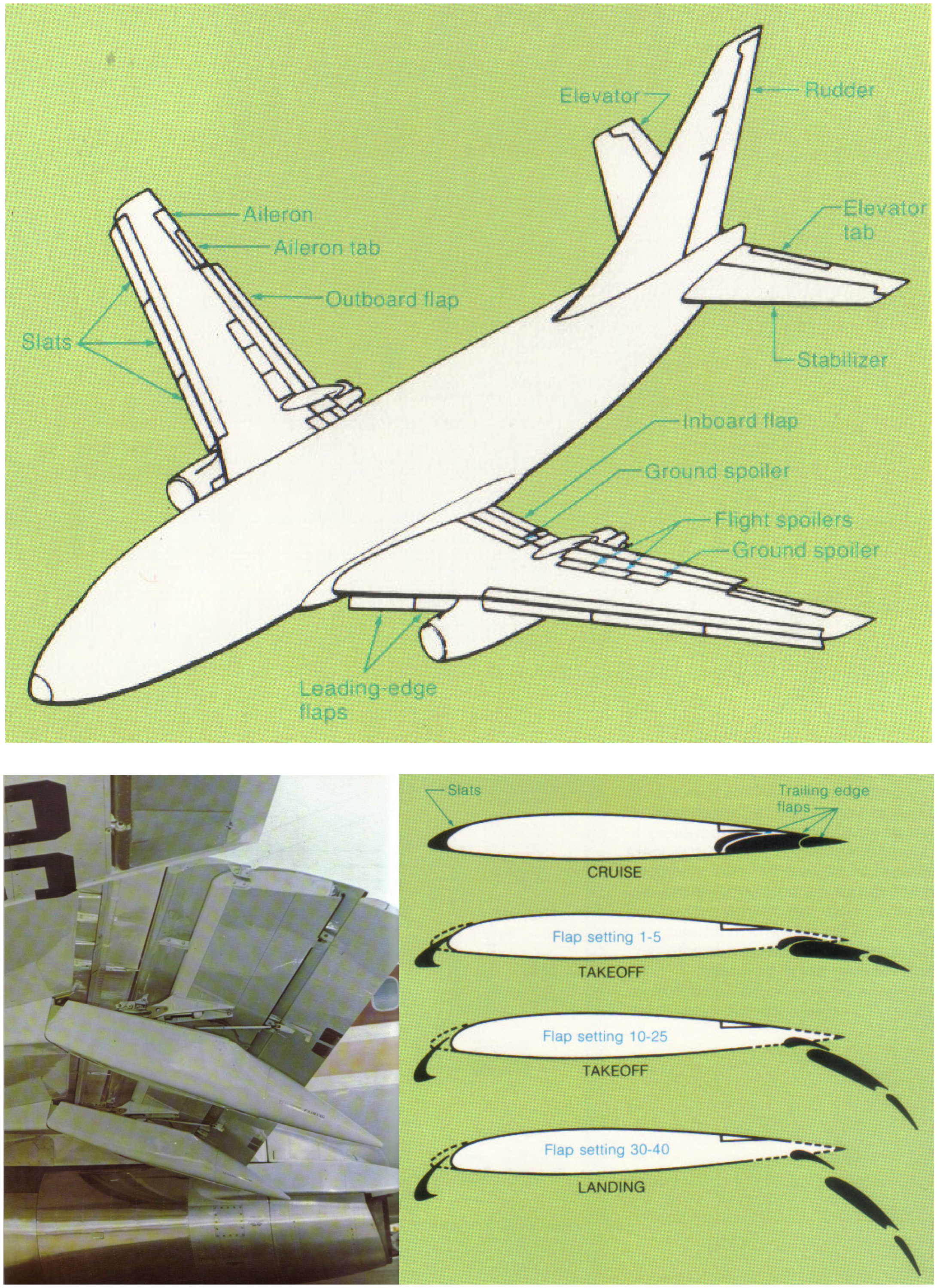


Figure 4.25

B737-200 Flight Controls (Above), Triple Slotted Flaps & Configurations (Below)

(Boeing Commercial Airplane Company, 1984)

Figure 4.26

B737-200 Spoilers Deployed

(Boeing Commercial Airplane Company, 1984)

In the "737 Airplane Characteristics for Airport Planning" D6-58325-6 document published by Boeing, they advertise this fact along with the other features:

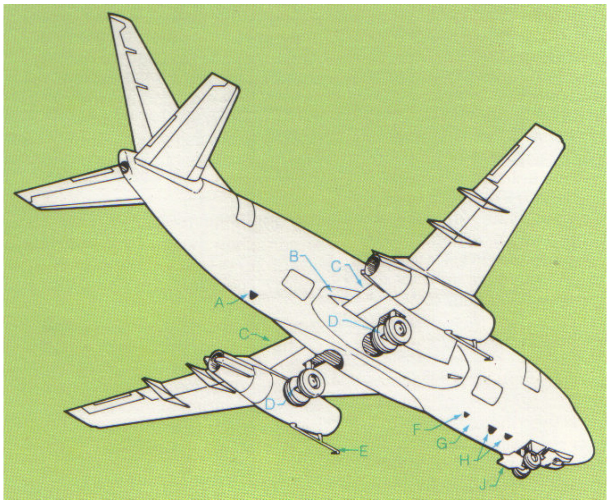
> *"The 737 is a twin-engine airplane designed to operate over short to medium ranges from sea level runways of less than 6,000 ft (1,830 m) in length.*
>
> *Significant features of interest to airport planners are described below:*
>
> - *Underwing-mounted engines provide eye-level accessability. Nearly all system maintenance may be performed at eye level.*
> - *Optional airstairs allow operation at airports where no passengers loading bridges or stairs are available.*
> - *Auxiliary power unit can supply energy for engine starting, air conditioning, and electrical power while the airplane is on the ground or in flight."*

Boeing did not stop there. In order to attract operators seeking to provide service in remote Alaskan and northern Canada communities, Boeing decided to certify the aircraft for rough or unpaved runways. This involved modifying the aircraft landing gear to add gravel deflectors on the landing gear and vortex dissipators to protect the engine intakes.

These modifications made their way onto Indonesian Air Force B737s that were used as transports but were also modified with side looking surveillance radar fitted in two pods at the rear of the fuselage. This was just one of many military derivatives of the B737 platform. The United States Air Force bought 19 of the aircraft with the designation T-43A and used them as advanced navigation trainers. The wider cabin helped to beat the DC-9 competitor to fit multiple student and instructor stations (Nicholls, 2003).

It should be noted that through the 1970s Boeing continually improved the aircraft’s take-off and landing performance including later certifying the different degrees of flap vastly improving short field performance. It further redesigned the leading edge flaps and slats, improved braking and anti-skid systems and added the more powerful Pratt & Whitney JT8D-15 engines.

Incorporating as well new use of graphite composite material to reduce weight, this package from 1972 resulted in the Advanced 737-200 which was to become the standard production model (Nicholls, 2003; Shaw, 1999).



A VHF Comm

B Metal edge band on elephant ear fairing

C Inboard flap protection, right and left

D Main gear deflector

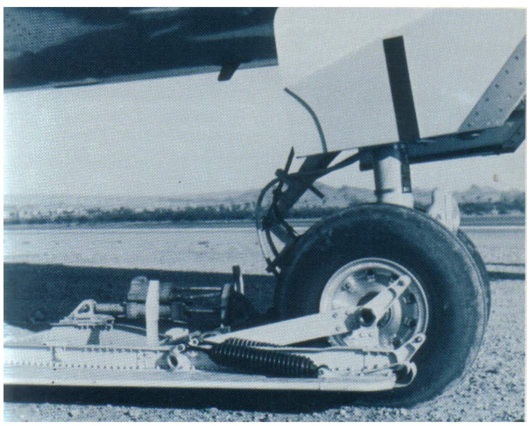
E Vortex dissipator

F DME

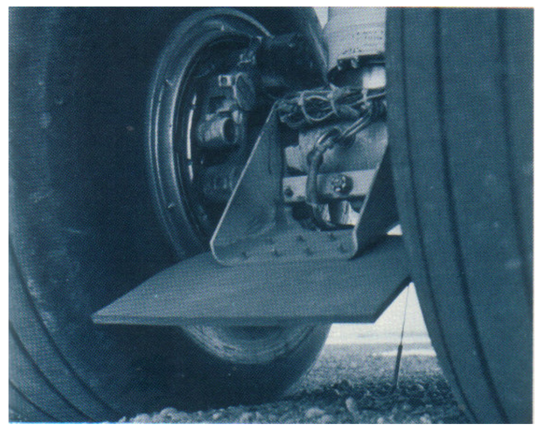
G Abrasion resistant finish

H ATC

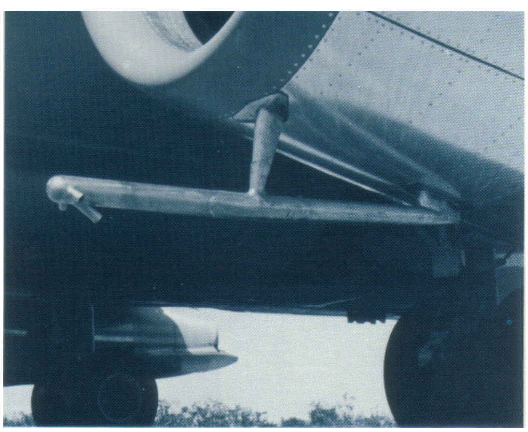
J Nose gear deflector



Nose Gear Gravel Deflector



Main Gear Gravel Deflector



Vortex Dissipator

Figure 4.27

B737 Gravel Runway Equipment

(Boeing Commercial Airplane Company, 1984)

Figure 4.28
Indonesian Air force 737MP Surveiller
(Note the vortex dissipators mounted below the engine inlets)
(Nicholls, 2003)

Eventually, emulating the B727 again, Boeing offered a B737-200C convertible passenger/cargo version that came with a main deck cargo door. Quick Change (QC) models were offered similar to the B727 where passenger seats and galleys were fitted to cargo pallets. Interestingly unlike its competitors who had smaller cross-section cabins, the B737-200C could utilize standard cargo containers that were used on larger B707 or Douglas DC-8 aircraft allowing easy inter-lining of the cargo (Nicholls, 2003).

The B727 cargo door design eventually made its way to all generations of the B737, particularly military applications, and even to the larger Boeing 757PF (Package Freighter) for UPS (United Parcel Service), certainly demonstrating the advantage of a common main upper fuselage configuration.

Figure 4.29

B737 Main Deck Cargo Door & Cargo Loading

(Boeing Commercial Airplane Company, 1984; Nicholls, 2003)

4.5. Boeing 737 Classic Generation (B737-300, -400, -500)

Deregulation of the United States airline industry in 1978 and rising fuel costs were the impetus for a re-design of the B737. Unlike the B727 which was replaced by a new design the Boeing 757 or B757, Boeing sought to update the existing B737-200 design.

There were several possible factors in this decision but probably the most significant was the engine selection. Probably by default having a limited choice of engines at the time of its design, the B727 had three engines, one less than the B707 to scale its size down. Its replacement, the B757, had two engines (Rolls Royce RB211-535 or Pratt & Whitney PW2000) with much improved fuel economy but with much higher thrust capability.

To fit those two new engines to the B727 would have involved a major re-design of the aircraft not to mention severe weight and balance (center of gravity) issues were the engines to be mounted at the rear as the existing B727 engine locations. The B727 has a center engine with an S-duct air inlet that is integrated into the rear fuselage.

The B737 had fewer issues to fit a new engine but to meet new fuel and noise requirements, a high bypass turbofan engine was required. In a turbojet engine, air is compressed to improve combustive efficiency when mixed with fuel. However typically 80% of the compressed air is used for cooling rather than combustion due to the low heat tolerance of the combustor material and this represents a loss of energy.

By adding a fan in the front of the engine driven by the core turbine, a larger proportion of energy is used for propulsion and allows engine designers to improve overall fuel burn efficiency relative to thrust. With the fan, only a small portion of the air goes into the compressor and a large portion bypasses the core, hence the term "bypass". The larger the proportion of bypass air, the higher the overall propulsive efficiency. The existing JT8D engine was a turbofan but had a low bypass ratio.

High bypass turbofan engines have higher fuel burn efficiency and were just being introduced at the time. However this meant a bigger fan which meant clearance problems between the wing and the ground. Extending the landing gear of the B737 would have been one solution but would mean a heavier gear as well as higher to reach access for all the aircraft's maintenance points, which was a marketing advantage of the B737. A longer gear would also mean a major re-design of the wing mounting and wing structure itself.

The engine chosen for the re-engine was the CFM56-3, jointly developed by SNECMA of France and GE (General Electric) of the United States. The core of the engine was derived from the GE F101 engine used to power the B-1 bomber. Earlier versions of the CFM56 were used to re-engine Douglas DC-8s (CFM56-1), military KC-135/B707s (CFM56-2). While bidding with a new smaller fanned version for a new 150/160 seat jet airplane proposed by Dutch manufacturer Fokker (which never materialized), CFM sent the same design to Boeing unsolicited.

Surprisingly Boeing took the design and matched it to its studies for a new B737, which eventually became the B737-300. The resulting CFM56-3 fan used scaled down versions of the recently developed GE CF6-80A fan rather than clipped CFM56-2 fan blades and hence incorporated the latest technology (Flight International, 1999).

To fit this larger fan under the wing, Boeing and CFM first relocated the engine accessory drive gearbox and transfer gearbox from the bottom to the side of the engine. The inlet was also flattened at the bottom to improve ground clearance. And finally the engine was hung from a pylon so that it was positioned forward of the wing rather than under it (Flight International, 1999; Shaw 1999).

This was really a masterpiece of engineering that enabled the existing wing and landing gear configuration to stay the same as the B737-100/-200, hence preserving the "platform" and all the corresponding benefits of maintaining the original design, such as easy maintenance access and a relatively short and lightweight landing gear.

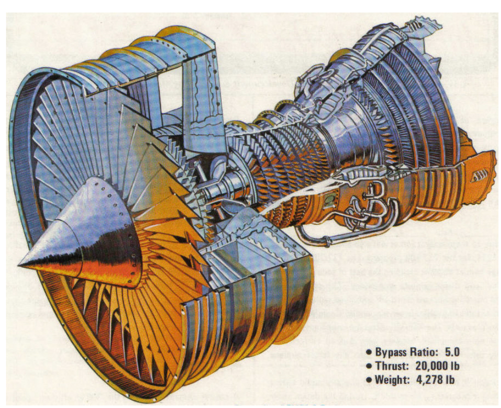


Figure 4.30

CFM56 Engine

(Taylor, 1983)

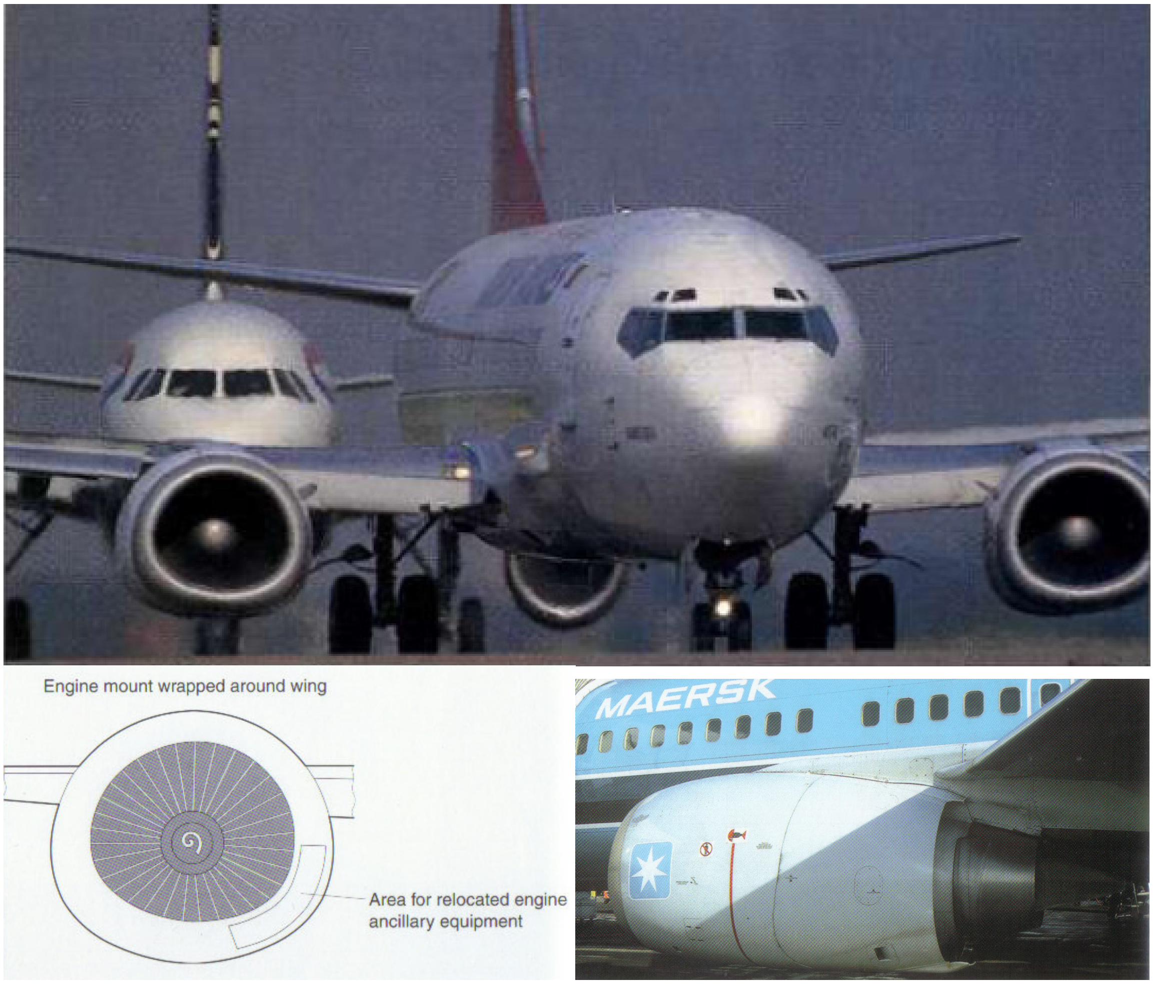


Figure 4.31

CFM56 Engine mounted on B737-300

(Flight International, 1999; Shaw, 1999)

The CFM56-3 offered up to 22-23,000 lb of thrust compared to the 15,000 lb of the JT8D-15 of the 737-200 Advanced. With this increased thrust, Boeing could increase the size of the aircraft for increased payload (passengers and/or cargo). The wingspan was increased by 1ft 9 in while the fuselage was lengthened by 9 ft 5 in to seat an increase of about 20 passengers.

In developing the B737-300, Boeing was careful to improve only what was necessary and keep as much commonality as possible with the B737-200. The figure below gives an example of how Boeing preserved much of the original wing design configuration but managed to get increased lift to manage increased operating weights by increasing the wing area through a chord design extension but only of the leading edge (Taylor 1983).

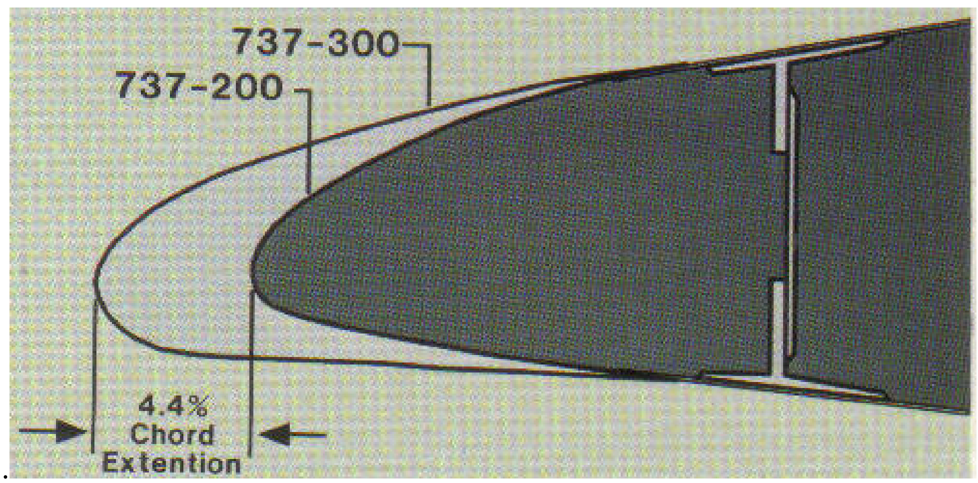


Figure 4.32
B737-300 Leading Edge Slat Revision
(Taylor, 1983)

Other improvements are shown below (See Appendix E for complete summary).

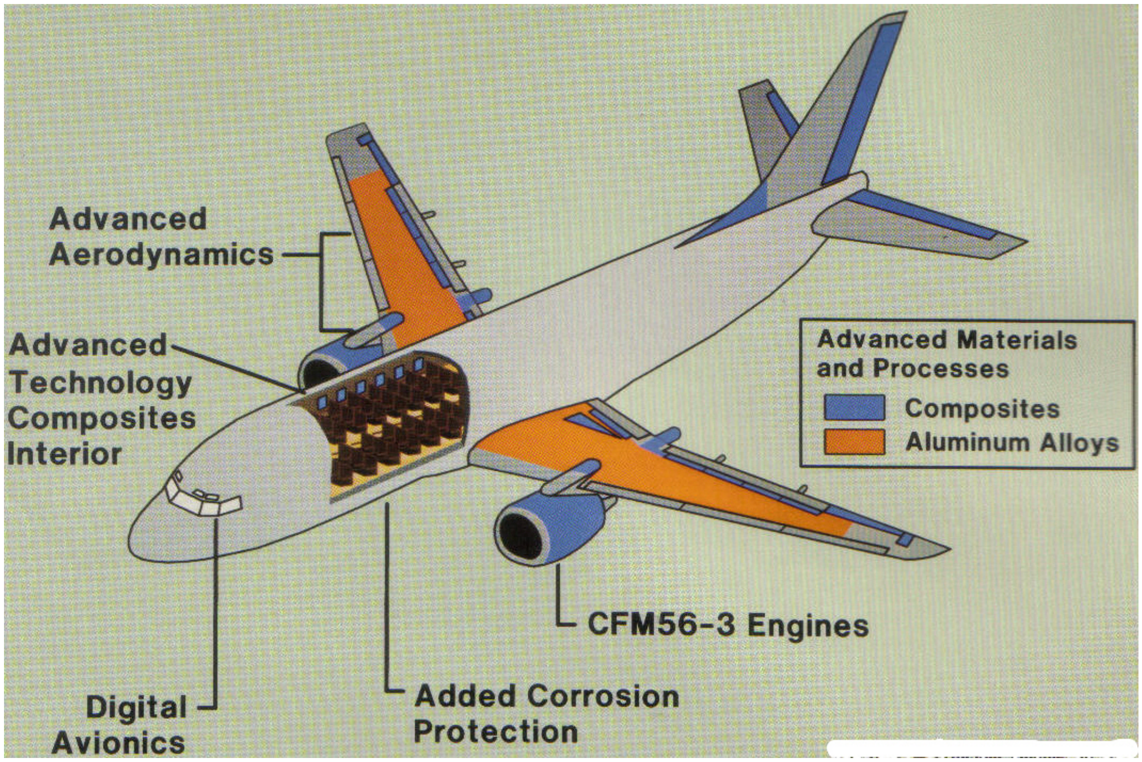


Figure 4.33

B737-300 Improvements

(Taylor, 1983)

Some of these improvements were borrowed from the B757 development program. One was the interior which featured large overhead bins, recessed lighting, and passenger emergency chemical oxygen generators (which reduced maintenance considerably compared to old tube and bottle systems). The other was the Flight Management System or FMS and the Inertial Reference System or IRS, both of which were identical to the B757 and B767 aircraft systems.

Figure 4.34
B737-300 Interior
(Taylor, 1983)

Advanced composite materials which were making a significant introduction on the B757 and B767 aircraft were also introduced on the B737-300 to obtain weight savings.

With the fit of the B757 and B767 FMS, IRS, interiors, and composite materials, it was evident that Boeing was taking full advantage of the latest applications that could be incorporated from other product lines.

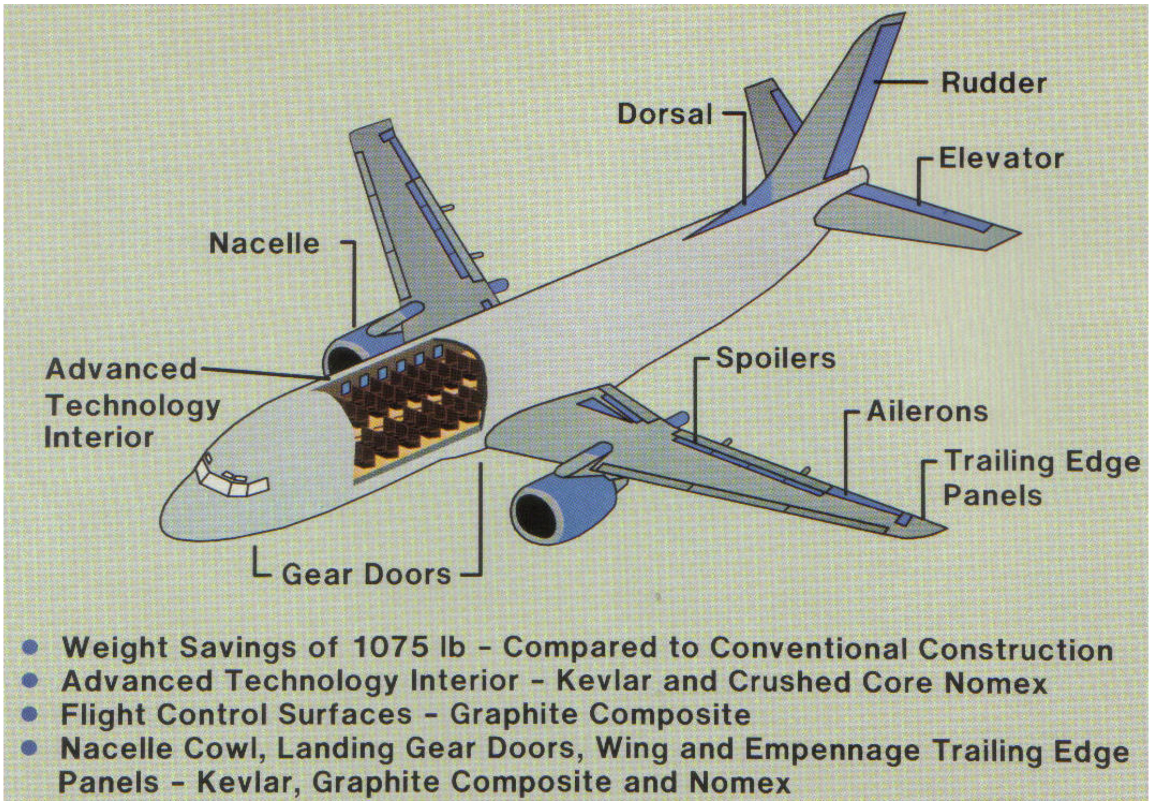


Figure 4.35

Use of Advanced Composites in the B737-300

(Taylor, 1983)

The 737-300 first flew in 1984 and the prototype was the 1,001st B737 built (Shaw, 1999). The B737-300 was a commercial success with orders received for 18 years running from 1981 up until 1999.

Notably the payload or passenger and cargo carrying capacity as well as the range of the aircraft were increasing. The B737-300 was now capable of carrying nearly 50% more passengers than the original B737-100.

Figure 4.36

Boeing 737-200 & 737-300 Advertisement

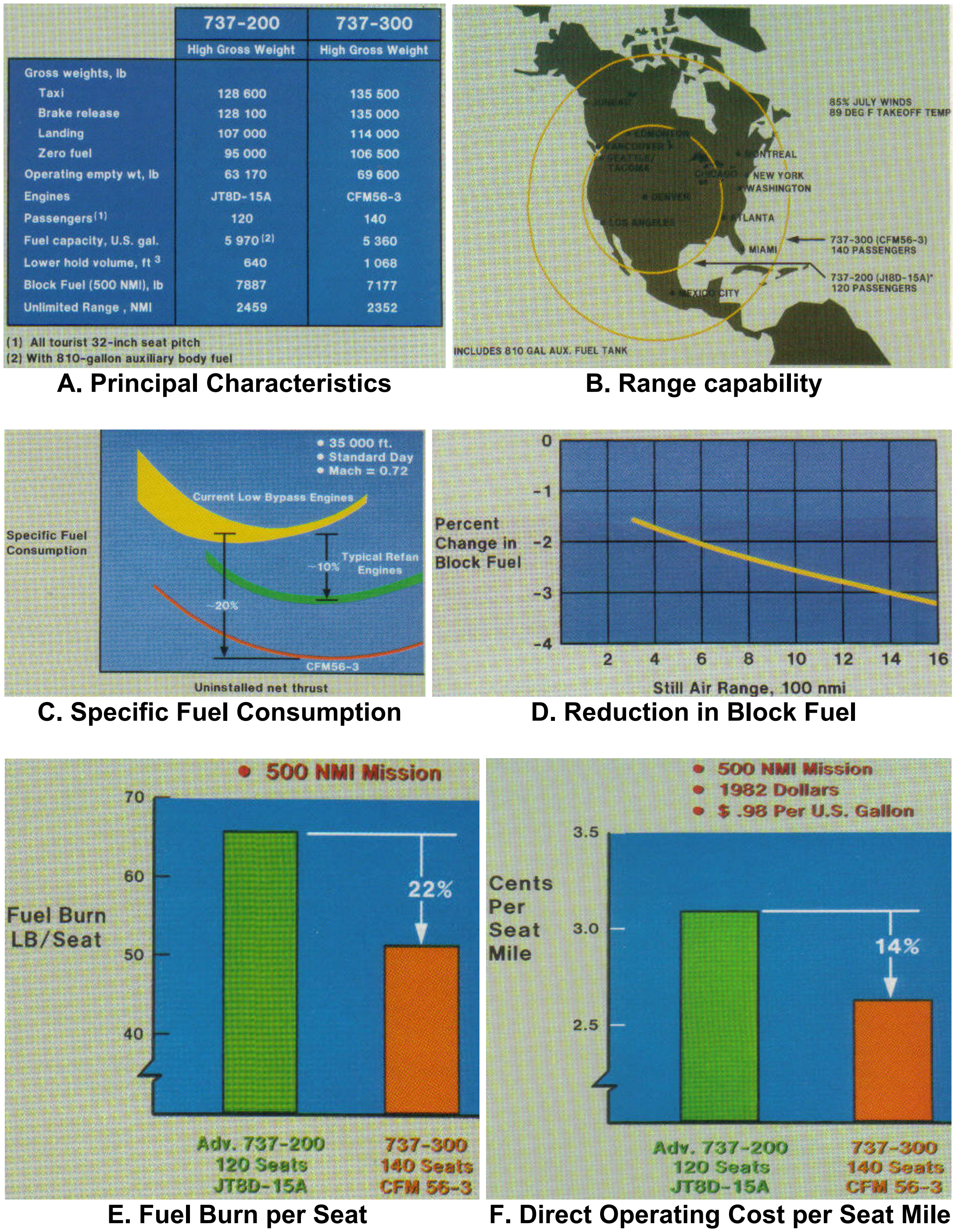
(Flight International, 24 April 1982)

Hence it was unsurprising that orders continued for the B737-200 from operators that wanted the smaller size (and presumably operating costs). Existing operators of B737-200s also preferred to keep the same model with their expansion plans. With a large degree of commonality between the two generations of aircraft, Boeing even marketed them side by side as can be seen in the advertisement below. This amazing co-existence of new and old generation orders lasted 7 years between 1981 and 1987.

A review of the performance charts (see Figure 4.37) reveals perhaps why. The B737-300 can fly further and carry more and burn about 20% less fuel per seat than the 737-200 (Chart C & E). However this assumes the need to fly further as well as carry a greater amount of passengers.

If the operator did not fill the aircraft up, the savings in fuel burn per seat would be much reduced and the increased complexity of flying a new aircraft version might not be worthwhile.

In Chart D, we see also that the big gain in block fuel (total fuel burnt from taxi out to taxi in) is greatest at long distances up to 1,600 nautical miles (2,963 kilometers). However if an operator were to fly short distances say 300 nautical miles (556 kilometers), then the B737-300 advantage over a B737-200 would be just over 1%, while paying higher airport fees for operating a heavier aircraft.



	737-200 High Gross Weight	737-300 High Gross Weight
Gross weights, lb		
Taxi	128 600	135 500
Brake release	128 100	135 000
Landing	107 000	114 000
Zero fuel	95 000	106 500
Operating empty wt, lb	63 170	69 600
Engines	JT8D-15A	CFM56-3
Passengers (1)	120	140
Fuel capacity, U.S. gal.	5 970 (2)	5 360
Lower hold volume, ft^3	640	1 068
Block Fuel (500 NMI), lb	7887	7177
Unlimited Range , NMI	2459	2352

(1) All tourist 32-inch seat pitch
(2) With 810-gallon auxiliary body fuel

Figure 4.37

B737-200 versus B737-300 Performance Comparison

(Taylor, 1983)

While the 737-300 was selling well, in 1984 Boeing observed the first orders for a new competitor across the Atlantic, the Airbus A320. Airbus was a European aircraft manufacturer's consortium made up of then British Aircraft Corporation (BAC), Hawker Siddeley, Aerospatiale, Dornier, MBB, VFW-Fokker, and Dassault-Breguet.

The A320 had some similarity to the B737-300. It was a single-aisle passenger aircraft capable of seating 6-abreast in Economy Class. It also had two wing mounted CFM56 engines, but otherwise incorporated some significant differences. The engines were CFM56-5s with better fuel burn than the CFM56-3s and had higher thrust range of 22,000-26,000 lb (Flight International, 1999).

The A320 carried more passengers, up to 180 in all Economy Class. It had a sophisticated Fly-By-Wire (FBW) technology which used computers to translate pilot joystick controls into flight control movements to control the aircraft instead of traditional mechanical cables and pulleys. FBW also allowed Airbus to program through software the cockpits of their different aircraft to feel the same to pilots in terms of handling (Lynn, 1997).

The A320 was also faster, cruising at Mach 0.78 (0.78 times the speed of sound) compared to the B737-300's cruising speed of Mach 0.74 (0.74 times the speed of sound), and had a maximum cruising altitude of 39,000 ft compared to 37,000 ft for the B737-300 (Yenne, 2005).

Ironically the A320 was built with the original intention of competing with the B727 rather than the B737 (Kemp, 2006), hence its larger size. However last orders for the B727 were taken in 1983 while first orders for the A320 were taken in 1984.

Boeing at the time was working on a new 7J7 design project which would also feature FBW technology and propfan engines. Neither technology was warmly greeted by the airlines, and eventually pressure on Boeing was instead to produce a larger capacity B737-300, the B737-400 while keeping the existing 737-300 technologies and operating practices.

The fuselage was extended by some 10ft to give an increased seating capacity of up to 170 passengers in all Economy Class or even up to 189 in a high density configuration. This put it in the capacity class of the A320 and offered a stop-gap product for those that preferred the familiarity of the B737 systems. It also filled the capacity gap between the B737-300 and the larger B757 which could only be filled with the A320 (Shaw 1999). Interestingly the increased length put it just 5in shy of the Dash 80, the prototype 707/KC-135 (Hill, 2002).

Other main differences were a tail bumper to protect the rear fuselage during take-off rotation due to the increased length, a strengthened wing spar, and a glass cockpit (using Cathode Ray Tubes instead of conventional mechanical instruments) incorporating EFIS (Electronic Flight Instrument System) displays, similar to those on the B757 and B767. The B737-400 was as popular as the B737-300 and orders ran from 1986 until 1999.

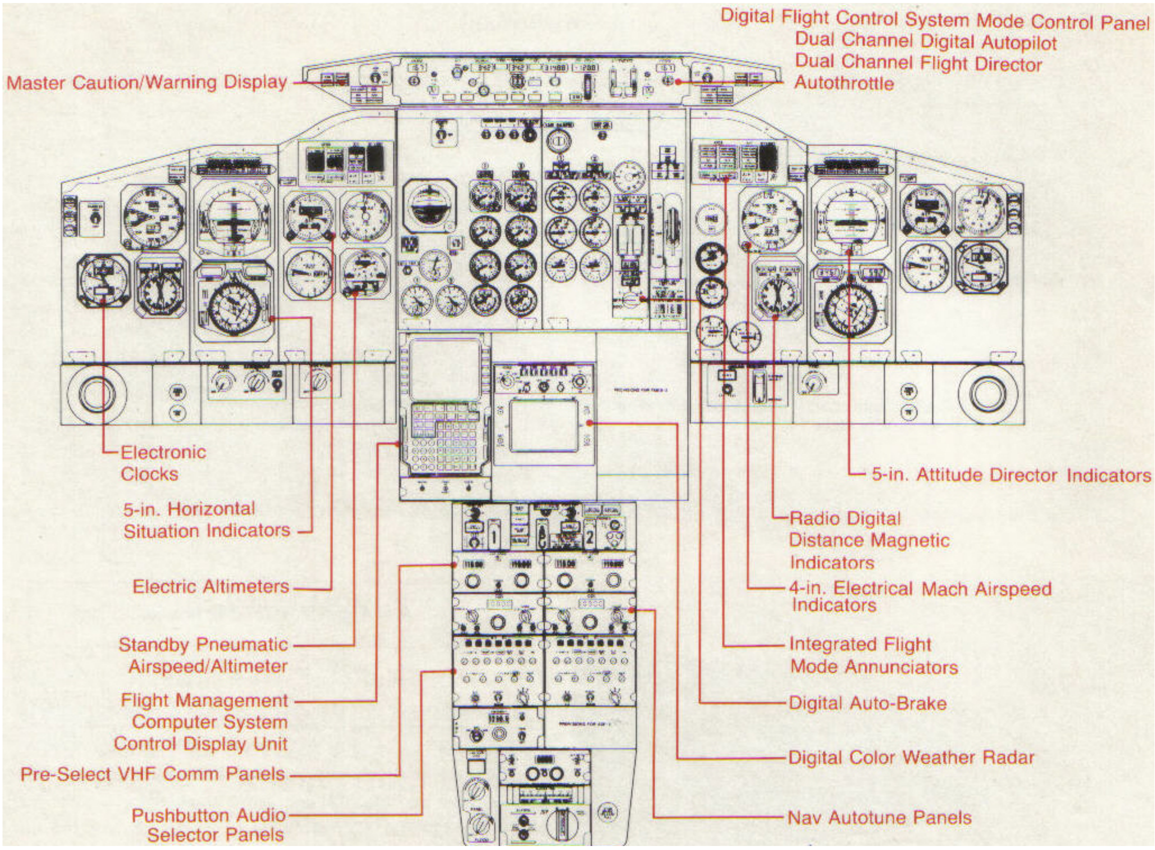


Figure 4.38

B737-300 Original Cockpit (without EFIS)

(Taylor, 1983)

Eventually the need for a B737-200 replacement came about due to noise regulations coming into force. To meet this Boeing launched the B737-500, this time a 94in shortened version of the B737-300 incorporating all the improvements with that generation (Hill, 2002). It was just about 1ft 7in longer than the B737-200 and offered existing operators a direct replacement in terms of capacity.

The family was thus complete for what is now called the 737 “Classic” generation made up of B737-300s, B737-400s, and B737-500s.

Like the B727s and B737-200s prior, B737-300 and B737-400s were also offered with a main deck cargo door to provide cargo or QC (Quick Change) versions.

4.6. Boeing 737 Next Generation (B737-600, -700, -800, -900, BBJ)

From the late 1980s through the 1990s, Airbus began to create its own family of aircraft using the A320 as the basis. The A321 had a stretched fuselage version that could carry up to 220 passengers putting it in direct competition with Boeing's B757. The A319 on the other hand had a shortened fuselage that could carry 145 passengers, putting it in direct competition with the 737-300. Another shrink of the fuselage produced the A318 with 136 seats that put it in competition with the B737-500.

When the A320 was alone it had the benefits of better fuel burn, higher cruising speed and altitude but suffered the disadvantage of not being part of a family like the B737 which could span varying market segments of capacity and range and enjoy the benefits of operating commonality. Once the A320 started growing its own family, the Classic generation of B737 began to suffer as more and more sales went to the A320 family. In 1990, orders for the A320 family exceeded that of the B737 family for the first time.

Hence Boeing was compelled to come up with a new product to compete not so much with the A320, but with the A320 family. This was particularly important to key existing

B737 customers such as Southwest Airlines that really wanted to stay with the B737 family. Even when it was expanding, it sought to acquire other airlines such as Morris air in 1993 because Morris Air only flew B737s.

> *"Southwest uses only one type of aircraft – the Boeing 737.*
>
> *Flying one type of aircraft has a strong impact on the bottom line. First of all, training requirements are simplified. Pilots, flight attendants, mechanics, and provisioners concentrate their time and energy on knowing the 737 - inside and out. Thus all Southwest pilots are qualified to fly, all flight attendants are qualified to serve in, all maintenance people are qualified to work on, and all provisioning crews are qualified to stock every plane in the fleet. This make it easy for Southwest to substitute aircraft, reschedule flight crews, or transfer mechanics quickly and efficiently. With only one type of aircraft, the company can reduce its parts inventory and simplify its record keeping, which also results in savings."* (Freiberg & Freiberg, 1996)

Southwest would in fact be the launch customer for the B737-700, ordering some 63 of the aircraft in 1993. With that in hand, Southwest had a considerable influence in the aircraft design nudging Boeing to keep changes compatible with the previous generations, keeping the aircraft simple, and asking for design changes to minimize aircraft turnaround times.

A look into main new features of the B737 next or B737NG was given in the article in Figure 4.39 from Flight International in early 1993. Importantly it highlights an increase in the “family” capacity to range between 100 and 185 seats, meeting the A318 to A321 capacity, as well as an increase of cruising speed to Mach 0.78+, slightly faster than the A320.

A review of the manufacturers’ performance data also indicates that the B737NG maintains this cruising speed for even lighter weight operations, whereas the A320 family’s cruising speed tends to go down with operating weight. Maximum cruising altitude also increased to 41,000 ft, greater than the A320’s 39,000 ft capability.

To achieve these aerodynamic improvements the two significant changes are a new CFM56-7 engine, with yet better fuel burn and higher thrust range, and a new wing that also provided 25 percent greater wing area and a 30 percent increase in fuel capacity. Remarkably, the wing was not all new but a modification of the old wing, keeping parts such as the rear spar and high lift devices behind it, per the comments from Stephen Ford of Boeing in the article below.

Upgraded avionics and a B777 style interior further made the new B737 a formidable competitor (See Appendix E for summary).

Boeing briefs airlines on 737-X

BY GUY NORRIS
IN SEATTLE

Boeing has started briefing key airlines on its proposed 737-X product-development study. The Seattle-based manufacturer has finalised the study in outline and earlier this month began giving the airlines their first look at what is expected to become the successor to the world's most successful commercial jet.

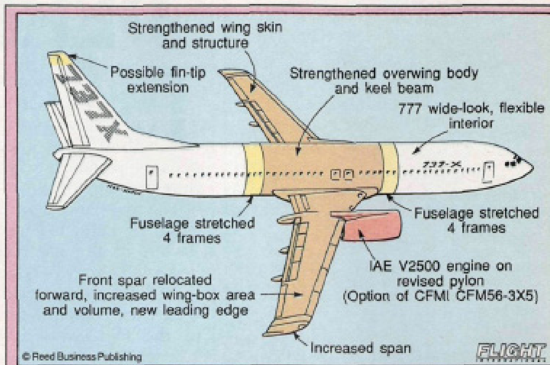
As expected, the 737-X concept is being shown as a future twinjet family, with between 100 and 185 seats, and is not just a stretch of the 737-400. "The fuselage stretch is just an option," says 737/757 marketing management regional director, Stephen Ford.

"At the moment, we're still listening and not selling this configuration," he adds.

The main features of the revised design is a larger wing and updated engines. Both are key features in a concept which Boeing believes could offer higher levels of reliability, maintainability, operating flexibility and lower noise levels than the present generation.

"We asked operators what they needed up to 2000 and beyond. Now we've got to a point where we understand the issues. We want an aircraft that is considered modern beyond 2000," Ford says.

The wing of the 737-X is increased in span and chord over the current 737 family, allowing the fuel capacity to be increased by 24%, or up to around 25,000litres. This would give the 737-X an extra 1,100km (600nm) range, allowing it to be operated on transcontinental routes such as Los Angeles to New York.



Boeing 737-X principal changes from 737-400

The newer wing would also have increased aerodynamic efficiency, providing cruise speeds between Mach 0.78 and 0.8, yet giving a shorter take-off run at maximum gross take-off weight than is possible with the present models.

The longer span and wider chord will expand wing area to around 106m², some 20% greater than that of the 737-300/400/500. The wing growth will be achieved through extending the forward spar of the wing box to open up the area for increased fuel capacity. The leading edge will therefore extend further forward and the span will be increased, possibly to almost 34m.

To keep the cost down and to benefit from existing performance, Ford says that the area aft of the rear spar will not be changed, to "...preserve the high-lift devices".

Boeing performed cost-benefit analyses on several wing configurations, including "...a couple of developed 737 wings and a whole new wing. We even looked at taking a chunk of the 757 wing and using that." It is thought that one of the more radical wing concepts explored was a "gull wing", which would have provided slightly more ground clearance for the engines.

"By modifying the wing, we achieve 90-95% of what we wanted with a new wing," adds Boeing's Ford.

Current leading contenders to power the 737-X are CFM International, with its CFM56-3XS, and International Aero

FLIGHT INTERNATIONAL 14 - 20 April, 1993

Figure 4.39

Boeing 737-X

(Flight International, 14-20 April 1993)

The family concept occurred faster on the B737NG family as test flying of the B737-700 included the even larger B737-800 and smaller B737-600 in the same program. Hence an almost instantaneous family was developed, rather than an afterthought as in previous generations.

As with previous B737 generations, iterations of the basic platform ensued and a variety of versions were developed as shown below including freighter versions and executive jet as well as semi-executive jets. On the BBJ (Boeing Business Jet), an interesting development is the mating of the B737-700 body with the higher strength B737-800 wing allowing it to operate at higher take-off weights and longer ranges. Auxiliary fuel tanks are available to increase ranges even further.

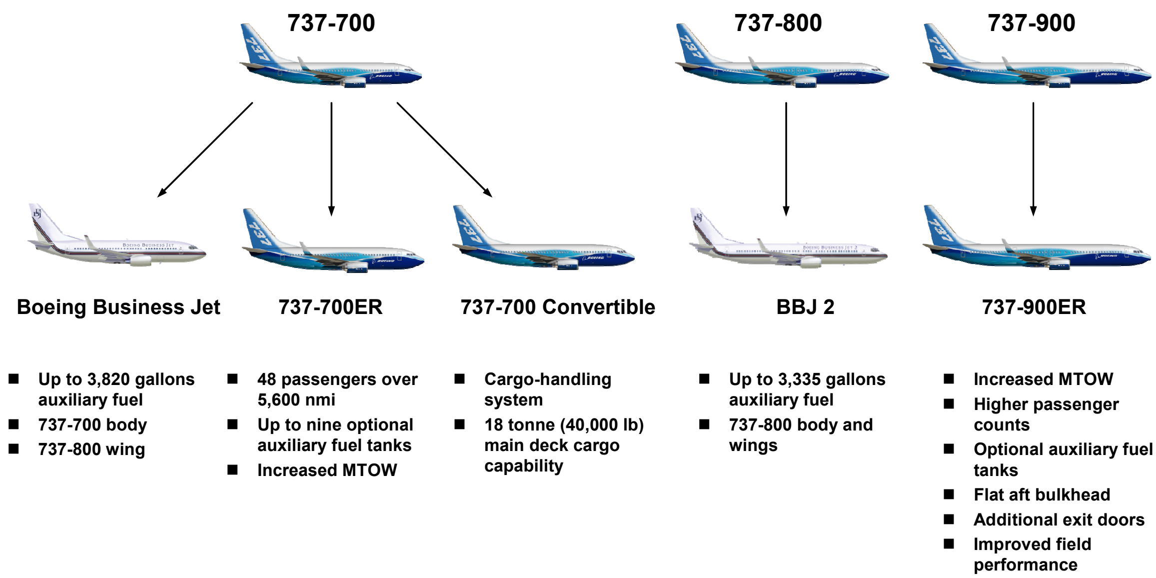


Figure 4.40
B737NG Family
(Adamson, 2010)

The largest family member developed was the B737-900 which has since been supplanted by the B737-900ER with a potential of up to 215 passengers using additional exit doors. A prime difference between the B737-900 and B737-900ER is the use of a flat aft cabin pressure bulkhead rather than a conventional rounded one to increase cabin space for seating. This option is now available on the other models.

Winglets developed by Aviation Partners Boeing, a jointly owned company of which Boeing has a share, were first introduced on the BBJs to improve fuel burn and hence increase operating ranges. These winglets are now a standard option on all B737NGs and operators use them not only to save fuel but also to increase speeds to improve aircraft utilization.

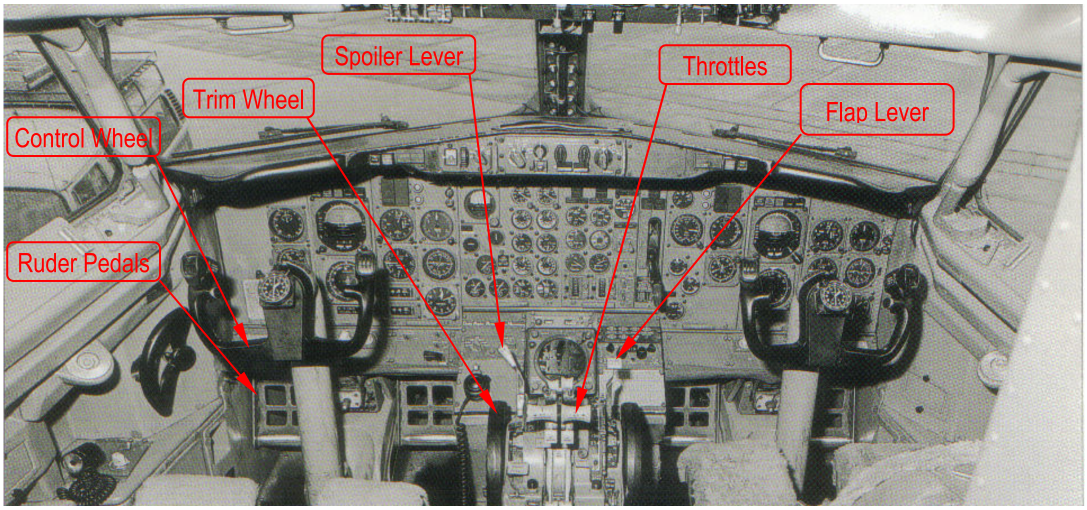
Hence we see here an interesting but rich mish mash of design and technology combinations. It would appear that the product "platform" is one that is continually evolving.

Significantly, despite FBW (Fly By Wire) being a selling feature on the competing A320 series, airlines asked Boeing not to include the technology in the new B737NG although Boeing was fully capable of it having developed the FBW B777. Southwest Airlines in particular wanted to maintain the existing B737's basic simplicity as well as commonality with previous models. Here we see a very shrewd decision not to adopt technology that did not have a significant economic benefit for the consumer, with the preference instead to have commonality (Hill, 2002).

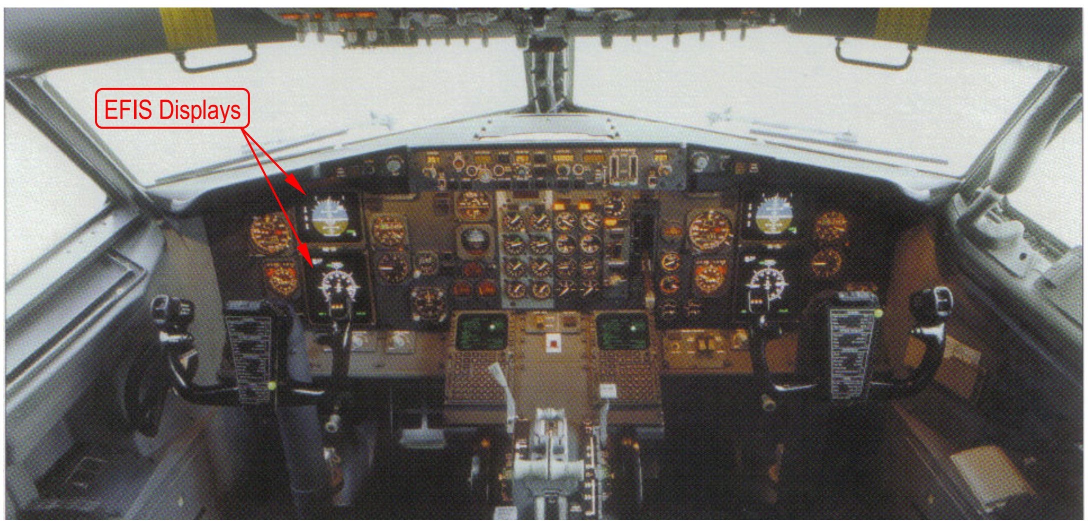
Probably the engineering masterpiece this time was the addition of fully electronic cockpits. Boeing was in a dilemma which type of cockpit display to provide. Many customers wanted the latest which was a B777 type display, Southwest Airlines wanted an EFIS (Electronic Flight Instrument System) type display common to their B737-300s, while some even wanted the old analogue instruments. Any of these options could have been taken but would have meant difficulty for pilot training or transitioning between different models. This could also complicate aircraft values and integration into operations as they transferred between different owners and operators.

In response Boeing used the B777 type Honeywell multifunction liquid crystal displays but incorporating a CDS (Common Display System) where electronically the primary flight and navigation displays could be easily re-configured to whichever display the customer wanted. In Figure 4.42, the upper screen shows a B737-300 style EFIS display while the lower display is more common to the B777. These displays are switchable by a simple software update. This way the airplane hardware stayed the same and each operator had a choice of customizing their display.

The three figures below illustrates the three generations of cockpits. Notably the mechanical parts such as the control wheel, rudder pedals, throttles, flap lever, spoiler levers, trim wheels have stayed in the same configuration, maintaining that part of the product architecture, through all generations greatly simplifying flight training.



B737-100 Cockpit (First Generation)



B737-300 Cockpit (Classic Generation)


B737NG Cockpit (Next Generation)

Figure 4.41 B737 Cockpits (Nicholls, 2003)

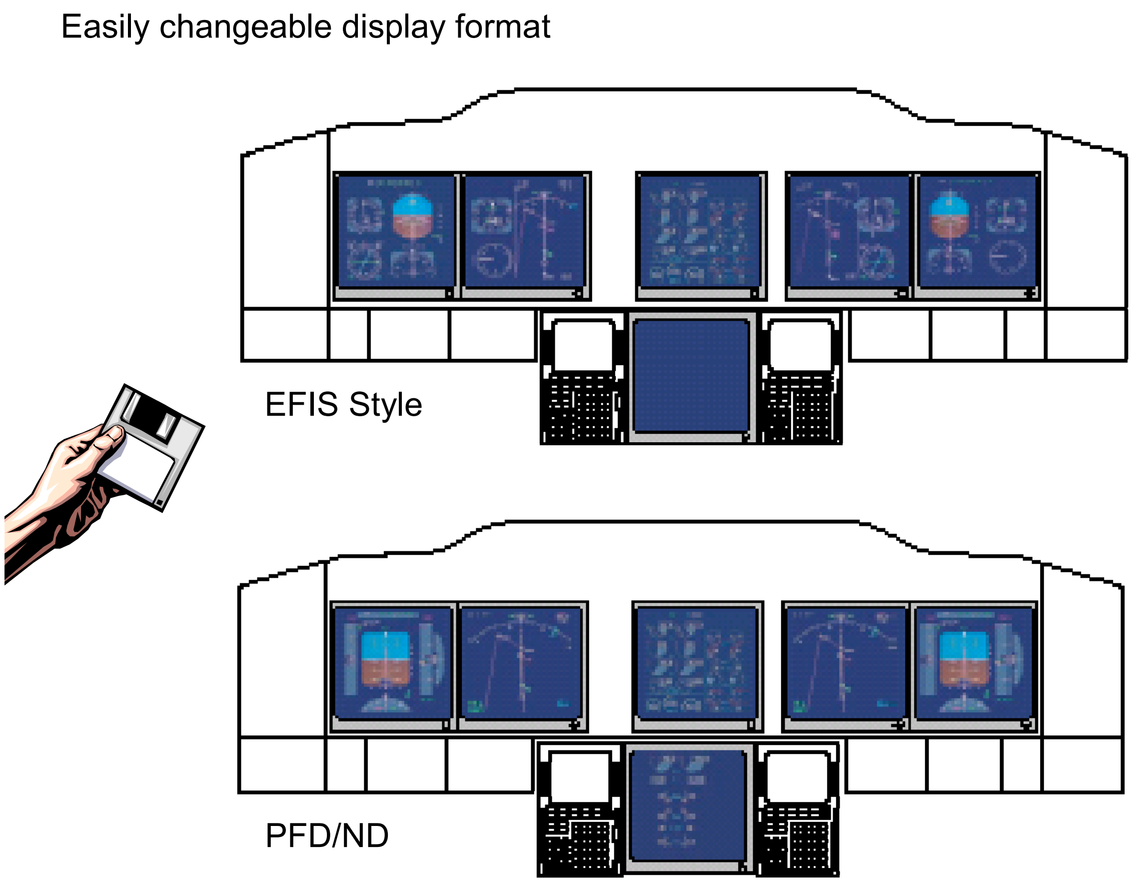


Figure 4.42

B737NG Common Display System

(Adamson, 2010)

Similarly the cabins have gone three generations of makeover as in Figure 4.26. In the First generation, one can even see open overhead bins with very little capacity. These would not be able to store the roller bags common today for hand carry luggage. The B737NG interior uses many of the same materials as used in the B777 to give weight savings, fire protection, albeit to give a more roomy feel and space as demonstrated by the Boeing employees in the overhead bins.

The extreme would be a Boeing Business Jet luxury interior as below, though often custom fitted by parties external to Boeing.

Figure 4.43

Boeing Business Jet Cabin

(Nicholls, 2003)

B737-100 Cabin (First Generation)

B737-300 Cabin (Classic Generation)

B737NG Cabin (Next Generation)

Figure 4.44 B737 Cabins (Nicholls, 2003)

Military versions on the B737NG also exist with at least 3 known versions as follows.

- C-40A Navy Airlift Aircraft

  The C-40A is essentially a B737-700 that was ordered by the U.S. Naval Reserve to replace its fleet of aging C-9 Skytrains (DC-9s). With a main deck cargo door, the C-40A is certified to operate in three configurations: an all-passenger (121 passengers) configuration; an all-cargo configuration of up to eight pallets; or a combination, or "combi" configuration that will accommodate up to three cargo pallets and 70 passengers (http://www.boeing.com/defense-space/military/c40).

- 737 Airborne Early Warning and Control (AEW&C)

  The B737 AEW&C or Airborne Early Warning and Control provides airborne surveillance, communications and battle management. Using a B737-700 increased gross weight (IGW) airframe, it incorporates a Northrop Grumman electronically scanned array radar system that can track airborne and maritime targets simultaneously and an integrated identification friend or foe (IFF) function that shares the primary radar arrays to reduce weight, improve reliability, and simplify target correlation (http://www.boeing.com/defense-space/ic/aewc).

- P-8A Poseidon

  The P-8A Poseidon is a long-range anti-submarine warfare, anti-surface warfare, intelligence, surveillance and reconnaissance aircraft capable of broad-area, maritime and littoral operations. The U.S. Navy plans to purchase 117 P-8As to replace its fleet of P-3C aircraft. Interestingly the aircraft is based on the B737-800 airframe but uses the stronger B737-900ER wing. Accordingly Maximum Take-off Gross Weights are closer to the B737-900ER.

The aircraft will have aerial refueling capability and hard points on the wing to carry missiles and a weapons bay to carry torpedoes and mines (Croft 2010). Interestingly the wingtips will feature raked wingtips similar to the B777-300ER/200LR or B767-400ER instead of the usual blended wingtips from Aviation Partners Boeing. This was primarily because of concerns of icing buildup if the aircraft flew at 10,000-15,000ft for maritime operations (Warwick, 2005).

The latter two applications are particularly interesting.

By using the B737-700 commercial airplane as its platform, the B737 AEW&C is almost a history repetition of the Indonesian air Force B737MP Surveiller which used the First Generation B737 airframe to fit side looking radars.

The P-8 Poseidon is a great example as it uses different designs and technologies from different model B737NGs (mating the B737-900 wing onto the B737-800 airframe) as well as outside the B737NG line (such as the raked wingtips). There is precedence from the Boeing Business Jet where Boeing mated the B737-800 wing to the B737-700 airframe.

Figure 4.45

B737 Airborne Early Warning and Control (AEW&C)

(http://www.boeing.com/defense-space/ic/aewc)

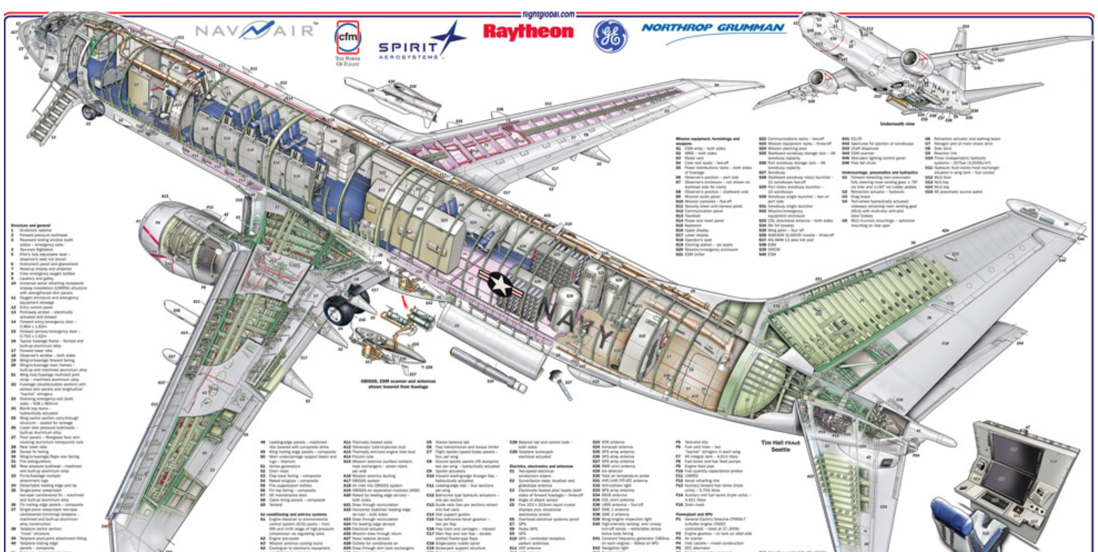


Figure 4.46

P-8 Poseidon

(Croft, 2010)

Hence it can be observed the “platform” is not necessarily one of design components attached to each other by of technologies and concepts that can be adapted from various models.

Notably with these military versions, the CFM56 engine is returning to a military role, considering its origins from the B-1 Bomber. It is ironic that it will again (the CFM56 was used to re-engine KC-135s and other B707 based military aircraft) be used in significant numbers with the United States Military as the U.S. government originally did not want to give approval to the joint venture between GE and the French company SNECMA to develop the CFM56 due to security concerns and release of proprietary technology from the F101 engine (Flight International, 1999).

Boeing is also proposing to replace a B707 based surveillance aircraft the Northrop Grumman E-8C Joint Surveillance Target Attack Radar System with a modified version of the P-8 (Trimble, 2010). If successful, the B737 will have done a full circle in replacing an airframe of its origin.

4.7. Boeing 737 Continuous Improvement

It would be too much to clutter up the history with all the smaller improvements that Boeing continued to add in each generation. Hence a separate section is added here to note some of those improvements that were added later in each program to show that Boeing did not stagnate the product in-between generations of aircraft.

- Improved Thrust Reverser (First Generation)
- Gravel Kit (First Generation)
- Improved Aerodynamic Nacelle/Wing Fairings (First Generation)
- Rear Fuselage Vortex Generators (First Generation)
- Increased Flap Selection including Flap Track Strengthening (First Generation)
- Increased Thrust Engines
- Cabin lighting and aesthetics
- Digital Autothrottle (First Generation)
- Colour Radar (First Generation)
- Performance Management System (First Generation)
- Head-Up Flight Guidance System
- Enlarged Leading Edge Slats and redesigned Krueger Flaps
- Nosewheel Braking System
- Modified Anti-Skid System
- Redesigned Engine Nacelle with Sound Absorbent Acoustic Lining (First Generation only)

- EFIS and Digital Engine Indicating System (Classic Generation)
- Auxiliary Fuel Tank (s)
- Main Deck Cargo Door and Cargo capability
- Quick Change Cargo-Passenger Conversion Kits
- CFM56-7B Tech Insertion (Next Generation)
- In-Seat Video System
- Carbon Brakes (Next Generation)
- Flat Aft Bulkhead (Next Generation)
- 180-Minutes ETOPS (Extended-range Twin-engine Operational Performance Standards) (Next Generation)
- Blended Winglets (Next Generation)
- BigBins (Next Generation)
- Category IIIB Landing Capability (Next Generation)
- Improved RNP (Reduced Navigational Performance) capability from 0.11 to 0.1 nautical miles (Next Generation)
- Vertical Situation Display (Next Generation)
- Flight Deck Noise Reduction Kit
- GPS Landing System
- Eyebrow Window Deletion
- High Altitude Airport Capability
- Short Field Performance Kit
- Electronic Flight Bag
- Aerodynamic Improvement Kit (Next Generation)

5. Analysis

5.1. *Family Concept*

As we can see the B737 family eventually developed into 3 distinct generations of B737 families. However it was not intended so from the beginning. In fact the “family” that Boeing wanted was for a small B737 (even smaller than the B737-100) to be a stable mate to the B707 and B727, i.e. a Boeing commercial jet family rather than a B737 family.

For the First Generation, the main reason there were two different sized models was because the first customer was Germany based Lufthansa and Boeing really wanted a United States based customer to reduce the risk to the program. United Airlines wanted a larger B737 than Lufthansa so Boeing ended up developing both B737-100 and B737-200 variants simultaneously.

In the Classic generation, the B737-700 was partly developed because of the new CFM56 offering more fuel economy and noise reduction. However the increased thrust that also came along also permitted Boeing to increase the size of the aircraft. And for a time the B737-200 of the First Generation and the B737-300 was in fact the marketed “family”.

The B737-400 was developed as a result of competition from the A320 and as a stop gap to the B7J7 program that never materialized. The B737-500 was finally added due to noise and fuel motivations that was making the B737-200 obsolete.

Only in the Next generation series was there a conscious effort to develop a complete family, primarily to compete with the Airbus A320 family of aircraft. However although the first two family developments were not completely intentional, Boeing at each step was very careful to maintain as much commonality as possible while all the time inserting new technologies and improvements, often from other Boeing aircraft models.

The chart below shows the family lineage, excepting military and cargo variants for simplicity.

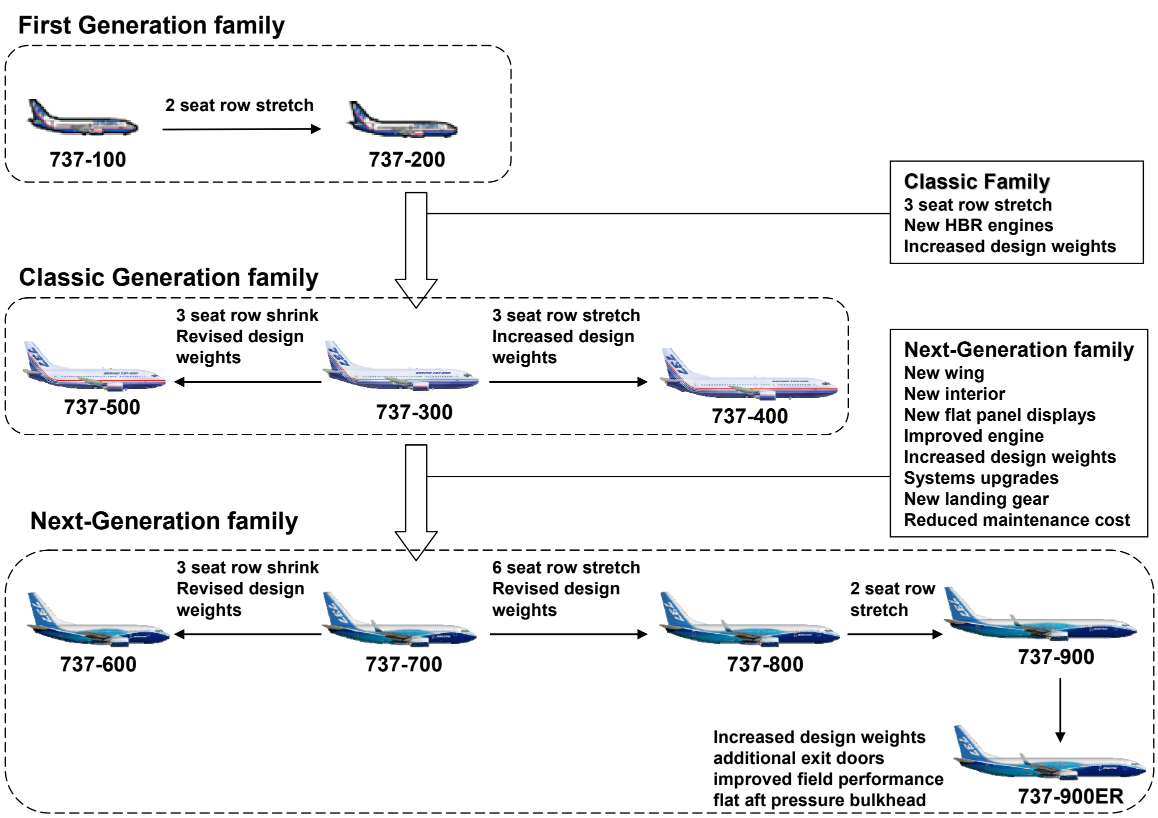


Figure 5.1

B737 Family Generations

Derived from Chart provided by Boeing (Adamson, 2010)

Each family was and has been a commercial success and is a testament to the family product concept. Between the Classic and Next Generation product families, Boeing has also maintained competitive parity against the much later lineage of the A320 family.

In terms of CoPS (Complex Products and Systems), there is no denying that a commercial jet such as the B737 falls into such a category. However by both market motivation and intention, the B737 history demonstrates that a CoPS product can in fact be developed in such a way that development costs are minimized using a product platform, and by doing so that production quantities are increased beyond the traditional low rate concept of a CoPS product.

For example the cockpit structure between all generations of the B737 has hardly changed. In fact it has lineage dating back to the Dash 80, B707, and B727 days. Hence that particular component design has enjoyed a much larger production rate than even the B737 itself.

It is difficult to get an accurate cost of development of each aircraft model and variant. However an idea can be gained by looking at the flight test part of the development program of each aircraft model before certification and entry into service.

The First Generation (B737-100 & B737-200) and Next Generation (B737-600, B737-700, and B737-800) models were all flight tested in simultaneous programs so it is not easy to allocate testing efforts to each model. The Classic Generation models however were tested separately as they were developed in sequence.

Model	First Flight	Certification	Duration (Days)	Number of Aircraft
B737-300	24 Feb 1984	14 Nov 1984	264	3
B737-400	19 Feb 1988	02 Sep 1988	196	2
B737-500	30 Jun 1989	12 Feb 1990	227	1

Figure 5.2

B737 Certification Flight Testing Record

(Derived with data from Nicholls, 2003; Shaw, 1999; Sharpe and Shaw, 2001)

As per the above chart, it can be seen that as each variant was developed, less and less flight testing was required by a factor of roughly 20-30% simply by looking at the number of aircraft.

Obviously many tests that would have been needed on a first model would not have to be repeated in subsequent variants if the design and function had not changed significantly. In fact while the B737-400 required 500 hours of flight testing, the B737-500 which followed later required only 375 hours, some 25% less (Nicholls, 2003; Shaw, 1999; Sharpe and Shaw, 2001).

This gives an indication of how much less investment Boeing had to make compared to developing an all new aircraft with new designs. Boeing in fact saved even more with each generation as each time previous designs were adopted from either previous generations of B737, or other aircraft types in Boeing such as the B727, B757/B767 (e.g. Flight Management Systems), or B777 (e.g. cockpit displays). Even the Pratt & Whitney JT8D engine used in the first B737s were similar to those used on the B727 hence Boeing already had familiarity on their characteristics and installation requirements.

It is not known if this was intentional, but when developing the first B737, Boeing was also heavily committed on B747 development. Hence adopting existing designs and technologies such as the cockpit and wing high lift devices from the B727 would seem a natural way to save on development and production costs.

A side benefit of course is commonality. Commonality of spare parts, operating practices, training requirements, and even having to deal with the same manufacturer was a feature first marketed to existing operators of B707s and B727s. The benefit compounds when different variants of the same family are operated in the same fleet to meet different market segments. For this reason many low cost operators such as Southwest Airlines and Westjet choose to fly the same aircraft (often between the B737 and A320) family in their fleets.

This becomes quite evident in the expensive business of training pilots where regulations require constant re-training and refresher courses. A pilot can be trained to fly multiple variants in the same fleet. This is true of the A320 family as well as the B737NG. In the figure below, we see that pilot training requirements are also much less for pilots transitioning from different generations of B737s. For a large operator this can mean significant cost savings.

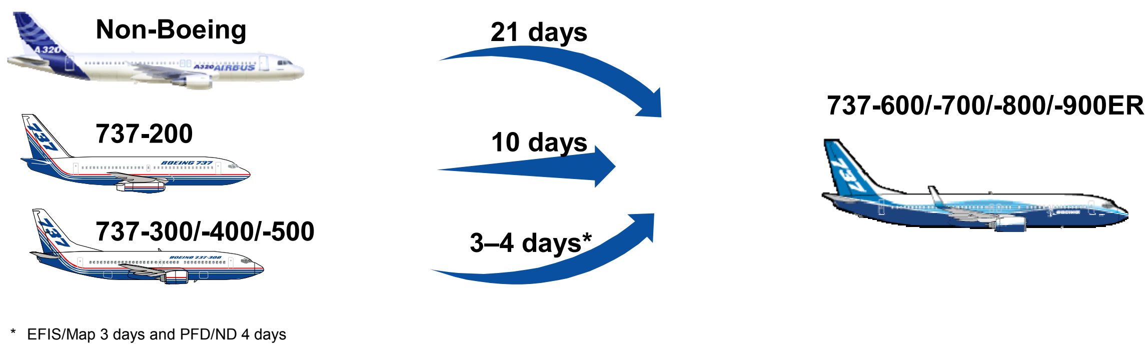


Figure 5.3
Pilot Training Duration Requirements for 737NG
(Adamson, 2010)

Remembering that Boeing fitted an easily reconfigurable Common Display System (CDS) on the B737NG that could be switched to show Classic (EFIS/MAP) or Next Generation (PFD/ND) cockpit displays, this was a feature that provided great flexibility for operators. Since the system came from the B777 which is now used on other Boeing aircraft such as the B747-8, the transition training commonality advantages expand further into those types of aircraft.

While physical parts commonality is an obvious inventory cost saving, a less visible advantage is that of multiple thrust ratings using the same physical engine and accessories (such as the gearboxes). Similar to the easily re-configurable cockpit, the

CFM56-7 engine can be electronically configured to provide different maximum thrust settings. Higher thrust settings offer greater take-off performance but with the trade-off of lower overhaul shop visit intervals and higher maintenance costs. Hence an operator not requiring high thrust levels can use a lower maximum thrust setting to achieve engine maintenance cost savings. On the B737NG, maximum sea level thrust settings can be set between 18,000 lbs to 27,000 lbs for various models as in the figure below (The middle numbers indicate thrust in 1,000s of lbs e.g. -7B18E means 18,000 lbs thrust)..

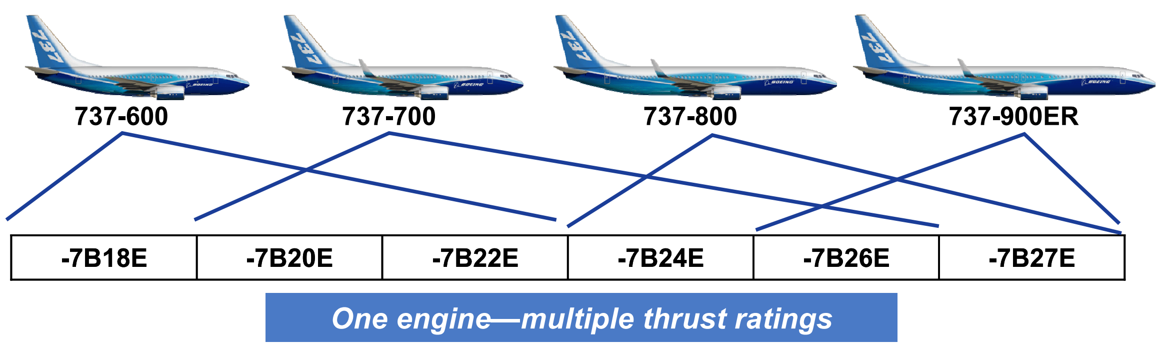


Figure 5.4

B737 Engine Ratings by Model

(Adamson, 2010)

In terms of inventory, this offers great flexibility for example for an operator that might be operating B737-700s but is thinking of adding another model such as the B737-600 or B737-900ER. The existing spare engines on hand can be used to support a new model entry. Outstation support where airlines may keep or have agreements to share spares with other operators is also greatly simplified.

Furthermore distribution channels and production channels are simplified with a product family approach (Meyer and Utterback, 1993). Even when shifting to a new generation of product family, it is much easier to use existing support networks than to create altogether new ones for a completely different type of product.

The involvement of customer input in all three generations of the B737 is also positive. "High levels of customer recognition are the cumulative effect of a robust product family" (Meyer and Utterback, 1993). This seems to be a cornerstone of many successful Boeing commercial jet programs including the B707, B747, B757, B767, and B777 (Gardiner and Rothwell, 1985; Sabbagh, 1996).

The family concept was to prove instrumental in winning sales for Boeing where the customer needed capacity flexibility in the face of uncertain future passenger loads as was the case in October of 1988 when Boeing won an order for twenty four B737s in the face of stiff competition from Airbus. This was despite the fact that British Airways had just absorbed British Caledonian which had ten A320s on order. The reason for the Boeing win was that ". . . the 737 comes in three versions. The Series 300 has 124 seats. The Series 400 has 141 seats. The Series 500 has 106 seats. BA does not have to specify how many it wants of each until relatively late in the acquisition process. If there is an upsurge in air travel, they can go for more 400s. If growth tails off, then the 500 will be the answer. Flexibility. Commonality. The elimination of risk." (McIntyre, 1992).

This flexibility can also be an attractive feature for leasing companies. Many airliners now operate leased aircraft where such aircraft can be a large percentage of their fleets (Newhouse, 1997). Since aircraft orders have along lead time but leasing companies have to secure delivery slots, the ability to switch between smaller and larger members of a product family can be extremely helpful in reducing demand risk. This in turn improves the prospect of larger orders and production runs.

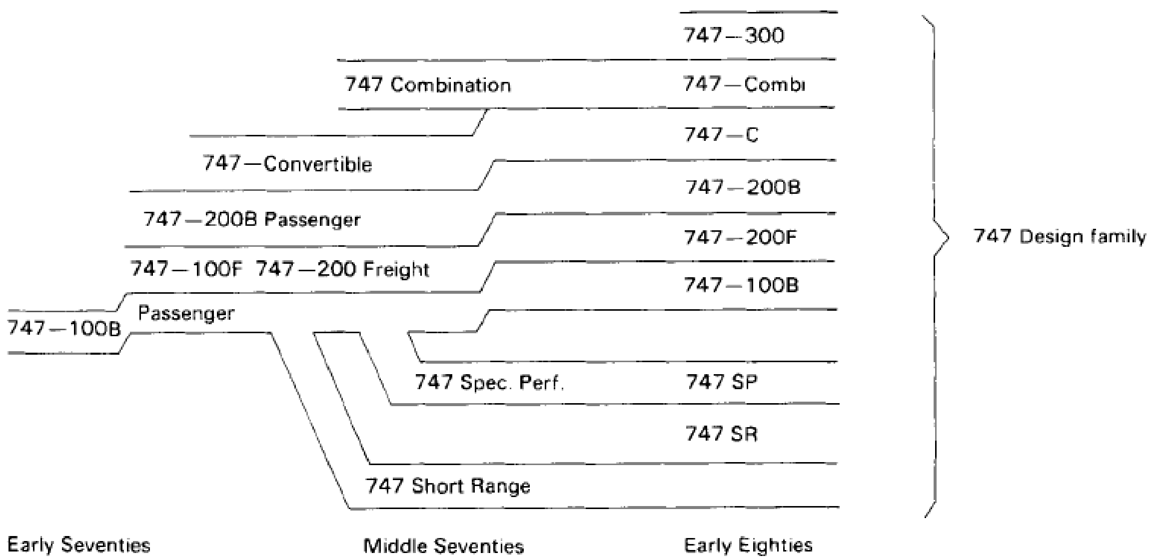


Figure 5.5

Boeing B747 Design Family

(Rothwell and Gardiner 1989)

Unsurprisingly even the largest member of Boeing's commercial jet family has a similar family background as shown below. Hence the innovation culture seems to run though similarly in all programs. Missing in the figure are later models, the B747-400, B747-400ER, B747-8I (Passenger), B747-8F (Freighter), and military versions such as Air Force One.

Yet this is despite CoPS having a characteristic feature that heavy customer input can hamper development. It may be that it depends how the customer input was taken. Boeing was always careful to absorb input from a variety of customers taking special account of major customers such as Southwest Airlines. Development of British commercial jet aircraft such as the Hawker Siddeley Trident and BAC 1-11 on the other hand were constantly hampered by British Government demands that the aircraft be tailored only to local airlines such as BOAC and BEA at the time (Kemp, 2006).

5.2. Reflections on “The Nature of Technology”

These findings of this thesis echo many of the features that Brian Arthur writes about in his 2009 book “The Nature of Technology”. In this book Arthur notes that new technology is often constructed from components of existing technologies.

This reflection is significant as we considered the idea of a concept when developing the “platform” method of building a CoPS product family. As we see in the Boeing 737, many variants and derivatives were developed over successive generations, but the overall concept was maintained. For example despite growing in size and engine thrust in later models, the Boeing engineers maintained a low ground to cargo door height by adjusting the engine mounts and engine inlet design.

The easy option would have been to simply increase the landing gear height. Although this has wing dimensional and structural implications, it was a high possibility when they re-designed the wing for the Next Generation series of B737.

But the two parts of the concept Boeing maintained even with a new generation, was the idea of easy access to the cargo doors without a mechanic to waste time positioning stairs, and the commonality aspect of aircraft components.

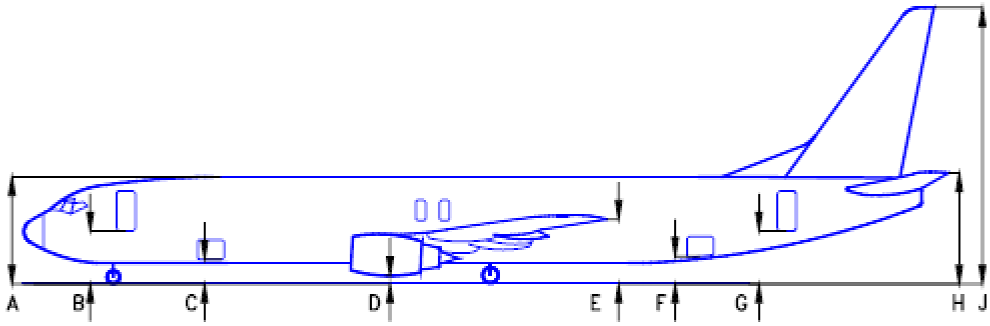
> "Strut mounting the engines beneath the wings would also require the 737 to sit high off the ground on long landing-gear struts to give the engine nacelles sufficient ground clearance.
>
> I frowned. The airlines wouldn't like that. From my fact-finding discussions with them, I knew how important this issue of airplane height is to short-haul flight operations. Small jets typically make short flights on routes a few hundred miles long or less. They can log up to six or seven of these per day. The less time they spend on the ground between flights, the more time they can be in the air generating revenue for their operators.
>
> If I kept the design of the 737 low to the ground, it would turn around more quickly and be back in the air sooner. Why? Because no time would be wasted retrieving, positioning, and removing ladders and maintenance stands. Airline mechanics could walk right up and perform line maintenance on the engines and other systems from ground level. And when late-arriving passengers showed up at the gate, airline employees could simply take those last-minute bags out to the jet, pop open its cargo hold, and toss them in." – Joe Sutter, Head of Design, Boeing (Sutter & Spenser, 2006)

The above quote was from when Joe Sutter developed the first B737, but it has followed true for over thirty years as Boeing has maintained that philosophy for all models of the B737.

Reviewing the Airplane Characteristics Airport Planning Document of the B737, the forward cargo door sill height from ground is less than 5 feet whether it is the original B737-100 or the latest B737-900ER (See dimension C in Figure 5.6). In contrast, and doing the same exercise with the Airbus A320, the same dimension is over 6 feet, well above the height of most airline ground staff (See dimension B in Figure 5.7).

It was important then to note that while a typical product platform consists of a major assembly of already designed parts that have been proven to work well, that these parts did not necessarily have to be attached to each other. Each of these parts may be sub-assemblies and have their own functionality or may even be a platform of its own with its own concept.

The integral folding airstairs option for example on the B737 was an idea and design copied from the B727 to provide greater operability into remote airfields. The main deck cargo door was also transplanted from the B727 into the B737, and eventually further transplanted into the B757PF Package Freighter. The Flight Management System, Inertial Reference System (IRS), and cabin interior were adopted from the B757 for the Classic Generation of B737. Similarly the B777 cockpit was used as the basis for the design of the B737 Next Generation cockpit, but modified so that it could be electronically switched to display an older format if desired.



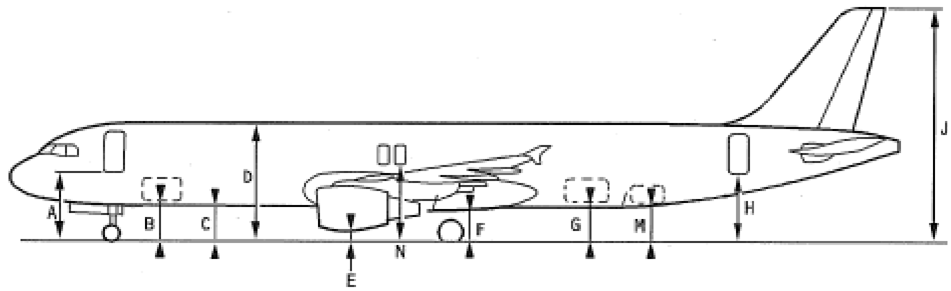
	DESCRIPTION	737-800				737-900			
		MAX (AT OEW)		MIN (AT MTW)		MAX (AT OEW)		MIN (AT MTW)	
		FT - IN	M	FT - IN	M	FT IN	M	FT IN	M
A	TOP OF FUSELAGE	18 - 3	5.56	17 - 9	5.41	18 - 4	5.59	17 - 10	5.44
B	ENTRY DOOR NO 1	9 - 0	2.74	8 - 6	2.59	9 - 0	2.74	8 - 6	2.59
C	FWD CARGO DOOR	4 - 9	1.45	4 - 3	1.30	4 - 9	1.45	4 - 3	1.30
D	ENGINE	2 - 1	0.64	1 - 7	0.48	2 - 1	0.64	1 - 7	0.48
E	WINGTIP	12 - 10	3.91	12 - 0	3.66	12 - 10	3.91	12 - 0	3.66
F	AFT CARGO DOOR	5 - 11	1.80	5 - 5	1.65	5 - 11	1.80	5 - 5	1.65
G	ENTRY DOOR NO 2	10 - 3	3.12	9 - 9	2.97	10 - 3	3.12	9 - 9	2.97
H	STABILIZER	18 - 6	5.64	18- 0	5.49	18 - 7	5.66	18 - 1	5.51
J	VERTICAL TAIL	41 - 5	12.62	40 - 7	12.37	41 - 5	12.62	40 - 7	12.37

NOTES: CLEARANCES SHOWN ARE NOMINAL. ADD PLUS OR MINUS 3 INCHES TO ACCOUNT FOR VARIATIONS IN LOADING, OLEO AND TIRE PRESSURES, CENTER OF GRAVITY, ETC.

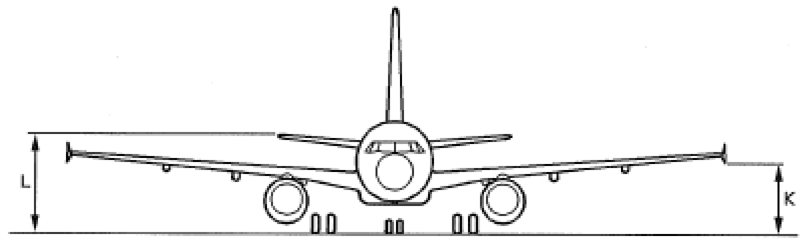
Figure 5.6

Ground Clearances Boeing 737-800 & 737-900ER

(737 Airplane Characteristics Airport Planning, D6-58325-6, Boeing Commercial Airplane Company, 2005)



NOTE: POINT 'K' IS THE BOTTOM OF THE WING TIP FENCE.
POINT 'M' IS AN OPTION.



		OPERATING WEIGHT EMPTY		MAXIMUM RAMP WEIGHT FORWARD CG		MAXIMUM RAMP WEIGHT AFT CG		AIRCRAFT ON JACKS *	
		m	ft	m	ft	m	ft	m	ft
A		3.47	11.39	3.39	11.12	3.48	11.42	4.11	13.48
B		2.09	6.86	2.01	6.59	2.07	6.79	2.70	8.86
C		1.86	6.20	1.77	5.81	1.81	5.94	2.43	7.97
D		6.00	19.69	5.91	19.39	5.96	19.52	6.58	21.59
E	CFM56	0.68	2.23	0.59	1.94	0.61	2.00	1.24	4.07
	V2500	0.78	2.56	0.68	2.23	0.71	2.33	1.83	6.00
F		1.72	5.64	1.62	5.32	1.63	5.35	2.26	7.42
G		2.25	7.38	2.13	6.99	2.08	6.82	2.70	8.86
H		3.73	12.24	3.60	11.81	3.48	11.42	4.11	13.48
J		12.14	39.83	12.00	39.37	11.83	38.81	12.45	40.85
K		4.04	13.26	3.92	12.86	3.87	12.70	4.49	14.73
L		5.57	18.28	5.42	17.78	5.25	17.23	5.87	19.26
M		2.51	8.24	2.38	7.81	2.30	7.55	2.92	9.58
N		3.96	12.99	3.87	12.70	3.87	12.70	4.50	14.76

Figure 5.7

Ground Clearances Airbus A320-200

(Airplane Characteristics for Airport Planning, Airbus 1995)

This concept was also important when developing the idea of a product platform. This phenomenon of "borrowing was observed by Jones (2003) who wrote ". . . empirical and conceptual analysis in the broader literature on the performance of individual development projects have been dominated by the assumption that projects are independent or nearly so. However, during the often prolonged period of incremental change following radical technological change, the potential for one design project to depend upon another, through borrowed parts for example, is much enhanced because technological continuity is greater. Therefore, in general firms may benefit from planned and coordinated family relationships among products - platform strategies - that incrementally renew or extend their product lines."

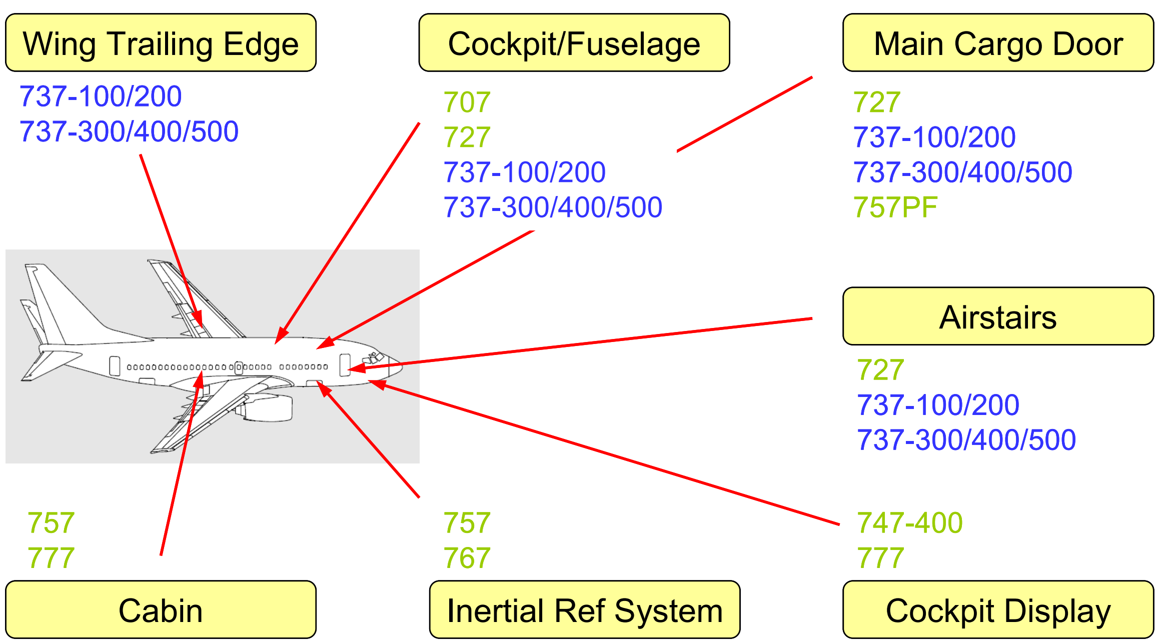


Figure 5.8

B737 Shared Designs

This ties into several of Arthur's comments. One is that technologies tend to be built from components of prior existing technologies or designs. This is blatantly obvious when looking at the history of the B737 per Figure 5.8. Not only do successive models take advantage of previous B737 designs, but Boeing has also taken advantage of designs and technologies from other models or families outside the B737 product line. Starting from the use of the B707 fuselage into the B727, this liberality has enabled Boeing to take full advantage of spreading development programs and hence development costs, across several product lines.

This obviously breaks the mould of CoPS where new programs are considered expensive and difficult to lower costs due to low production rates. Simpson (2004) even describes a "bottom-up (reactive redesign) approach, wherein a company redesigns or consolidates a group of distinct products to standardize components to improve economies of scale". Combining this with Arthur's theory, this would powerfully indicate that a CoPS product that suffers high development and production costs and low production rates may mean a poor strategic approach to the initial design rather than it being a natural feature that all CoPS type products should suffer the same disadvantages.

A main deck cargo door design that is used on four different product lines obviously enjoys higher production rates than if it were to be installed only on one product line. The development cost on the last product line is probably minimal and would enjoy refinements from the installation on the earlier product lines.

As a result the concept of a product "family" is more complex than as first glance. The B737-300, B737-400, and B737-500 could be considered as one family, the "Classic" B737 family. However if we consider say the nose and cockpit structure and the fuselage, the "family" could in fact be extended to the B707, the B727 and other B737 generations. Sub-components hence have the possibility of belonging to their own sub-component families.

It can thus be deduced that a product that has a large number of these sub-component type families interwoven in would enjoy considerable lower development costs as well as a much more net longer development history than the complete product assembly development program would imply. More importantly it can be seen as an accelerator of evolution time for design refinement which a competitor without such advantages could simply not replicate on an all-new product design.

For example when incorporating in the B777 cockpit into the B737 Next Generation, Boeing would already have the confidence that the system would have high reliability and have few entry-into-service issues due to the development work already done and in-service experience from the B777 program.

In fact the best an all-new competitor could do is to buy or partner with sub-system manufacturers. This is in fact what happened with Airbus as Airbus is in fact a conglomeration of different companies such as British Aircraft Corporation (later becoming part of British Aerospace) and Aerospatiale who have grouped together to share designs, capabilities and experience to develop products to compete with Boeing and at the time, McDonnell Douglas. The wing origin of the A320 comes from prior studies done by British Aircraft Corporation on a proposed BAC 3-11 aircraft, a growth version of the then existing BAC 1-11 airplane (Laming and Hewson, 2000).

Arthur (2009) describes also the combination effect. Not unlike the Lego designs where toy bricks of different shapes and functions can be combined in endless possibilities, technologies can similarly be combined to create new products. Not all combinations put together at random would make sense, but when opportunities arise to combine to provide functionality to the central concept, then obviously this is simpler to incorporate and develop than trying to design something new and untried to fit the desired functionality.

Sony did just this to develop the Sony Walkman when it happened to match development of a high fidelity portable cassette player with an otherwise separate development of lightweight headphones. The two development teams were unaware of each other's product development until the then Sony's Honorary Chairman Masaru Ibuka happened to drop by and made the connection between the two projects (Sanderson and Uzumeri, 1995).

5.3. *Reverse Disruptive Innovation*

While Disruptive Innovation (Christensen, 1997; Christensen and Raynor, 2003) typically refer to incumbents being attacked by new entrants with products of lower performance but which meet customer expectations of sufficient performance at lower cost and/or with an attribute that existing products do not have, what is less obvious in this oft spoken theory is that while the theory is not disputed, the mechanics of the theory can in fact be applied in reverse. One could be forgiven that this scenario typically works in an environment of new products and new entrants. This aspect is actually unnecessarily important.

What is in fact more critical is the use of having adequate performance capability to meet customers' needs. With this, the superior product can be the new entrant, and the defending lesser performing product can be the existing one. Schmidt (2004), Utterback and Acee (2005), Schmidt and Druehl (2008), Sood and Tellis (2011), describe such disruptive scenarios but with the difference that the new superior is the disruptor and eventually achieves dominance over the older product. Reverse Disruptive Innovation uses more of one of Charitou and Markides' (2003) defense strategies which is to "develop a third game, attacking the innovators by emphasizing still different product attributes". This strategy can thus be considered in an environment where a company needs to respond to a competitive threat.

Significantly it can be used to buy valuable time against threats from more technologically advanced competitors and save cash flow on new product investments. In parallel what might be expected to become obsolete products with time may actually have longer product lives with the application of this type of strategy.

The key point is to consider what the end customer considers as value attributes of the product. Even if a new product is more technologically advanced it may be more than what the customer needs and is willing to pay for. In fact the converse may be true since operating a familiar product is usually easier. For complex products training and equipment set-up costs are reduced as opposed to introducing an all new design.

In the aircraft manufacturing industry, aircraft cost billions of dollars to develop and are inherently complex machines with many features upon which customers have to make multi-disciplinary decisions when purchasing amongst the various options available at the time. Due to the cost and complexity, new aircraft models typically have a long time lag measured in tens of years before manufacturers will invest in developing a completely new model.

If competing products are close enough in technological genres, the competitors can take on a battle of incremental improvements to stay somewhat competitive. But what if for example an incumbent company is faced with a competitor that comes along with a new product that is twenty years ahead of its latest product? This case is not dissimilar to when Airbus introduced the Airbus A320 that would challenge the Boeing B737.

The A320 featured many new technologies such as fly-by-wire or FBW flight controls which were highly publicized. FBW eliminated the pilot's control wheel and instead featured a joystick for the pilot to use. The joystick inputs were filtered by computers to manipulate flight control surfaces to manoeuvre the aircraft. With the computer in the loop the inputs could be programmed to prevent incorrect pilot input such as over-controlling the aircraft when the limits of the flight envelope were reached, such as stalls.

Whether intentionally it did so or not, the study shows that Boeing focused primarily on improving only the features of the B737 that needed to be developed to attain competitive standing with the A320. These features were those that would provide the highest values to the customer in terms of the customers' businesses.

Initially on the Classic Generation, Boeing simply stretched the fuselage to provide more capacity in the form of the B737-400. However in the Next Generation, the B737's aerodynamics were also improved to give an edge of cruise speed as well as maximum cruising altitude over the Airbus A320 family, together with the latest more fuel efficient CFM56 engines.

Traditional Disruptive Innovation theory states that good businesses naturally try to improve their products in a continuous fashion to further this goal. These improvements to feed the same market and product purpose are deemed as "sustaining". By doing so the improvements often surpass the level or performance which customers actually want. The argument is that customers' demand for improved product performance is often on a slower rate than that which the industry can offer. New entrants can then enter as lower cost alternative providers with less developed products that are not as good as incumbent firms, but which meet the customer's needs and levels of performance that they are willing to pay for. New entrants can come in via a completely different market to serve different customers but for a different type of application where again the product performance is not as good, but viewed in the absence of anything else, is better than nothing. As the product improves, the firm eventually develops sufficient product performance to eventually step into the mainstream market.

The interesting part is that for both low end and new market entrants, incumbent firms often choose to flee up-market as the lower end is typically lower margin and by going upscale their profit margins only improve. This gives an illusion of all is well until the new entrants improve yet again and move higher and higher until the incumbents have nowhere to go (Christensen and Raynor, 2003). It would seem however that the word "disruptive" is a relative term. Christensen (1997) typically uses examples where large corporations have a significant market and are "disrupted" by new less capable or less mature firms.

Oddly enough in the case of the B737, the disruptive part of the story comes from within Boeing itself with a stimulus from Airbus. At the lower end of the market of the 1990s, Boeing had in its product line up the Boeing B737 and B757 while Airbus had the A319, A320 and A330 in respectively bigger sizes and range. The jump from A320 and A330 was huge however (150 to 300 seats) and Airbus did not have an intermediate aircraft like a 200 seat B757.

What Airbus did was to stretch the A320 fuselage and increase the thrust rating of the engines to produce the 180-seat A321. While this heavier model had poor performance on demanding airports and missions (customers often buy this model with an additional fuel tank), it was sufficient for many European operators that had short hop operations of typically 1-2 hour flights.

For these operations, the lighter A321 was in fact cheaper than the B757 to operate. With additional fuel tanks, the aircraft has increased range and can do most intercontinental flights of 4-5 hours. Boeing's response was to extend the performance of the B737 to the Next Generation with more engine upgrades and a matching family of fuselage stretches and shrinks to match. However the improved economics and capability of both the B737-800/-900 and A321 suddenly made the B757 uneconomical in comparison. Notably Aircraft Commerce (2001 and 2005c) provides studies that show this potential displacement.

The B757 still had the best take-off performance for hot and high airports where the lower air density reduces the engine thrust and subsequently the corresponding payloads, but second hand B757s were available in sufficient numbers to fill this almost niche market. The B757 customer base dried up and Boeing stopped producing the B757 a few years ago. Here, we see that incremental innovations actually caused a disruptive change where the price and performance of the B757 was more than what customers wanted once the smaller offerings became available (Christensen and Raynor, 2003).

A pattern hence emerges beyond Christensen's staple theory. While Disruptive Innovation theory does work to an extent, it does not fully explain how some incumbents can compete and successfully stay ahead of potential new competitors. In the case of the B737 versus the A320, it is simpler to think of the B737 as the new entrant and the A320 as the incumbent. In effect the roles are reversed in a Reverse Disruptive Innovation way.

Interestingly this is similar to what Christensen et al (2004) said if Boeing were to decide to compete in the lower end of the regional jet market against companies such as Embraer and Bombardier. Embraer and Bombardier would be the incumbents while Boeing would be the entrant (Christensen et al, 2004). However Boeing as an established aircraft manufacturer would have the resources to make an up-to-date aircraft with any performance level so desired.

Hence when Airbus, made up of a conglomeration of experienced aircraft manufacturers, introduced the A320, the product did not enter the market as a poor performance aircraft with low but just good enough technology as in a classic Disruptive Innovation case. The A320 came with a larger passenger capacity than the then latest B737 model and could fly faster, higher and with better fuel efficiency than the B737. Hence it was not a low priced low performance new entrant.

The performance attribute or measure is the key. If a firm can change the customer's performance measures significantly, it is being innovative in a disruptive way. This different performance measure can be viewed in the context of the customer's operating environment, and significantly it can be cause by just one or more components of the product that has changed.

For example, to keep major existing customers of the 737 such as Southwest Airlines, Boeing offered with the New Generation B737s an electronic glass cockpit that could be easily reconfigured with a new or old display format. This greatly simplified training needs for airlines transitioning between new and old generation aircraft and was an advantage that Airbus could not emulate despite its new technology cockpit.

In the case of Airbus this could only be done if they could offer cockpit commonality with a competitor's proprietary cockpit, but even then it would clash in mechanical configuration (e.g. joystick versus control wheel). Boeing on the other hand simply had to ensure future cockpits had similar configurations. Even the much newer B777 has fly-by-wire technology but has retained a control wheel so flight crew operating procedures to older aircraft are similar despite the more advanced electronics beneath the mechanical interface.

Hence companies can use Reverse Disruptive Innovation as a defensive strategy against new entrants. As the trick is to improve an existing older product, component technologies come into play. These component item or items can be combined with other product features to make a new environment for the customer where performance measures are valued differently from before.

Christensen et al (1998) noted that companies with new architectural innovations tend to enter new markets. In the B737 case Boeing developed several modifications, such as the gravel kit to allow the aircraft to fly into unprepared airstrips, integrated airstairs for operations at remote airfields, main deck cargo doors for freight or quick-change passenger/cargo conversions, and short field aerodynamic kits to improve take-off performance at short runways. All these modifications created markets that otherwise were not accessible to a conventional jet at the time. Notably the A320 does not have as wide a range of modifications as options.

When improving the measures of cruise speed, maximum cruising altitude, and fuel burn, Boeing only developed minimal performance margins to be just ahead of the competing Airbus products. This is in keeping with the "just good enough performance" theme of Disruptive Innovation.

Michael Porter notes that "the selection of specific technologies in the value chain on which to concentrate development effort is governed by the link between technological change and competitive advantage. A firm should concentrate on those technologies that have the greatest sustainable impact on cost or differentiation…" He also notes that "Technologies seem to go through a life cycle in which early major improvements give way to later incremental ones" and "a technology can only be assumed to be mature with great caution". Most importantly "most products and value activities embody not one technology but several technologies or sub-technologies. It is only a particular combination of sub-technologies that can be assumed to be mature, not individual technologies themselves. Significant changes in any one of the sub-technologies going into a product or process may create new possibilities for combining them that produce dramatic improvements …" (Porter, 1985).

Hence any framework such as the Disruptive Innovation cycle has to be viewed in this manner, particularly for complex products such as an aircraft type and its operating environment. For example an aircraft that uses a new technologically fuel efficient engine may have significant competitive advantage against another aircraft that does not, all other things being equal. But that situation could be easily reversed should the competing aircraft be fitted with an equivalent or better engine, or the price of fuel drops significantly.

A potential point of confusion is that in disruptive innovation, examples are often given where the incumbent firm concentrates on just improving their existing technologies and give up their lower end of the market to new entrants with different technologies that eventually catch up and supersede the incumbent's technologies (Bower and Christensen, 1996). This is not the case here, where Boeing was continuously and deliberately ensuring price-performance parity or even superiority against the competition by modifying the "old" model in critical areas of the design.

With the B737, Boeing was very careful in each generation to improve only the parts that required upgrading such as the wings and engines. Parts that had little impact on the performance of the product were left alone and even whole sub-assemblies (such as the main deck cargo door from the B727) were imported as modules from other product lines.

Notably it did not incorporate fly-by-wire or FBW despite its competitor the A320 having such a feature, although it was fully capable of doing so having done so on its B777 aircraft. The FBW feature could be seen as one where the performance was more than what the customer wanted – as Southwest Airlines asked to maintain the older flight control cable system for simplicity.

It can be seen that in the case of the Boeing 737, existing products and technology were simply adjusted (through variants, families, derivatives, and other existing technologies) and adapted to create a better product. Although some technology change is inevitably involved, the redefining of an existing product and how it was provided to the customer was the emphasis.

Danneels (2004) says "A disruptive technology is a technology that changes the bases of competition by changing the performance metrics along which firms compete. Customer needs drive customers to seek certain benefits in the products they use and form the basis for customer choices between competing products. . . Customer needs determine which performance dimensions form relevant bases of competition - i.e., differentiate meaningfully between competing offerings. At any given time, a particular technology has performance constraints, which limit the current product attribute set."

Bower and Christensen (1995) note that companies often play a strategy of "second to invent" by letting other companies do the initial pioneering into uncharted territory. Then with the valuable lessons learnt they develop a more "mature" product faster. Certainly without the A320, Boeing would not have had a yardstick to measure how much more performance to put into the next generation of the B737. In a CoPS environment this can mean millions of dollars savings by knowing just how much development is required.

5.4. Performance

A remarkable aspect of aircraft design complexity is that a modification of one feature will often impact the performance of other features. For example installing a new in-flight entertainment system to attract more customers may add weight which in turn drives fuel consumption up and for long range missions could also restrict the number of passengers to be boarded, which in turn can defeat the purpose of the original objective.

However the reverse is also true. If a wing design is tweaked to improve fuel burn to minimize operating costs, the reduced fuel burn can also mean that the operator can carry more passengers or cargo, or fly longer range missions and hence open up new markets previously out of reach.

What is discussed are in effect product attributes (e.g., speed, price, reliability, capacity) that can be used as vectors to measure a product's performance (Krishnan and Ulrich, 2001). While these type of attributes may be difficult to use in terms such as aesthetics (beautiful, ugly, colours), they are certainly useful in terms of CoPS type products that have to deliver a high degree of functionality and ultimately profit to the end user.

For commercial jet aircraft, the four obvious attributes would be payload (passenger/freight or cargo) capacity, range (distance the airplane can fly with a full payload), speed (which is the main point of using airplanes rather than other forms of transportation), and operating cost. In recent years the latter is driven largely by fuel burn especially with the ever increasing costs of oil.

Holloway (1998a) quotes “Whilst range is likely to be an important battleground fought over by the B777, A330 and A340 (all large wide body aircraft) in particular, it is certainly not irrelevant as regards much smaller types. The transcontinental capability of the 737-600/-700/-800 family is opening thin US domestic point-to-point markets that cannot support the larger aircraft which have until recently been the only alternatives possessing this type of range at full payloads. Possible demand for aircraft capable of exploiting niche transatlantic and intra-Asian hub-bypass markets was behind the consideration Boeing began giving in the mid-90s to an “ER” (Extended Range) version of the B737-700, able to carry around 95 passengers over 4,000 nautical miles (7,408 kilometers) in two-class configuration.”

A new version of the aircraft always had what could be called a strong Customer Value Proposition or CVP as illustrated by Johnson, Christensen and Kagermann (2008). By doing so the value of the improved aircraft model could easily be quantified irrespective of the aircraft’s original configuration age. This in turn drove the flavour of the innovative impetus at Boeing. “Making highly differential products with strong cost advantages is a license to print money, and lots of it” (Christensen and Raynor, 2003).

For example with a large number of B737s already in service with a large number of customers, cost saving through commonality and familiarity with the existing product would be given an important decision factor for customers of a continuously improving B737.

As we have seen, Boeing in the Next Generation B737s provided glass cockpits that could be electronically configured to show latest or former digital cockpit display formats to allow easy integration with the older models. Combined with other features such as new interior cabins and improved aerodynamics, Boeing's product improvements had the ability to constantly change the impact on the customers' business models.

With Reverse Disruptive Innovation, the older product can be improved incrementally to better the features that have the most value to the customer, and in doing so place the new entrant with the product that has performance that can then be seen as overshooting the customer's needs. Better still by using a Customer Value Proposition, the older player despite having spent less on improving an existing product, can price equivalently to a newer product by showing value satisfaction and hence reap higher margins, or be able to discount more in a price war.

As we have seen on the B737 series of aircraft, one of the easiest ways to differentiate an aircraft is to stretch or shrink the fuselage which is mostly of constant cross-section dimensions, while keeping the rest of the aircraft the same. Hence the wings and engines, cockpit and nose, empennage and tail, and landing gear have typically high commonality between different models of an aircraft family. High commonality means lower developments costs but also easier operability for the operator in terms of training and spare parts inventory.

The trade off is that the performance contributing parts such as the wings and engines may be de-optimized for the shrunk or stretched models. For example the wings and engines would be larger and heavier than necessary for a shrunk model and vice versa for a stretched model.

However a larger than necessary wing and engines means the shrunk and lighter aircraft would have better performance in terms of range and this can be a marketing advantage. For the larger aircraft, the converse in performance will occur as range drops off with a heavier aircraft, but the increased capacity fuselage in turn becomes the positive marketing tool for operators seeking high capacity for short range missions.

The figure below illustrates this, though the comparisons between Boeing and Airbus aircraft should not be taken as validated as these charts were sourced from Boeing. Undoubtedly a similar chart from Airbus could show the converse.

The smallest aircraft models (B737-600/A318) ranges are artificially lowered due to artificially lowered certificated maximum take-off weights to save on airport charges. However the next three larger models for both Airbus and Boeing illustrate the reducing ranges with increased capacities. The one-class seating chart is typical of a low cost carrier, whereas the two-class is for a traditional type carrier.

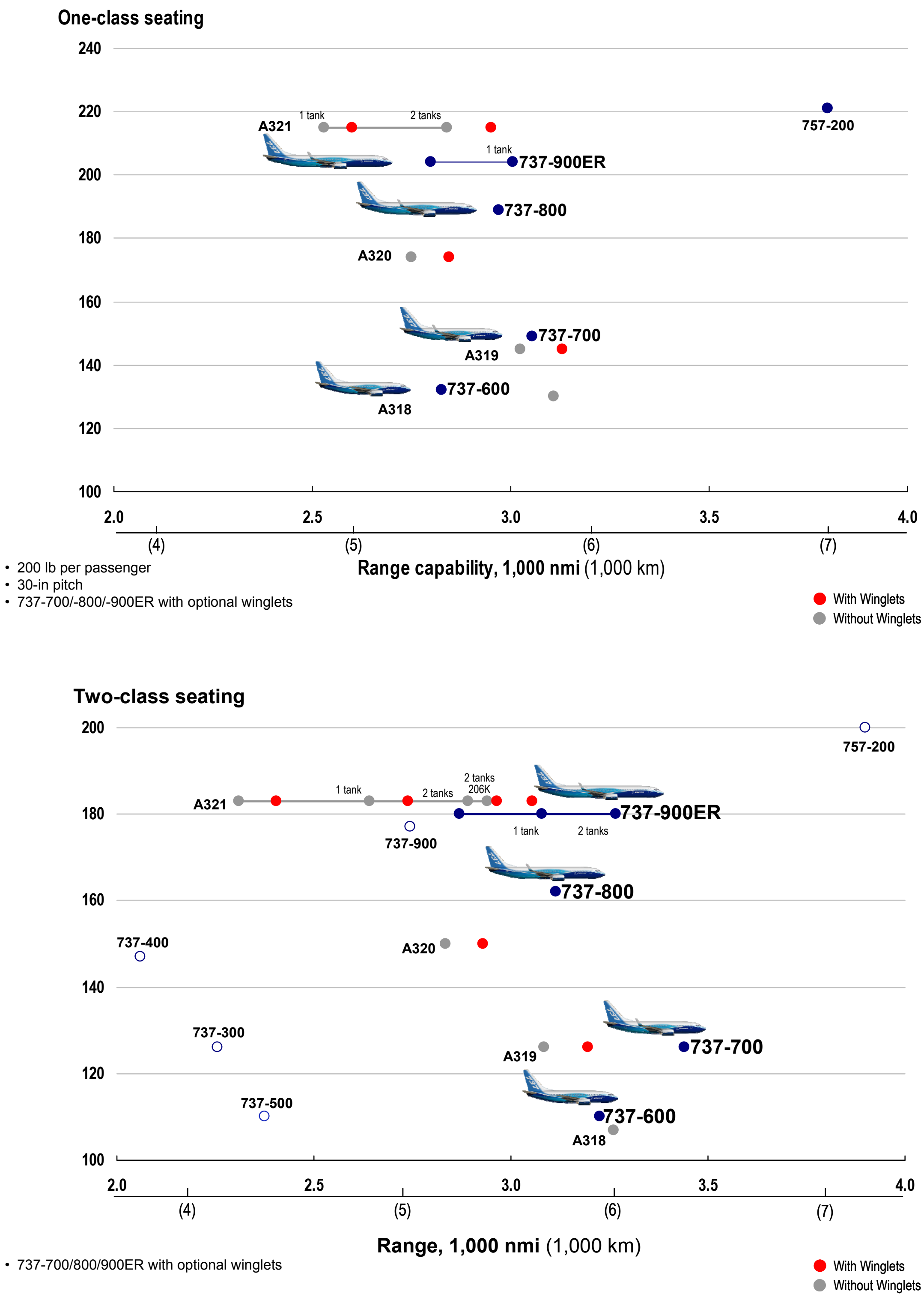


Figure 5.9

B737 Range Capability

(Adamson 2010)

Note that the charts become complex when we consider that the use of auxiliary fuel tanks becomes more common with the larger models (B737-900ER or A321) due to the drop-off in performance with the increased operating weights. However in the older Classic Generation, the B737-400, B737-300, and B737-500 models show a direct transverse correlation between capacity size and range.

Significantly we also see that the capacities of the larger B737-900ER and A321 are quite close to the B757, albeit with less range capability. However if the operator does not require the range capability of the B757, then the smaller B737-900ERs and A321s become very attractive options with the corresponding lower operating costs.

One thing that may occur is that if an incumbent is focused on competing with an entrant but the improved product develops a higher performance able to displace the next product line, this also means the product will be more and more optimized for that next product line's market segment. In retrospect, that also means the product becomes less optimized for its original market segment. This then makes it vulnerable to competition from new entrants in that segment and a classic Disruptive Innovation cycle can occur.

We see this in the figure below where the successive generations have tended to get larger and larger physically in dimensions (including wingspan) as well as operating weights. If we recall the original B737-200 continued selling well for many years despite the availability of the B737-300 with new CFM56 engines until noise regulations curtailed its sales.

The original B737-200 had an operating empty weight of about 60,000 lbs. Its subsequent replacements, the B737-500 and B737-600 had operating empty weights in the order of about 69,000 lbs and 80,000 lbs respectively (737 Airplane Characteristics Airport Planning, Boeing 2005). Hence if the operator did not need the range of a B737-600, it was stuck with an increase of approximately some 10,000 to 20,000 lbs of unnecessary weight compared to the original B737-200.

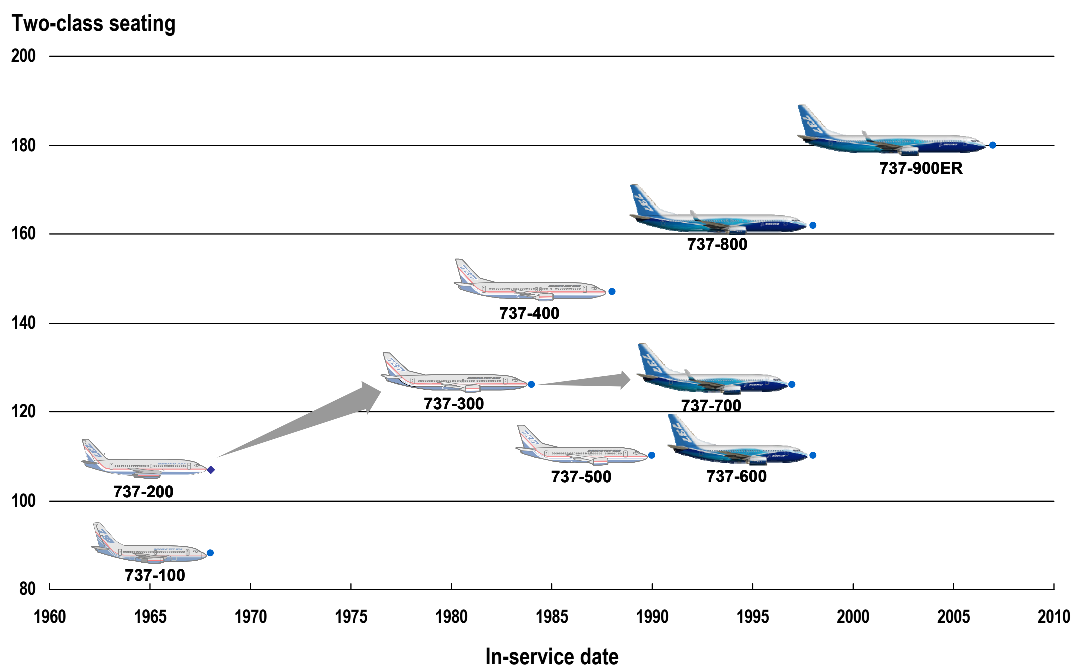


Figure 5.10

B737 Families Seating Capacities

(Adamson, 2010)

The costs of these trade-offs in weight and performance are best shown on a "fan" chart as shown below. Again this data is sourced from Boeing so comparisons against the

Airbus products are not necessarily validated. However it is sufficient to illustrate the trade-off between relative seat-mile costs versus relative trip mile costs.

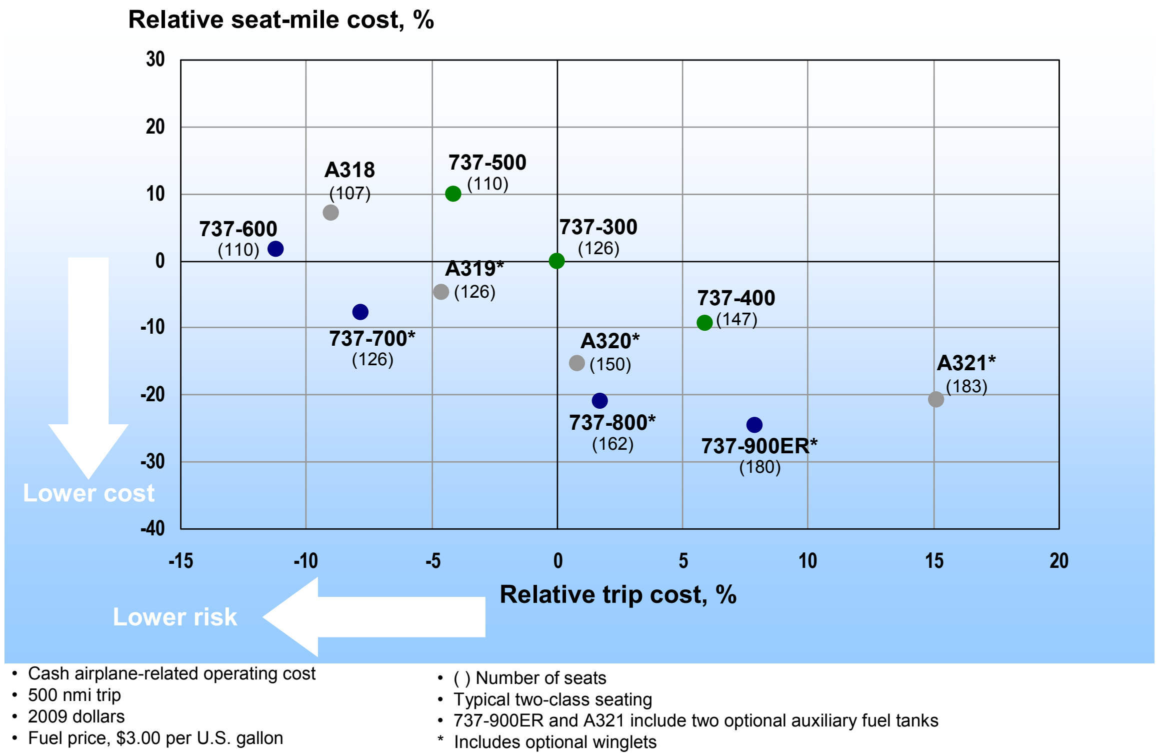


Figure 5.11

Relative Seat-Mile Costs versus Relative Trip Mile Costs

(Adamson, 2010)

To read this chart, the B737-300 is used as the reference point. Relative to this reference point hence, the B737-400 is about 10% better in terms of seat-mile costs, as it carries more passengers, but it is say 6% worse in trip costs as it burns more fuel for the same mission. The B737-500 on the other hand has higher seat mile costs as a result of carrying fewer passengers, but has 4% less trip costs as it burns less fuel for the mission.

The mission in this case is a 500 nautical mile (926 kilometers) trip so it is just one chart of many that could be developed for any individual operator's unique network.

Hence we can see that it depends on the operator's network as to which aircraft model is optimal. A route requiring less capacity and more range would favour the smaller aircraft and vice versa.

As both B737 and A320 families offer a range of capabilities, both manufacturers thus offer differentiated products to meet different market segments, but with essentially the same product platform offering the benefits of commonality. A large operator with varying route networks could select more than one model to fit but enjoy the ease of using the same operating flight and cabin crew as well as common maintenance requirements.

While it may be unfair to compare the Airbus product line here, it becomes obvious that the two generations of B737s shown (B737-300/-400/-500 & B737-600/-700/-800/-900ER) show distinct banana-like patterns for each family, and these banana shapes move towards the bottom left with the newer generation having improved efficiency in both seat-mile and trip-mile costs. The general optimal aircraft models hence tend to be the centre-of-banana models (B737-300 or B737-700/-800) in terms of design efficiency. For the Airbus the optimally designed models would be the A319/A320.

With the B737 and A320, the latest versions smallest size models in the family product line are the B737-600 and A318 respectively. As a consequence of being heavy, both these models have sold poorly and are now subject to encroachment by the top line smaller manufacturers such as Bombardier and Embraer. In fact Bombardier's current development product will be their largest aircraft yet, the "C-Series" and this will compete directly in the original B737-100/-200 one-hundred plus seat passenger airplane market.

5.5. Product Platform

Notably the B737 series of aircraft did not start as a product platform of its own, being instead just a part of the B707 and B727 aircraft "family" which were also quite different in configuration despite having common parts. The original B737-100 and B737-200 models were developed concurrently due to customer demands but never really marketed as a family.

It was only in the Classic Generation where Boeing really began making the B737 a product platform, but only because it was nudged to by competition (to stretch the B737-300 into the B737-400 to compete against the Airbus A320) and later to find a replacement for the obsolete B737-200 (by shrinking the B737-300 into the B737-500). The Next Generation B737 family of models was just the first time that Boeing actually intentionally developed as a product family, where all the initial three models (B737-600, B737-700, and B737-800) were test flown and certificated together.

Hence should a company developing, particularly a CoPS type product, straightaway establish a product platform and develop simultaneously different variants of the basic model? Simultaneous development is common nowadays being a feature of the Embraer E-jet family of E170, E175, E190, and E195; the Bombardier C-Series family of CS100 and CS130; and even lately the Chinese Comac C919 being developed in three sizes to compete directly against the B737 and A320 families with entry into service planned for 2016. The C919 is designed as a product platform with three more versions to follow for use as executive jet, freighter, and military emulating the B737 family history (Ostrower, 2010).

One could argue that while it is a noble intention, a missing factor is the timescale for evolution. Simply speaking while it would be great for multiple variants to be using a common product platform, simultaneous development means the platform itself has no time to iterate and improve.

For example the first glass cockpits featuring electronic displays to appear in the Classic Generation of B737s did not appear on the first model (B737-300). They first appeared in the later B737-400 and were later optioned on the other variants. The Boeing Business Jet (BBJ) and P-8 Poseidon variants mixed the fuselages of smaller models with stronger wings of larger models.

While it is fortunate for Boeing that many later improvements such as carbon brakes and winglets could be retrofitted on earlier models prior to their introductions, it can be seen that Boeing was constantly improving the products and developing new variants based on new knowledge and experience from across its entire product line.

Hence this is a potential disadvantage of simultaneous variant family development. Even on the first B737-100 and B737-200 generation, the latest B737-200 Advanced model had so much significant changes from the earlier B737-100, such that Boeing no longer produced the B737-100. This is not unlike the Bombardier series of CRJ passenger regional jets that spanned from the CRJ100, through the CRJ200, CRJ700, CRJ900, and lately the CRJ1000. The CRJ700 and later models of the CRJ900 in particular incorporated many performance improvements that were not available on the earlier CRJ100s or CRJ200s.

Hence a strategy could be to space out the time between developments of different variants to allow time for improvements that come in time. Boeing has done this in fact on the B787 in deliberation, spacing years between developments of different variants, particularly because the B787 incorporates considerable new technologies such as a composite material airframe.

An evolving type product platform and architecture would appear the preferred way to go, particularly for a CoPS type product which can be complex in nature. Incremental changes to the platform as we saw on the B737 evolve the product and keep it up to date.

When significant changes are required such as improved cruising speed and altitude for the B737, changes are deliberately made to major components such as the B737 wings.

The B737 wings are components that would be labeled as ‘‘carry over-modified’’ by Suh et al (2007). These are components that are similar to previous design existing components, but not exactly the same. However the development of the new design is based on the prior design. In both the Classic and the Next Generation B737 families, the wing was a modification of the earlier design. In the Classic it was mostly just an increase of wingspan to increase wing area for more lift. In the Next Generation mainly just the rear wing spar and associated high lift devices (spoilers, flaps) were retained.

It might be convenient to think of the wing itself as a sub-product with the rear wing spar as the product platform. However this was not intended by Boeing when it built the first B737. The more appropriate description would be evolving product architecture. By modifying the wing thus for the Next Generation B737, Boeing kept the wing design, and correspondingly the product platform, up to date in terms of cruise speed and altitude yet maintaining the advantages of the proven high lift devices.

As per Krishnan and Gupta (2001), the low end variants in a product platform family may be disadvantaged by having parts common to the product platform that are overdesigned for the high end. Notably the smallest models of both Boeing and Airbus in the B737-600 and the A318 tend to be heavier than desired due to their heritage of being a variant of a larger basic model. The temptation during development would be to minimize cost by using the same components as in the larger variants and instead just market the advantages of commonality to the customer.

On the B737, even interchangeable components exist such as the landing gears where operators have the choice to fit a standard but heavier landing gear able to meet the requirements of different models to maximize commonality, or optimized landing gears for each model to maximize performance where commonality is less of a requirement.

The B737 case is complex enough to cater for different type market and performance segments since its markets are spread across a spectrum of “standard” commercial passenger jets, somewhat sub-standard freighter (cargo) jets, and specifically customized executive business jets or military applications. And as we have seen, Boeing liberally transposed sub-systems across not just the B737 family but also from outside that product line. Hence the complexity of CoPS can be taken advantage of in a strategy to maintain a competitive product line with time.

6. Discussion & Strategy Formulation

6.1. An Emergent Strategy

It can be observed that a pattern of utilizing the platform concept and developing the B737 to maintain competitiveness seems to emerge. The analysis indicates that this pattern may not actually have been deliberate nor was it a long term strategy from the outset. However from the outset even the first models of the B737 were borrowing component designs such as the fuselage cross-section from other existing models in the Boeing product family with the intention to save on research and development costs.

Many of these "restrictions" in the long term in fact became advantages for the product in the long term as the commonality and platform benefits to the customer were realized. These benefits both in research and development costs as well as to the customer were recognized by Boeing and applied consistently to become almost as a culture (as can be seen in much of the marketing material). In the case of the B737, many of the developments were spurred by competition especially after the A320 and its subsequent variants entered the market. The interesting part is that after the first round of developments (the B737-300), Boeing continued in a similar pattern of model improvements for later versions and generations of the B737. Albeit perhaps the actions by Boeing were reactionary, but the repeated patterns seem to suggest an emergent strategy that eventually becomes part of the company culture particularly with the B737NG.

6.2. *Negative Considerations*

Before formulating a CoPS innovation strategy for commercial product success and longevity, some of the potential negative aspects should be understood. This is particularly so if the organization is weighing up a decision between developing an all new product or following a strategy for development of an existing product in a similar way to Boeing.

- Firstly while the successive B737 generations of families can be considered a success, at best it only maintains parity with its competitor the A320 family. Prior to this it was a market leader. Airbus's aggressiveness to establish itself could mean that this might have been a deliberate strategy by Boeing which could have simply accepted it was sufficient to maintain just a significant portion of market sales instead of putting too much design effort and resources to gain full product superiority.

- Secondly a product platform strategy can mean somewhat of a design lock-down and rigidity in the bandwidth of that product family, and accepting some degree of optimization loss in extreme ends of the family, particularly at the low end. The B737 story might be deemed ultimately successful but what if for example Boeing had continued with the use of the B727 as a product platform by not recognizing the limitations and disadvantages of that design? With hindsight it is easy to see but perhaps not so in the spur of the moment.

McDonnell Douglas had limited success by stretching a rear engine mounted 5-abreast fuselage design from the DC9 to the MD80/90 series and then the B717. It too enjoyed a loyal customer following but ultimately lost the battle to Boeing and Airbus as the MD90 re-engine was not commercially successful. The B717 which was quite a lower end capacity model also lost sales to regional jets such as the Embraer and Bombardier products which were optimized for that end of the market.

Knowing when to switch product architecture would depend on the experience and ability of the company to forecast obsolescence towards making the right judgment. Too high or low a rate of change in product platform with correspondingly low or high numbers of derivative products developed can also impact firm performance (Jones, 1993). This type of judgment is not easy to define clearly and could perhaps be the subject of further study.

- On the B737 Boeing enjoyed the ability of adopting technologies and designs from its other newer product lines such as adopting the Main Deck Cargo Door from the B727 or the Flight Management System from the B757. These components in turn enjoyed longer production runs than had they been on only one product line. However not all companies have multiple product lines.

  Such innovations could be sourced from the outside but it would be probably more difficult to perform tasks such as adapting "carry over-modified" parts. Hence in the absence of this kind of facility, the strategy may not be appropriate, or the company may wish to reconsider if it should even be taking on such a challenge.

- A rejuvenated product may still suffer the stigma of being an "old" product. With aircraft, travelling public may not be aware that the model they have bought a ticket may be the latest and greatest derivative ever developed and could still think that it is an outdated (and perhaps less modern and safe) product simply by the model designation.

- Related to the above point, there is also an inherent danger of either losing the advantage of commonality or attain such a perception. The DC-9/MD80/MD90/B717 series all shared a somewhat common platform but discontinuity by the model numbers occurred (DC-9 to MD80/90, and MD80/90 to B717) particularly on the limited production B717 which was actually the MD-95, re-named as Boeing merged with McDonnell Douglas.

- The robustness of a product platform has been mentioned several times. But high dependency on a singular platform can also be a risk. What if after several variants have been developed a significant flaw is discovered in the product platform which affects safety, operation, and/or ultimately sales? By virtue of having a common platform, the entire product family would suffer the same flaw discovery accordingly which could be a significant financial risk to the manufacturer and operator.

The flaw might not even be a technical but one that is suddenly perceived to be undesirable by the customers. Again it would help to be like Boeing which enjoys the sales of various differentiated product lines but for a new market entrant with perhaps just one product family as its investment bet, the risk is very real.

- Continuously upgrading the performance of product platforms and hence generations could mean an encroachment up-market that could endanger the economic viability of other product lines in the upper end (such as the B737 versus the B757).

6.3. *Review of Research Questions*

In light of the prior sections a review of the key research questions posed at the beginning of the study is as follows.

- How could Boeing's strategy with the B737 be replicated for other companies and products?

  <u>Answer:</u>

  It is not possible to consider all potential scenarios but undoubtedly the many advantages of such a strategy would mean at least some parts if not all could be considered seriously by other companies. The case histories of the Ford Model T and Sony Walkmans are proof that it can be done in other scenarios. The Sony Walkman had a successful generation upgrade when it went from magnetic tape cassette technology to compact disc technology. The strategy described in section 5.1 is derived from the findings of the B737 study and is proposed as a generic one that could be employed. The big obvious advantage is that companies would not have to always re-invent a new product and new variants or derivatives can be marketed as somewhat new products but at a faster rate. Brought over components from the platform or original product can also offer product familiarity and reliability.

- Did Boeing employ a strategy to improve the B737s longevity in terms of competition and if so how did it do it? Was it by developing a family or families of models in terms of product platforms, variants of basic models, platform derivatives?

  Answer:

  Significantly the strategy as such was not deliberate in the Classic B737 generation but more as a reaction to defer product replacement (the 7J7 product that never materialized) and the entrance of the Airbus A320 competitor. Hence what followed in essence created an emergent strategy that Boeing appeared to follow up until present day. The answer to the second question is obviously yes to all.

- Was the competitive edge of the B737 maintained by radical or incremental innovations to its design?

  Answer:

  It would seem that most of the innovations were somewhat incremental. The B737 enjoyed and continues to enjoy continuous improvement by Boeing. Variant development design changes were mostly sustaining in nature such as varying the fuselage lengths. Perhaps the most radical part of the histories involve the evolutions of the product platforms, particularly the use of “carry over-modified” parts adapted from previous designs (such as the wing) to update the design’s performance. The overall product architecture however was maintained throughout all generations and hence such changes could alternatively arguably be defined as incremental.

- What were the downsides if any of its strategy? For example in its quest to maintain competitiveness and improve product performance, did it lose efficiency in certain market segments? For the same reason were other product lines in Boeing's product lines affected?

  <u>Answer:</u>

  The potential negative sides of such a strategy are listed in the previous section. But yes, Boeing did lose efficiency at the low end of the market as its Basic Model sweet spots were pushed further and further up-market to carry more payload over greater distances. As a result the smallest variants (B737-500, B737-600) of later generations were significantly overweight compared to the original model (B737-200) they were supposed to replace. Ironically the improved efficiency in the higher end of the market made models in that market such as the B757 comparatively and competitively less efficient.

- Was the lineage of the B737 an advantage or disadvantage? It may for example be that the infrastructure required to support the aircraft was common to successive generations and hence the user would save on training, tooling, and spare parts costs on a somewhat familiar product. Technology implications however could mean that one could be stuck with obsolete technology.

Answer:

One can only guess what would have happened if Boeing had developed an all-new design versus upgrading the B737 product line continuously. But with the decision to keep the model series, the lineage was undoubtedly an advantage when it came to competing but mainly because of existing large fleets of prior models with existing customers. By deliberate engineering (such as to incorporate the CFM56 engine onto the B737-300 without affecting the wing or landing gear significantly) to maintain high commonality of the concept as well as spare parts and operating practices, Boeing made the lineage a marketing advantage against the new competition that could not compete similarly without an existing customer base.

However that advantage has a time factor once the competition achieves significant sales as the A320 family also now enjoys similar advantages when sales campaigns are made for existing operators of the A320 family. In time, the A320 will have the same problem as previous generations of the B737. In facing eventual obsolescence Airbus has since decided to re-engine the A320 (Reals, 2010), and Boeing in turn is also doing a re-engine design of the B737 (Ostrower, 2011).

.4. *An Innovation Strategy for CoPS*

Following the case study analysis, a five step generic strategy is proposed for managing the innovation process of CoPS type products to offer greater commercial success. This strategy is not proposed to cover every scenario as each scenario could be unique. But it is a proposal for a possible starting point and adjustments could be made as necessary.

- Take Advantage of Heritage

  Prior to starting any development, the concept and primary function of the CoPS product should be reviewed. What are the intended mechanisms to purport this function? It is poignant to consider Brian Arthur's suggestion that any technology tends to have a history behind them or prior technologies or designs.

  In reality should a company be tackling a CoPS product, it surely must already have some experience since it would not otherwise get such a contract or attempt such a challenge. Hence it should consider existing experience of designs and technologies that must surely be present in the company (such as incorporating B727 component designs into the B737). Smaller companies or those without other appropriate product lines to borrow from can also consider exploiting technological alliances with other firms (Rothaermel, 2001).

- <u>Employ Product Platforms</u>

  To improve the probability of commercial success, a product platform would be an obvious path to pursue. The Ford Model "T" example shows how the limited production rates of CoPS products can in fact be circumvented. The product platform offers a higher degree for high production rates and maximized use of design resources to create different variants and derivatives of the product. Preferably the platform should incorporate proven technology or designs such as was ably demonstrated by the Have Blue stealth fighter prototypes, but consider the bandwidth of market segments it is planned to support with family variants. To do this suitable and relevant product performance factors need to be carefully selected as metrics that are appropriate for the task of measuring performance as variants are sized up or down.

  The effective bandwidth(s) would determine the number of basic platforms and accordingly the number of related product families that are desired to be launched. A limiting bandwidth factor would be the acceptable degree of de-optimization that could occur at the low end variant of the family. Acceptability would depend on the probability of new entrance competition.

- <u>Plan Family Variants</u>

  Planning the entry of variants should consider the inevitable improvements that would come with time. CoPS products by nature are not easy to build projects and time lags usually exist. By deliberating spacing out variants, companies also reduce the risk factor as it would allow design refinement iteration of the first variants.

Preferably service experience should occur before tackling the next variant. This allows feedback from customers to enhance the robustness of the product platform (noting for example Boeing abandoned the B737-100 fairly quickly although it was developed at the same time as the B737-200).

Once a product platform is considered robust, special variants or modification kits could be considered for development to simply extend the reach of the product into new market segments (such as the B737 cargo versions, gravel kits for unpaved runways, or specialized military and executive versions). This increases the protection of the product line from new competition as small specialized market segments are probably not attractive enough for new entrants looking to establish investment returns with a decent market share but with initially few models to offer.

Each time a variant is developed, it offers a re-visit to the design of the product platform though changes would be expected to be incremental in nature. If possible such improvements can be retrofitted to previous variant models, in effect becoming part of the product platform. Constant review of other newer technologies or design from outside the product family would allow importation and incorporation of such features that could be marketed as new to the product line.

- Exploit Commonality

With variant development, once a significant number of sales or customers are achieved, commonalities becomes a higher criterion as the customers become familiar with the product line and get locked into spare parts, training, and operating procedures. Although it begins to become a constraint to further improvements, it also becomes a marketing advantage should competition appear with novel but yet unfamiliar designs.

The greater the degree of commonality a new design has with older designs, the greater the advantage. Beyond commonality with product variants and derivatives, commonality with other product lines is also an advantage for customers looking to reduce operating costs. As both Boeing and Airbus now attempt to do, even reducing training costs through commonality is a significant marketing advantage.

As seen with the AH-1Z/UH-1Y helicopter upgrade program, Bell is doing this actively in the design of the upgrade by designing in common major components despite the two helicopters having very different mission objectives. With a subsequent reduction in spares, support, and training requirements Bell has been successful in beating off newer designs.

- <u>Decide On The Next Generation</u>

  Particularly with the existence of competition, when customers may want even significantly better efficiencies or performance that is beyond the scope of the existing product platform, a new derivative or significant change of the product platform has to be considered with a corresponding new generation of product family or families.

  Though the potential here could be an all-new design, serious consideration should be given as to whether the existing platform can be adapted with "carry-over modified" components, components modified based on existing component designs. The cost savings versus an all-new design could be substantial, while the functionality of the original designs could be maintained (such as the rear wing spar or low landing gear of the B737). With customer input, care should be taken to improve or modify only as far as necessary to achieve the performance improvement or characteristics desired, but maintaining commonality as much as possible with the previous product generations.

  A new family generation offers greater scope for incorporating new technologies than a new variant development. However the original concept for the CoPS product should be reviewed. Engineering the changes for incorporation of the technologies should be masterly to maintain the concept and product architectures, if still valid, as much as possible (as in the CFM56 engine integration for the B737-300, or the configurable cockpit displays of the Next Generation B737).

And hence the cycle repeats. The latter points are factors contributing to the longevity of the product platform. While the B737 is still in production, one could theorize perhaps that not upgrading the product platform enough to a new generation could have been what ultimately killed the Ford Model T. But it also depends on the original design configuration and its adaptability to evolve.

Boeing chose not to continue with the B727 because its rear-engine mounted configuration was too difficult to re-engineer the incorporation of new high bypass turbofan jet engines. A company's combinative capability hence comes into play. Even though the B727 was not carried forward, many parts of it and design philosophies were extended into the B737 as well as its successor, the B757.

7. Conclusions

7.1. Summary of Findings

The case study of the Boeing 737 story shows that the traditional view of CoPS having limited innovation and low production rates can be negated by employing a strategy using product platforms. The B737 has enjoyed at least three generations of product families and multiple variants and derivatives including specialized executive or military applications.

By using product platforms, variants to create a wider reach of market segments can be developed as product families. Development of variants however should be spaced out to allow time for evolution and refinement of the product platform architecture and design and to reduce the risk to the company in the case of a product platform flaw. The product platforms themselves would enjoy greater production rates than independently developed products. Commonality also means customers attain the benefit of lower spare parts inventory requirements, and simplification of training and operating procedures.

Incorporation of technologies and designs from other product lines also mean those components enjoy production rates higher than if they were deployed on just one product line. The ability to do this depends on the combinative capabilities of the company.

These engineering capabilities also determine the company's expertise in upgrading the product platform to engineer "carry over-modified" parts adapted from existing component designs to improve product performance when so desired. Care must be taken to upgrade a CoPS type product to maximize commonality with previous designs and to upgrade only where necessary. Upgrading the product platform offers the ability to create new generations of product families to maintain product longevity.

Such a strategy could be used in a Reverse Disruptive Innovation way to defend against a new high performance entrant, reversing new entrant and incumbent roles compared to a traditional Disruptive Innovation case. By adapting existing product designs to be just good enough to satisfy the customer, the incumbent can compete against over-performance by the new entrant and save considerable development costs, using the already installed customer base as a commonality marketing advantage.

A danger of such a strategy, if successful, is that the product may improve in performance towards the up-market segment where it could threaten other product lines of the company. Going up-market also means that lower end variants of the product family could suffer loss of optimization as the product platform would feature parts to meet higher end segments but which would be over-kill for the lower end market. In this case more than one product platform could be a consideration to reduce de-optimization.

A five step generic CoPS strategy is proposed employing similar features as observed in the B737 case study. These include:

- Take Advantage of Heritage
- Employ Product Platforms
- Plan Family Variants
- Exploit Commonality
- Decide On The Next Generation

The strategy is further supported by arguments but notably proven in prior historical case examples of other successful products such as the Ford Model T car, Have Blue aircraft prototypes, and the Bell AH-1/UH-1 helicopters. To maintain product longevity, evolving product architecture would be a healthy option. Interestingly some of these findings appear to be being employed by the flight simulator community (where CoPS was originally conceived) where common software platforms are being utilized to simulate different aircraft types and electro-mechanical positioning devices and visual display systems can be interchanged or upgraded.

Perhaps the most important issue is that the findings and arguments contribute a new view of CoPS theory where we go from an observatory status in the literature to one where a product manager can feel empowered to improve innovation and production rates, reduce costs, and improve the potential to increase commercialization CoPS products. With the consideration of time, many mass consumer items today which are not considered as CoPS would have been categorized as CoPS in the past. The strategies proposed simply help to advance the rate of innovation to achieve a faster product life cycle where the CoPS product or at least components of it can be commoditized. In addition Reverse Disruption Innovation is a new concept that can be used in concert as a defensive strategy.

7.2. Limitations

Despite arguments in Chapter 3 that a single case study offers richness in context and narrative to build theory, a limitation of this case study is that it is just one case study. However to attempt increased validation if say the study was made of say three completely different types of CoPS products or systems in different type scenarios and the generic strategy tested on all three is perhaps not so simple as CoPS by definition is complex. Even when researching for other cases such as the Ford Model T, there is a longitudinal time-shift in those cases that may have unknown effects. By being complex scenarios, it is virtually impossible to cover every potential possibility that could affect the case study results such as Governmental interference or corruption in sales.

For example, deploying a strategy of product platforms means requiring a prior agreement to invest in more than one variant model of product. This may not be easily done if the project is for example a nuclear powerplant and financiers are only willing to support one construction example. This leads us back to the CoPS definition and probably the best that could be done is to deploy just parts of the generic strategy such as using pre-designed sub-assemblies to reduce uncertainties and risk.

An aeronautical vehicle such as the B737 airplane lends itself nicely to "performance" factors and variation design methods to meet market segments are already quite established using fuselage stretches or shrinks and/or engine changes. However with other CoPS products appropriate performance parameters may be more difficult to determine and vary using unknown design components. Almost a subject matter expert is needed to select the appropriate parameters if the subject is overly complex in nature.

7.3. Potential for Further Research

The generic strategy proposed assumes a strategy from start. However knowing when to finally cease developing yet another generation and start an all-new product line such as Boeing did by replacing the B757 with the B727 would be a difficult multi-disciplinary decision that is not unlike a chess game in the face of competition. Clarifying how these decisions should be made would be a rich study field for further research.

The use of "carry over-modified" parts to upgrade product platforms also offers an area to be further studied. In hindsight Boeing's decision to modify the B737 Next Generation wing but maintain use of the existing rear wing spar and associated high lift devices appears to be genius. A simple component could be easily justified but whole sub-assemblies offer complexity and risk, particularly if they have interdependencies with other sub-systems (such as hydraulic systems) or performance effects (such as aerodynamics).

Determining performance factors and measuring the degree of sub-optimization in lower market segment ends of CoPS systems would be interesting to further study. Instead of simply accepting sub-optimization, perhaps strategies could be employed to mitigate those effects, such as offering lower end modular components (such as the B737 landing gear) as options.

The B787 aircraft for example comes with a revolutionary designed engine pylon on which either a choice of General Electric or Rolls Royce manufactured engines can be mounted. While in this case both engines are of comparable size and thrust rating, why not use the interchangeable pylon to offer a completely smaller or larger engine to match the market segment's performance requirement?

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Appendices

Appendix A – Aircraft Specifications

CHARACTERISTICS	UNITS	MODEL 737-100		
MAX DESIGN TAXI WEIGHT	POUNDS	97,800	104,000	111,000
	KILOGRAMS	44,362	47,174	50,349
MAX DESIGN TAKEOFF WEIGHT	POUNDS	97,000	103,000	110,000
	KILOGRAMS	43,999	46,720	49,896
MAX DESIGN LANDING WEIGHT	POUNDS	89,700	98,000	99,000
	KILOGRAMS	40,688	44,453	44,906
MAX DESIGN ZERO FUEL WEIGHT	POUNDS	81,700	85,000	90,000
	KILOGRAMS	37,059	38,556	40,824
OPERATING EMPTY WEIGHT (1)	POUNDS	58,600	59,000	62,000
	KILOGRAMS	26,581	26,762	28,123
MAX STRUCTURAL PAYLOAD	POUNDS	23,100	26,000	28,000
	KILOGRAMS	10,478	11,794	12,701
SEATING CAPACITY (1)	TWO-CLASS	85: 12 FIRST CLASS AND 73 ECONOMY		
	ALL-ECONOMY	96 AT SIX ABREAST; FAA EXIT LIMIT: 124		
MAX CARGO VOLUME - LOWER DECK	CUBIC FEET	650	650	650
	CUBIC METERS	18.4	18.4	18.4
USABLE FUEL	US GALLONS	3,540	3,540	4,720
	LITERS	13,399	13,399	17,865
	POUNDS	23,718	23,718	31,624
	KILOGRAMS	10,758	10,758	14,345

NOTE: (1) OPERATING EMPTY WEIGHT FOR BASELINE MIXED CLASS CONFIGURATION. CONSULT WITH AIRLINE FOR SPECIFIC WEIGHTS AND CONFIGURATIONS.

(737 Airplane Characteristics for Airport Planning D6-58325-6, Boeing Commercial Airplane Company, 2005)

CHARACTERISTICS	UNITS	MODEL 737-200				
MAX DESIGN TAXI WEIGHT	POUNDS	100,800	104,000	110,000	111,000	116,000
	KILOGRAMS	45,723	47,174	49,896	50,349	52,617
MAX DESIGN TAKEOFF WEIGHT	POUNDS	100,000	103,000	109,000	110,000	115,500
	KILOGRAMS	45,360	46,720	49,442	49,896	52,390
MAX DESIGN LANDING WEIGHT	POUNDS	95,000	95,000	98,000	99,000	103,000
	KILOGRAMS	43,092	43,092	44,453	44,906	46,720
MAX DESIGN ZERO FUEL WEIGHT	POUNDS	85,000	85,000	88,000	92,000	95,000
	KILOGRAMS	38,556	38,556	39,917	41,731	43,092
OPERATING EMPTY WEIGHT (1)	POUNDS	59,900	60,900	60,800	61,800	59,800
	KILOGRAMS	27,170	27,624	27,579	28,032	27,125
MAX STRUCTURAL PAYLOAD	POUNDS	25,100	24,100	27,200	30,200	35,200
	KILOGRAMS	11,385	10,932	12,338	13,699	15,967
SEATING CAPACITY (1)	TWO-CLASS	97: 24 FIRST CLASS AND 73 ECONOMY				
	ALL-ECONOMY	90 AT FIVE ABREAST, OR 124 AT SIX ABREAST; FAA EXIT LIMIT: 136				
MAX CARGO VOLUME - LOWER DECK	CUBIC FEET	875	875	875	875	875
	CUBIC METERS	24.8	24.8	24.8	24.8	24.8
USABLE FUEL	US GALLONS	3,460	4,190	4,230	4,780	4,780
	LITERS	13,096	15,859	16,011	18,092	18,092
	POUNDS	23,182	28,073	28,341	32,026	32,026
	KILOGRAMS	10,515	12,734	12,855	14,527	14,527

NOTE: (1) OPERATING EMPTY WEIGHT FOR BASELINE MIXED CLASS CONFIGURATION. CONSULT WITH AIRLINE FOR SPECIFIC WEIGHTS AND CONFIGURATIONS.

(737 Airplane Characteristics for Airport Planning D6-58325-6, Boeing Commercial Airplane Company, 2005)

	737-300			737-400			737-500		
Maximum Gross Weight, Pounds (Kilograms)				Basic		HGW			
Taxi	125 000 (56 700)	to	140 000 (63 500)	139 999 (56 700)	to	150 500 (68 260)	116 000 (52 610)	to	134 000 (60 780)
Brake Release	124 500 (56 470)		139 500 (63 820)	139 500 (63 280)		150 000 (68 040)	115 500 (52 390)		133 500 (60 550)
Landing	114 000 (51 710)		116 600 (52 890)	121 000 (54 880)		124 000 (56 240)		110 000 (49 890)	
Zero Fuel	105 000 (47 620)		109 600 (49 710)	113 000 (51 250)		117 000 (53 070)		103 000 (46 720)	
Engines (Thrust, lb)									
Basic	CFM56-3C-1		(20 000)	CFM56-3C-1		(22 000)	CFM56-3C-1		(18 500)
Option	CFM56-3-B1		(20 000)	CFM56-3B-2		(22 000)	CFM56-3-B1		(18 500)
Option	CFM56-3B-2		(20 000)	CFM56-3C		(23 500)	CFM56-3-B1		(20 000)
Fuel capacity, U.S. Gallons (l)	5311 (20 105)	5811 (21995)	6311 (23 890)	5311 (20 105)	5811 (21995)	6311 (23 890)	5311 (20 105)	5811 (21995)	6311 (23 890)
Passengers									
Mixed Class		128			146			108	
All Tourist, 32-in Pitch		140			159			122	
All Tourist, 30-in Pitch		149			168			132	
Lower Hold Volume, ft3 (m3)	1068 (30.2)	904 (25.6)	783 (22.2)	1373 (38.9)	1213 (34.4)	1088 (30.8)	822 (23.3)	660 (18.7)	562 (15.9)
Speed Capacity									
Maximum Operating Airspeed, Knots (KCAS)				340					
Maximum Operating Mach Number				0.82					

(737-300/-400/-500 General Familiarization Manuals TDOC737-15. Boeing, July 2003)

	737-600		737-700		737-700C	737-800		737-900	
Maximum Gross Weight, Pounds (Kilograms)									
Taxi	124 500 to (56 473)	144 000 (65 318)	133 500 to (60 555)	153 500 (69 626)	171 500 (77 791)	156 000 to (70 762)	173 000 (60 780)	164 500 to (74 615)	174 700 (79 243)
Brake Release	124 000 (56 246)	143 500 (65 092)	133 000 (60 328)	153 000 (69 400)	171 000 (77 564)	155 500 (70 535)	172 500 (60 550)	164 000 (74 380)	174 200 (78 240)
Landing	120 500 (54 659)	120 500 (54 659)	128 000 (58 060)	128 000 (58 060)	134 000 (60 781)	144 000 (65 318)	144 000 (65 318)	146 300 (66 360)	146 300 (66 360)
Zero Fuel	113 500 (51 484)	113 500 (51 484)	120 500 (54 658)	120 500 (54 658)	126 000 (57 153)	136 000 (61 690)	136 000 (61 690)	138 300 (62 732)	138 300 (62 732)
Engine Thrust, lb									
Basic	CFM56-7B18	19 500	CFM56-7B20	20 600		CFM56-7B24	24 200	CFM56-7B24	24 200
Option	CFM56-7B20	20 600	CFM56-7B22	22 700		CFM56-7B26	26 400	CFM56-7B26	26 400
Option	CFM56-7B22	22 700	CFM56-7B24	24 200		CFM56-7B27	27 300	CFM56-7B27	27 300
Fuel capacity, U.S. Gallons (liters)	6878 (26033)		6878 (26033)			6878 (26033)		6878 (26033)	
Passengers									
Mixed Class	108		128			160		177	
All Tourist, 32-in Pitch	123		140			175		189	
All Tourist, 30-in Pitch	130		148			189		189	
Lower Hold Volume, ft3 (m3)	Fwd 257 (7.3) / Aft 488 (13.8) / Total 745 (21.1)		Fwd 386 (10.9) / Aft 596 (16.9) / Total 982 (27.8)			Fwd 667 (18.9) / Aft 899 (25.5) / Total 1566 (44.3)		Fwd 840 (23.8) / Aft 1012 (28.7) / Total 1852 (52.4)	
Speed Capacity					Service Ceiling	41 000 feet			
Maximum Operating Airspeed, Knots (KCAS)			340			12 497 meters			
Maximum Operating Mach Number			0.82						

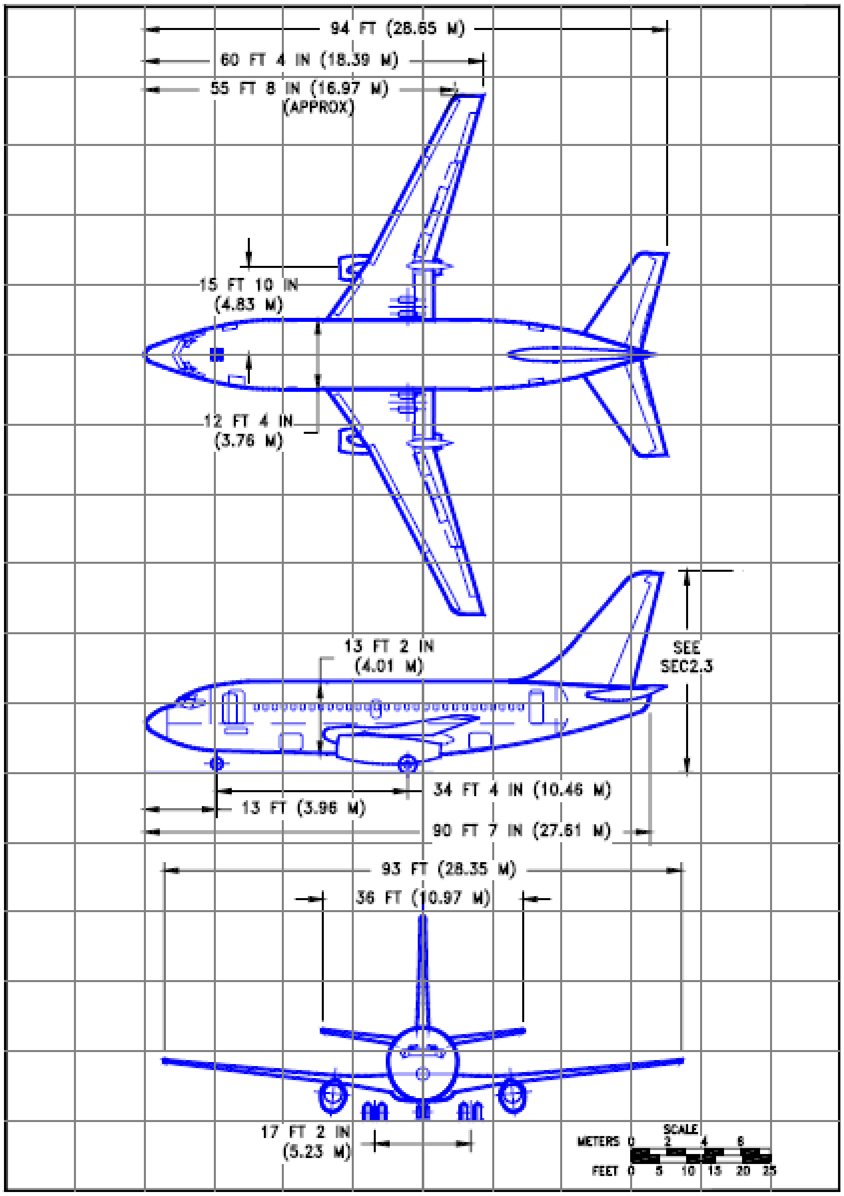
(737-600/-700/-800 General Familiarization Manuals TDOC737-16. Boeing, May 2003)

	757-200	757-2 Freighter	757-300
Overall Dimensions			
Length	155 ft 3 in	155 ft 3 in	178 ft 7 in
Height	44 ft 6 in	44 ft 6 in	44 ft 6 in
Tread	24 ft 0 in	24 ft 0 in	24 ft 0 in
Wheel Base	60 ft 0 in	60 ft 0 in	73 ft 4 in
Wing			
Span	124 ft 10 in	124 ft 10 in	124 ft 10 in
Area	1,951 sq ft	1,951 sq ft	1,951 sq ft
Sweep	25 deg	25 deg	25 deg
Engines, sea level static thrust			
Rolls-Royce			
RB211-535E4	40,100 lb	40,100 lb	40,100 lb
RB211-535E4-B	43,100 lb	43,100 lb	43,100 lb
Pratt & Whitney			
PW2037	38,200 lb	38,200 lb	41,700 lb
PW2040	41,700 lb	41,700 lb	43,850 lb
PW2043	— — —	— — —	43,850 lb
Fuel Capacity	11,278 USG	11,278 USG	11,490 USG
Design Weights			
Maximum Taxi	(1) 256,000 lb	(1) 256,000 lb	271,000 lb
Maximum Taxi	(1) 255,000 lb	(1) 255,000 lb	270,000 lb
Maximum Landing	210,000 lb	210,000 lb	224,000 lb
Maximum Zero Fuel	(1) 188,000 lb	188,000 lb	210,000 lb
Bulk Cargo Volume (Fwd & Aft)	1,790 Cubic ft	(2) 1,830 Cubic ft	2,382 Cubic ft

(1) These values may vary with configuration
(2) Total Freighter Vol.= 8,430 Cubic ft.

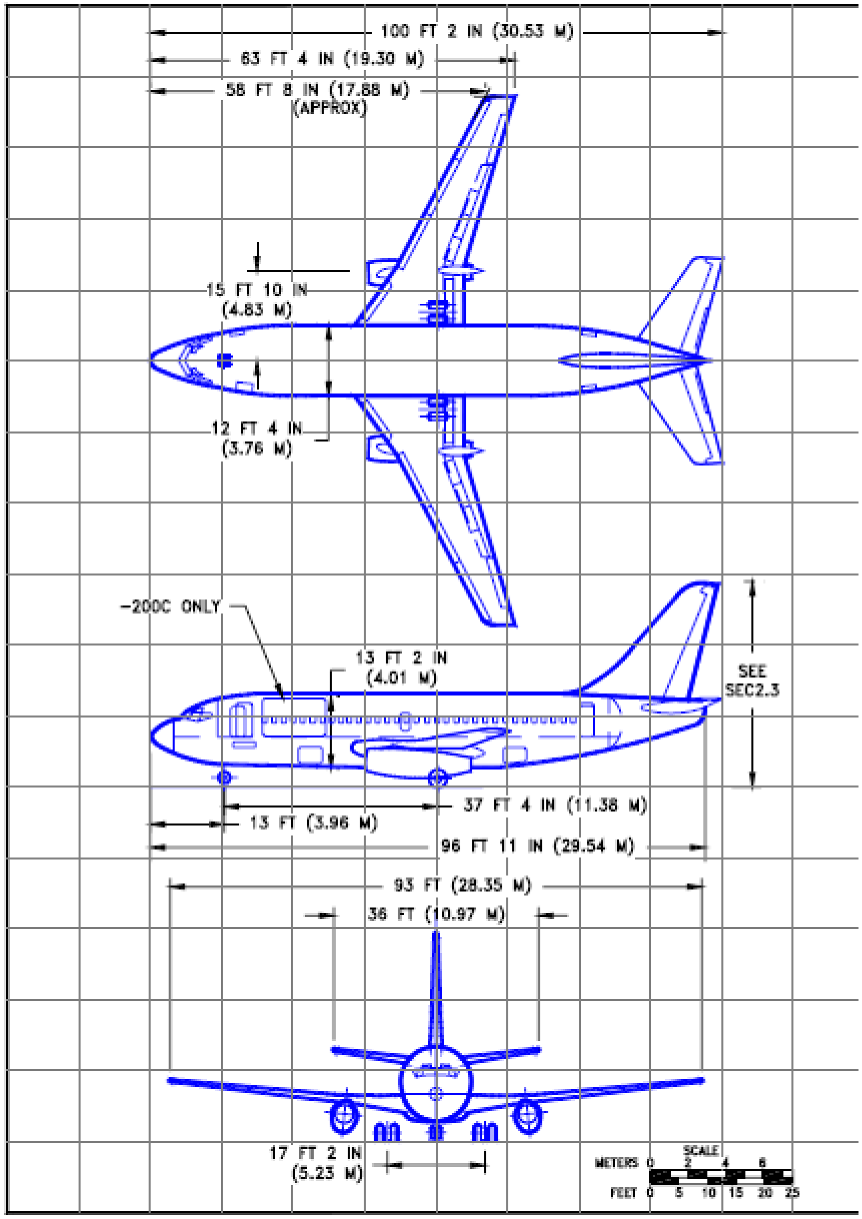
(757 General Familiarization Manuals TDOC757-03. Boeing, July 2003)

Appendix B – Aircraft Dimensions



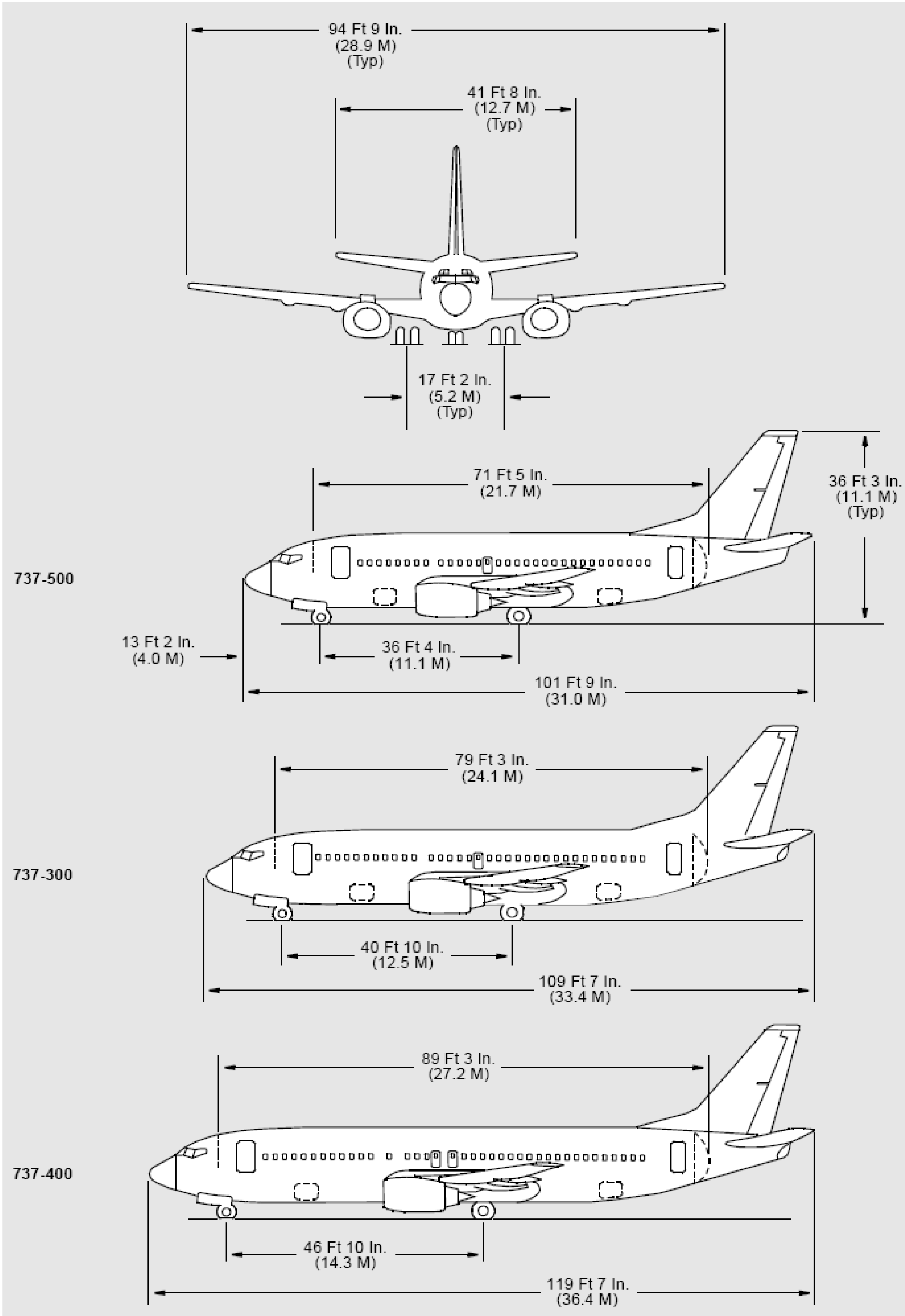
B737-100

(737 Airplane Characteristics for Airport Planning D6-58325-6, Boeing Commercial Airplane Company, 2005)

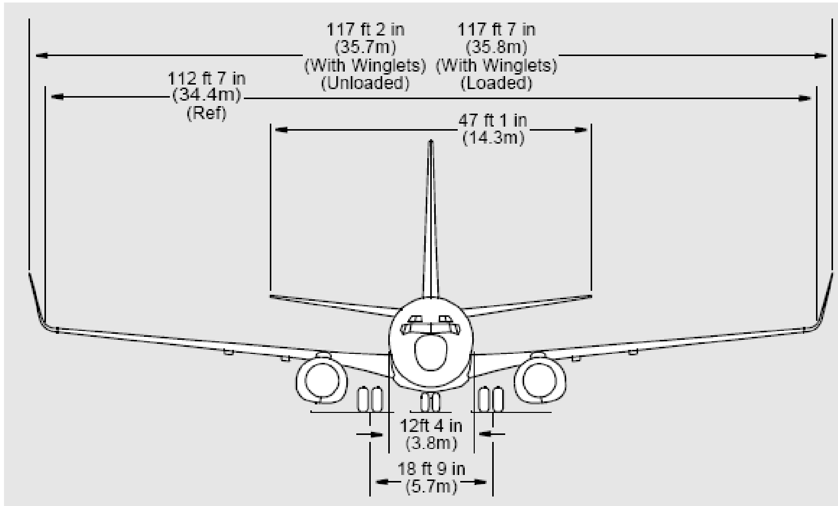


B737-200

(737 Airplane Characteristics for Airport Planning D6-58325-6, Boeing Commercial Airplane Company, 2005)

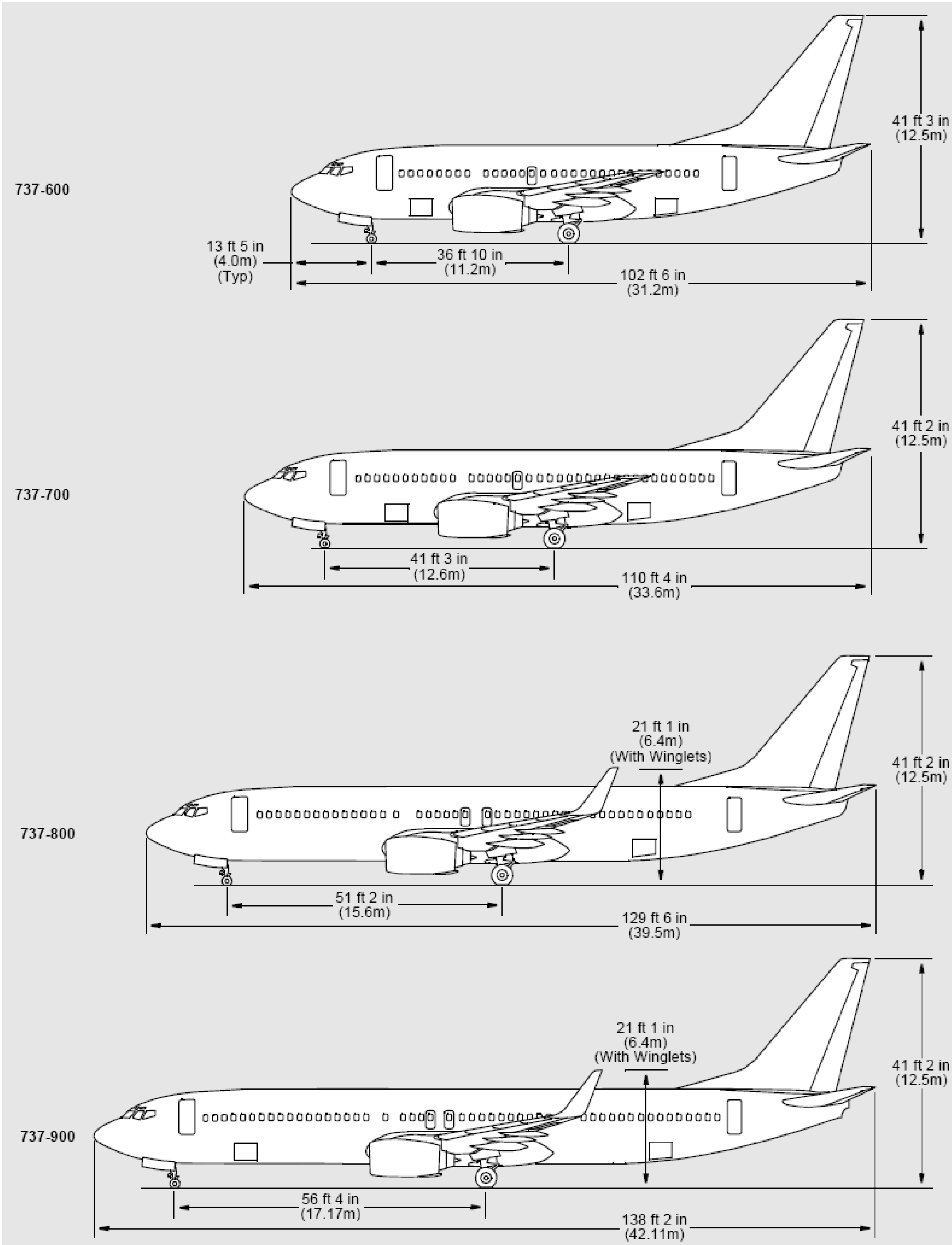


(737-300/-400/-500 General Familiarization Manuals TDOC737-15. Boeing, July 2003)

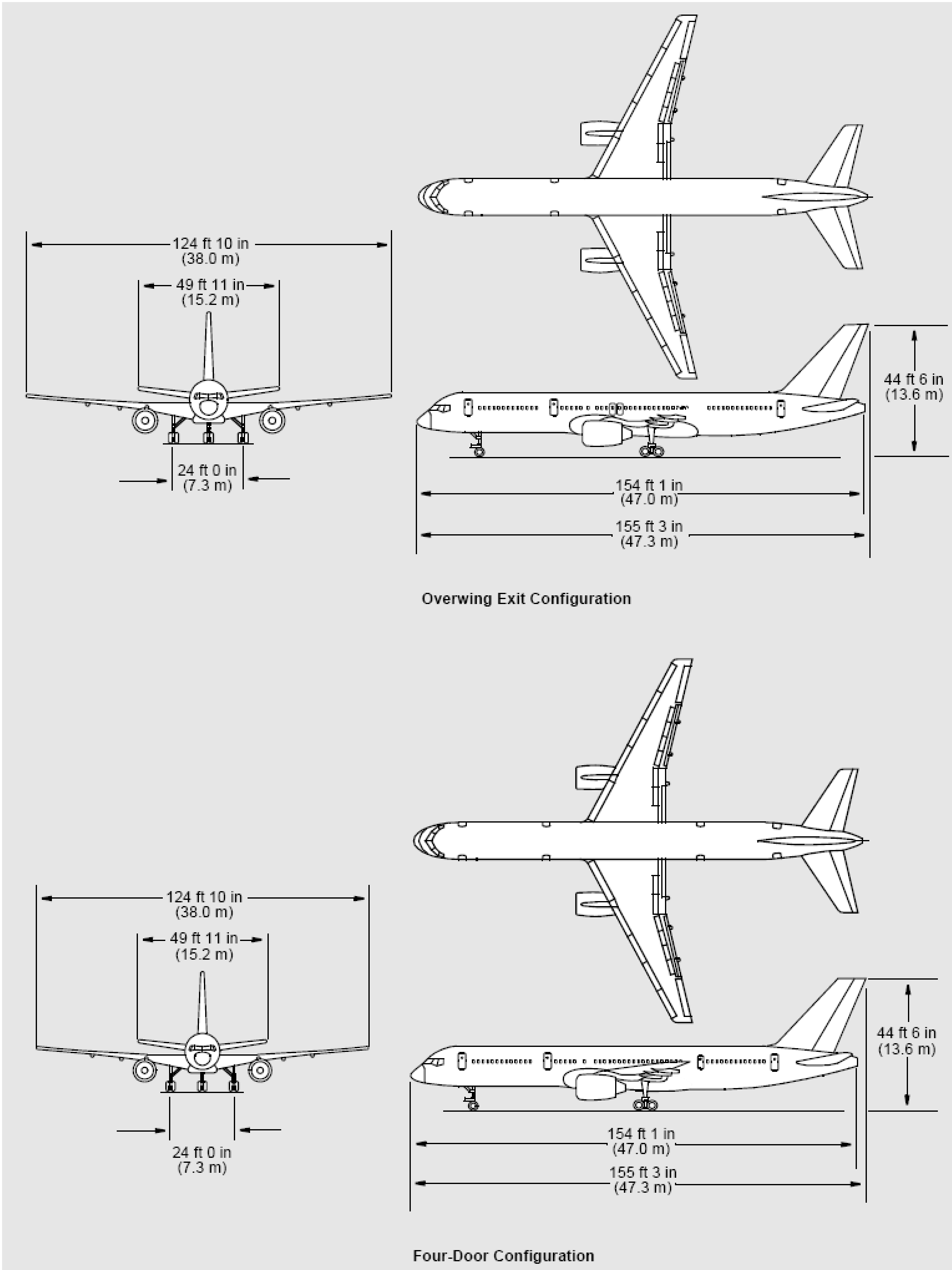


B737-600, B737-700, B737-800, B737-900

(737-600/-700/-800 General Familiarization Manuals TDOC737-16. Boeing, May 2003)



(737-600/-700/-800 General Familiarization Manuals TDOC737-16. Boeing, May 2003)



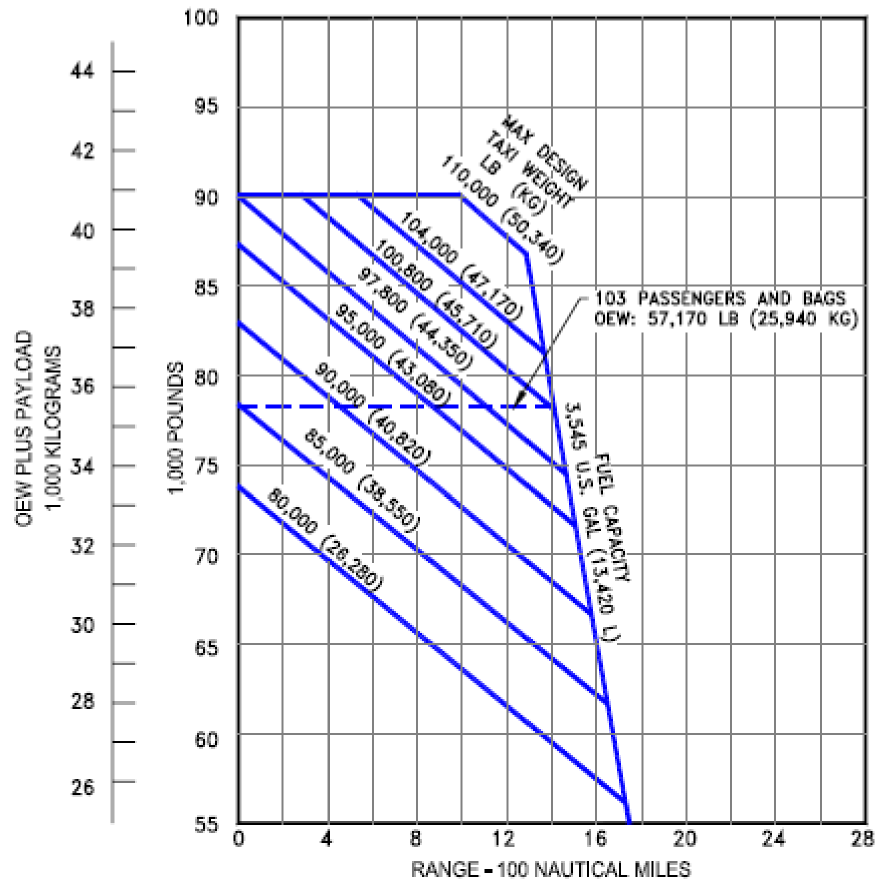
757-200 Passenger Airplane Configurations

(757 General Familiarization Manuals TDOC757-03. Boeing, July 2003)

Appendix C – Payload Range Charts

The following Payload Range charts are derived from the "737 Airplane Characteristics for Airport Planning" document D6-58325-6 by the Boeing Commercial Airplane Company, October 2005.

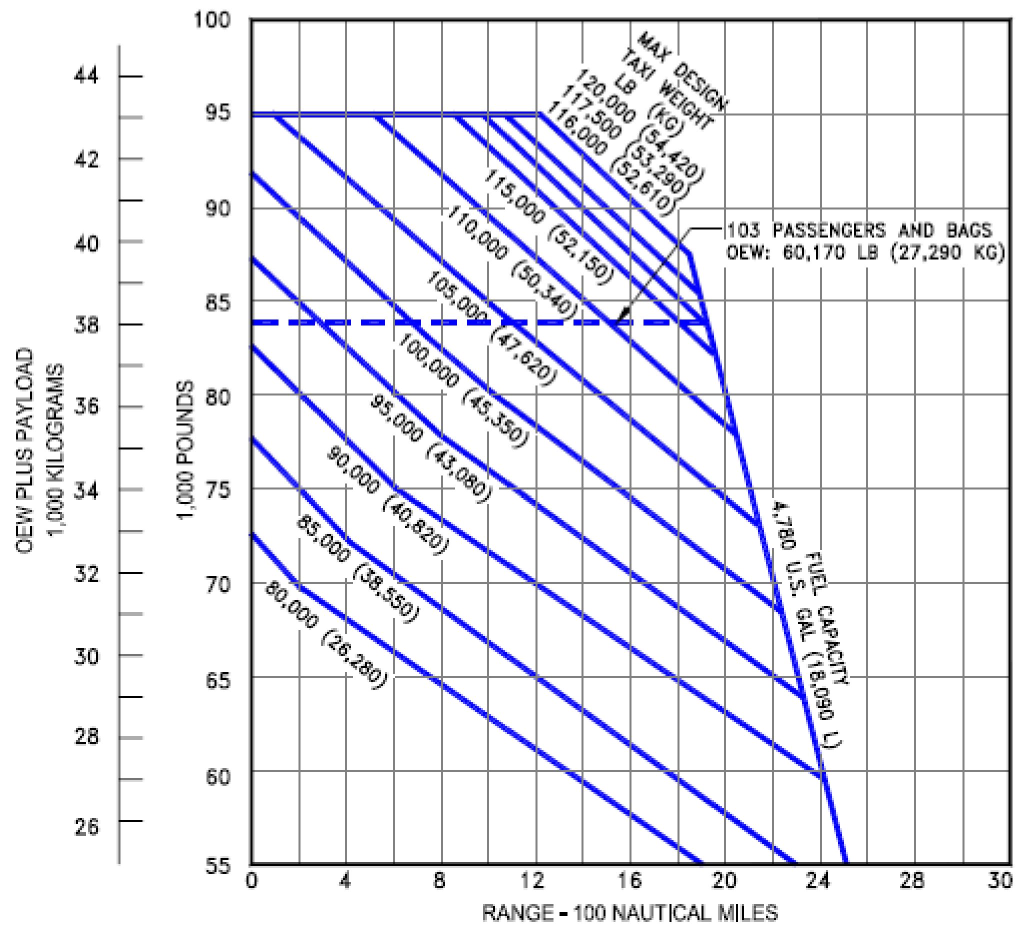
NOTES:
* DOMESTIC RESERVES
* JT9D-7 ENGINES
* STANDARD DAY, ZERO WIND
* LRC AT 30,000 FEET (9,150 METERS)
* CONSULT WITH USING AIRLINE FOR SPECIFIC OPERATING PROCEDURE PRIOR TO FACILITY DESIGN



* FOR TAKEOFF WEIGHT, SUBTRACT 500 LB (227 KG) FROM TAXI WEIGHT

3.2.1 PAYLOAD/RANGE FOR LONG-RANGE CRUISE
MODEL 737-100 (JT8D-7 ENGINES)

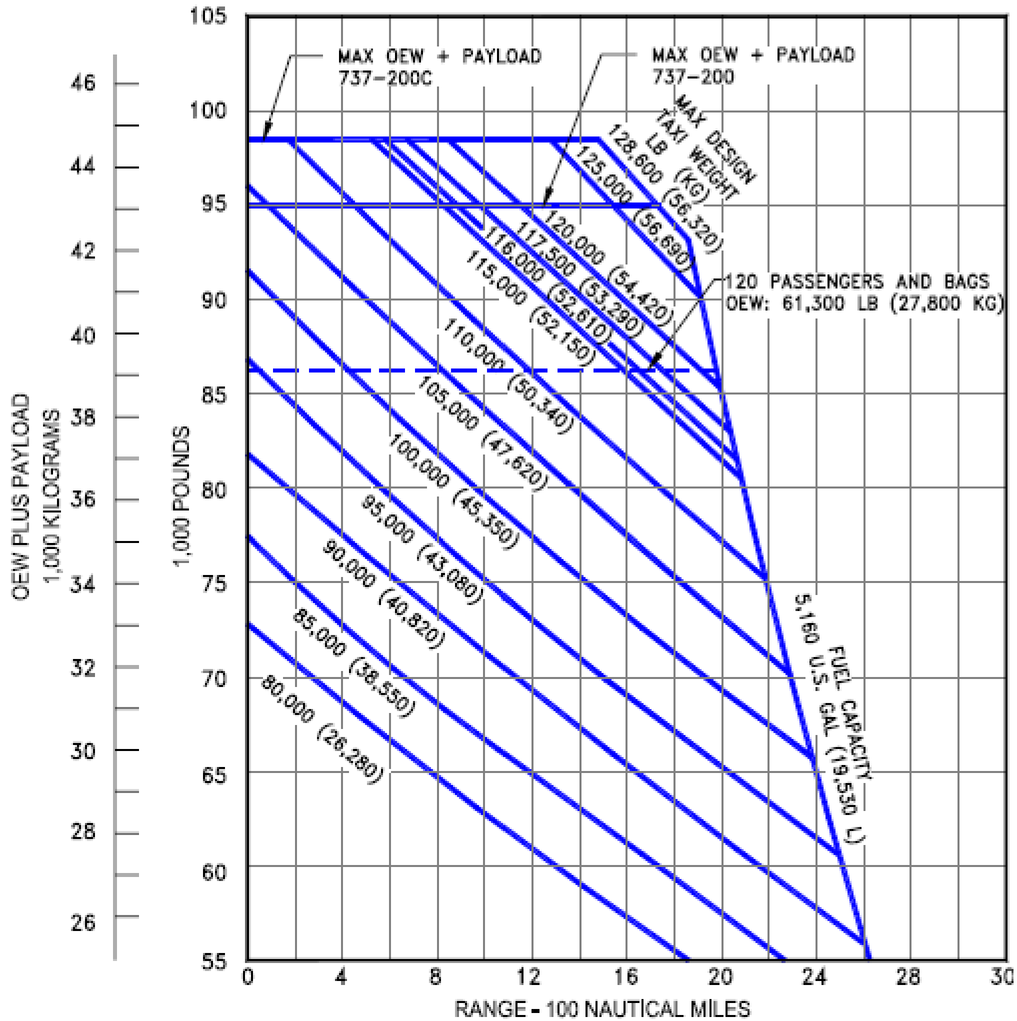
NOTES:
* DOMESTIC RESERVES
* JT9D-9/9A ENGINES
* STANDARD DAY, ZERO WIND
* LRC AT 30,000 FEET (9,150 METERS)
* CONSULT WITH USING AIRLINE FOR SPECIFIC OPERATING PROCEDURE PRIOR TO FACILITY DESIGN



* FOR TAKEOFF WEIGHT, SUBTRACT 500 LB (227 KG) FROM TAXI WEIGHT

3.2.2 PAYLOAD/RANGE FOR LONG-RANGE CRUISE
MODEL 737-200 (JT8D-9/9A ENGINES)

NOTES:
* DOMESTIC RESERVES
* JT9D-15/15A ENGINES
* STANDARD DAY, ZERO WIND
* LRC AT 30,000 FEET (9,150 METERS)
* CONSULT WITH USING AIRLINE FOR SPECIFIC OPERATING PROCEDURE PRIOR TO FACILITY DESIGN

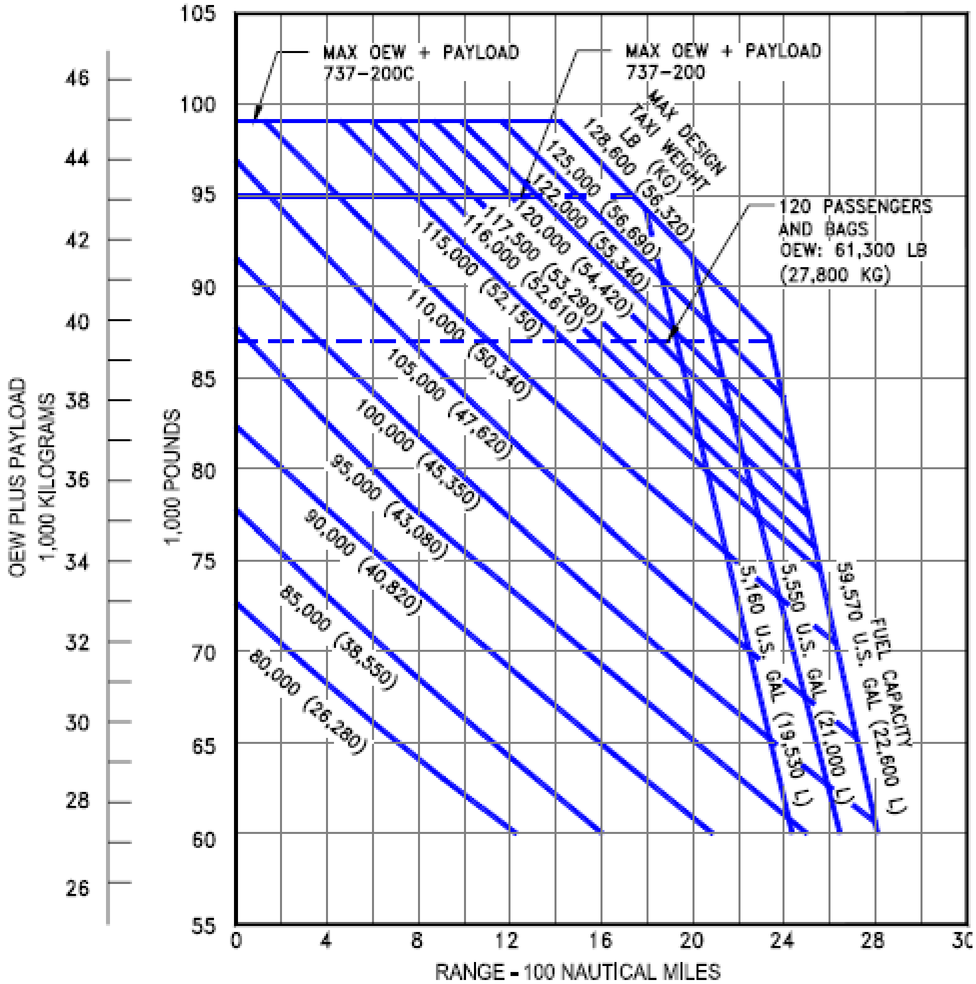


* FOR TAKEOFF WEIGHT, SUBTRACT 500 LB (227 KG) FROM TAXI WEIGHT

3.2.3 PAYLOAD/RANGE FOR LONG-RANGE CRUISE

MODEL ADVANCED 737-200 (JT8D-15/15A ENGINES)

NOTES:
* DOMESTIC RESERVES
* JT9D-17/17A ENGINES
* STANDARD DAY, ZERO WIND
* LRC AT 30,000 FEET (9,150 METERS)
* CONSULT WITH USING AIRLINE FOR SPECIFIC OPERATING PROCEDURE PRIOR TO FACILITY DESIGN

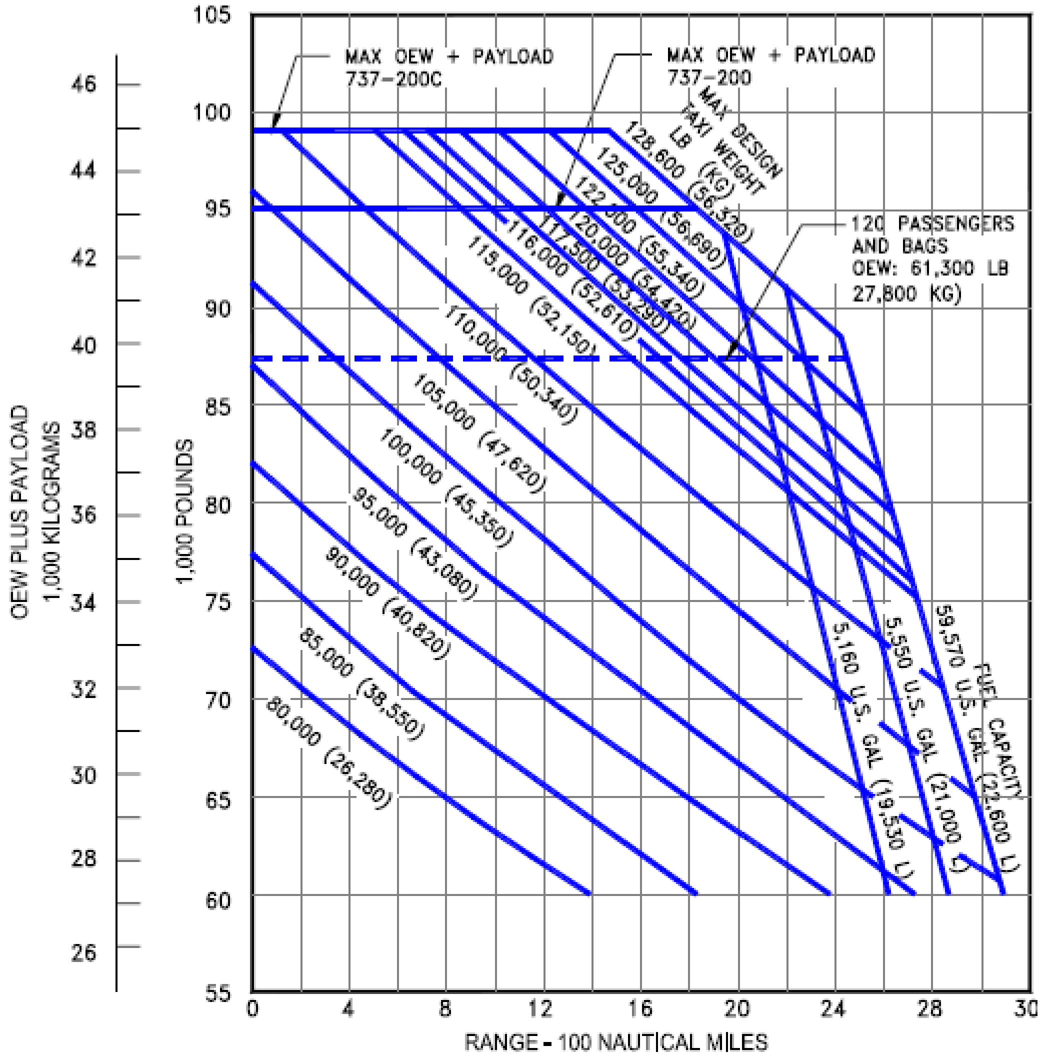


* FOR TAKEOFF WEIGHT, SUBTRACT 500 LB (227 KG) FROM TAXI WEIGHT

3.2.4 PAYLOAD/RANGE FOR LONG-RANGE CRUISE

MODEL ADVANCED 737-200 (JT8D-17/17A ENGINES)

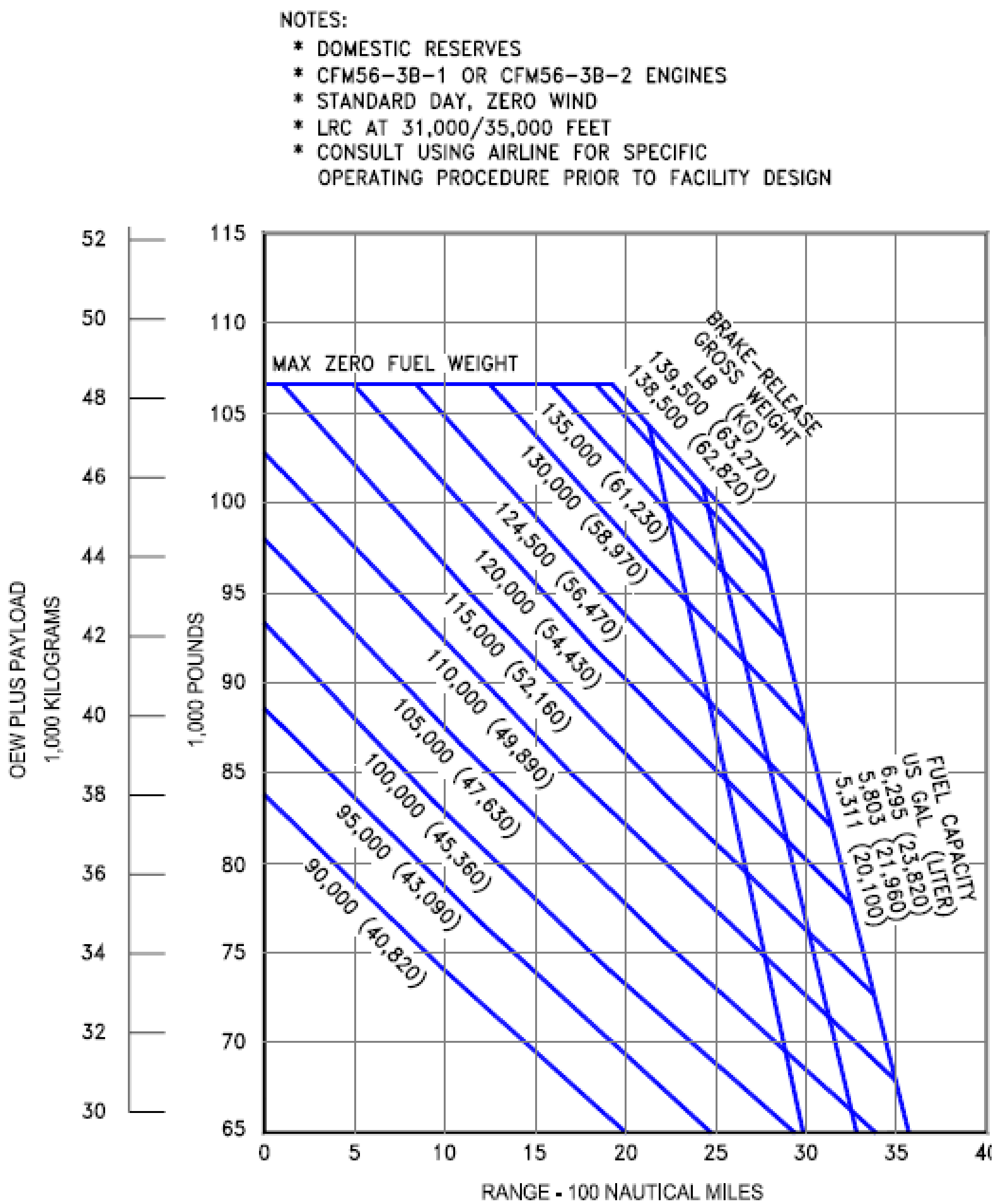
NOTES:
* DOMESTIC RESERVES
* JT9D-17R/17AR ENGINES
* STANDARD DAY, ZERO WIND
* LRC AT 30,000 FEET (9,150 METERS)
* CONSULT WITH USING AIRLINE FOR SPECIFIC OPERATING PROCEDURE PRIOR TO FACILITY DESIGN



* FOR TAKEOFF WEIGHT, SUBTRACT 500 LB (227 KG) FROM TAXI WEIGHT

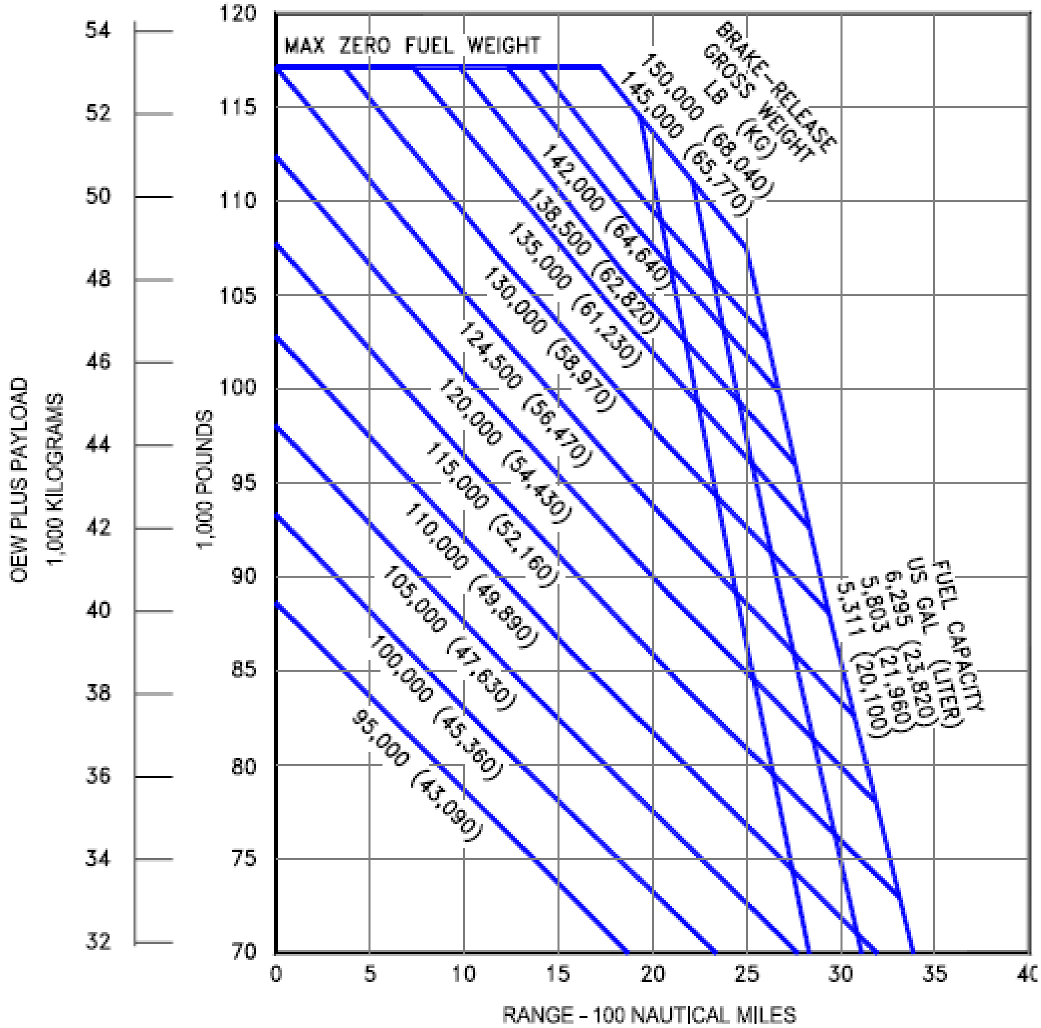
3.2.5 PAYLOAD/RANGE FOR LONG-RANGE CRUISE

MODEL ADVANCED 737-200 (JT8D-17R/17AR ENGINES)



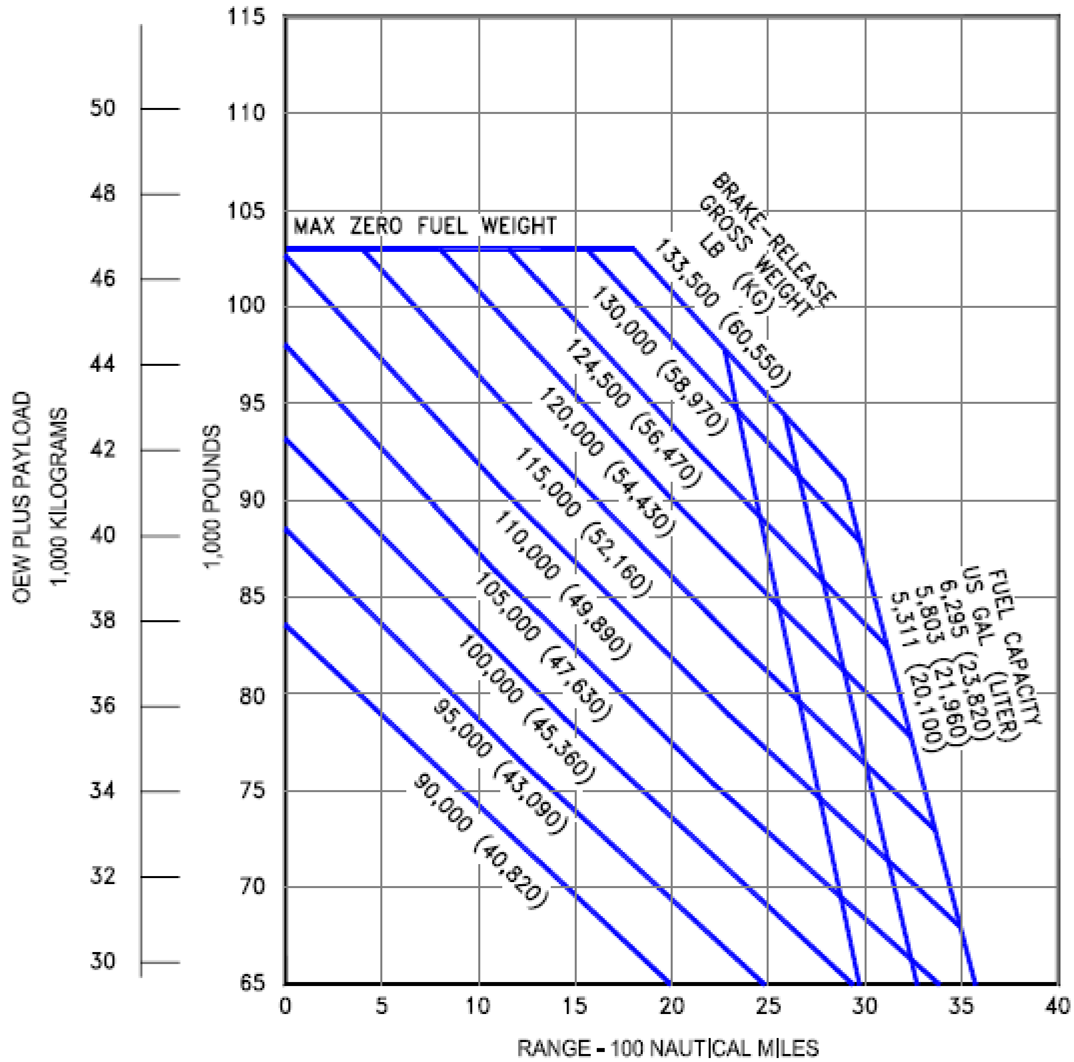
3.2.6 PAYLOAD/RANGE FOR LONG-RANGE CRUISE
MODEL 737-300

NOTES:
* DOMESTIC RESERVES
* CFM56-3B-2 OR CFM56-3C-1 ENGINES
* STANDARD DAY, ZERO WIND
* LRC AT 31,000/35,000 FEET
* CONSULT USING AIRLINE FOR SPECIFIC OPERATING PROCEDURE PRIOR TO FACILITY DESIGN



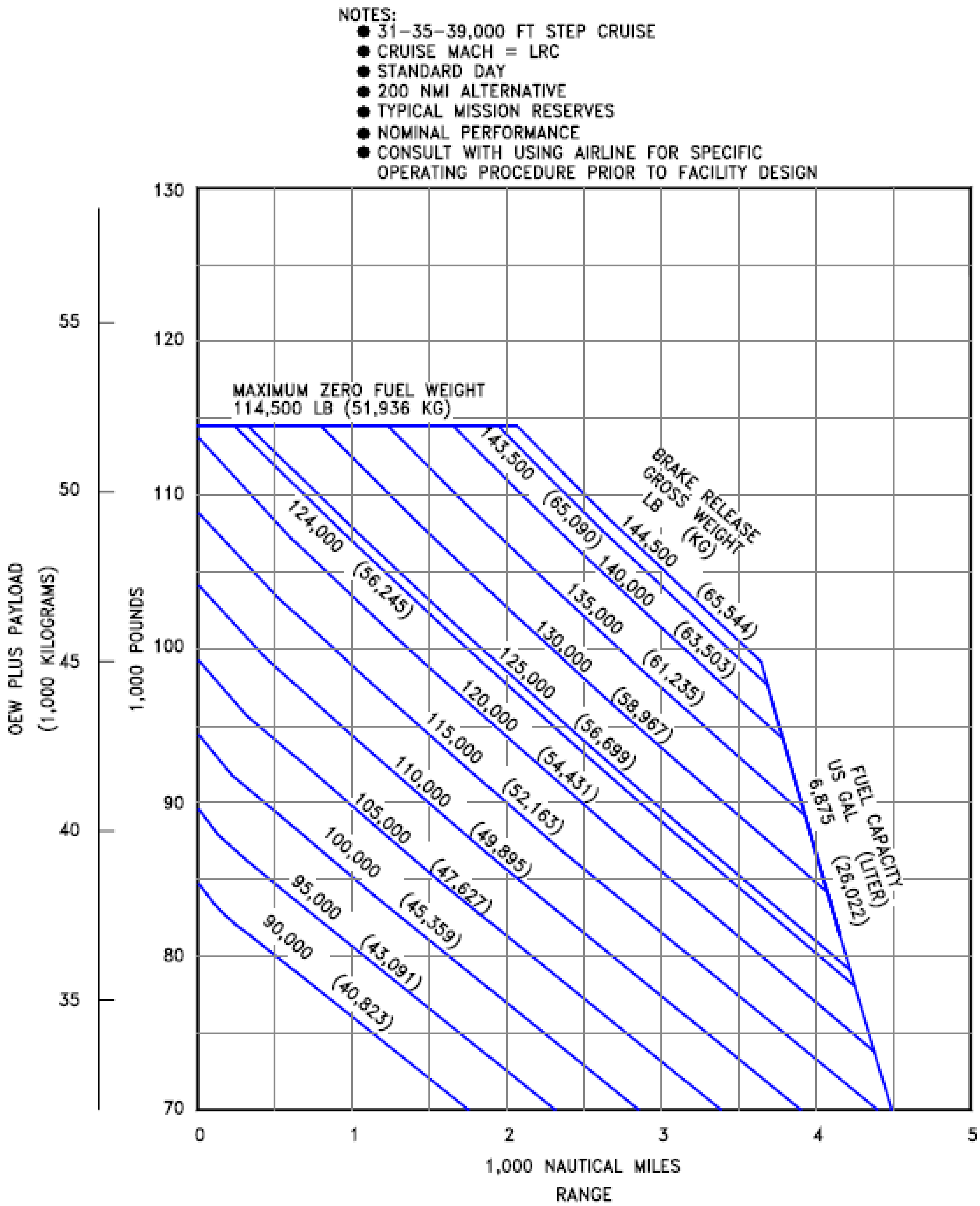
3.2.7 PAYLOAD/RANGE FOR LONG-RANGE CRUISE
MODEL 737-400

NOTES:
* DOMESTIC RESERVES
* CFM56-3B-1 ENGINES
* STANDARD DAY, ZERO WIND
* LRC AT 31,000/35,000 FEET
* CONSULT USING AIRLINE FOR SPECIFIC OPERATING PROCEDURE PRIOR TO FACILITY DESIGN

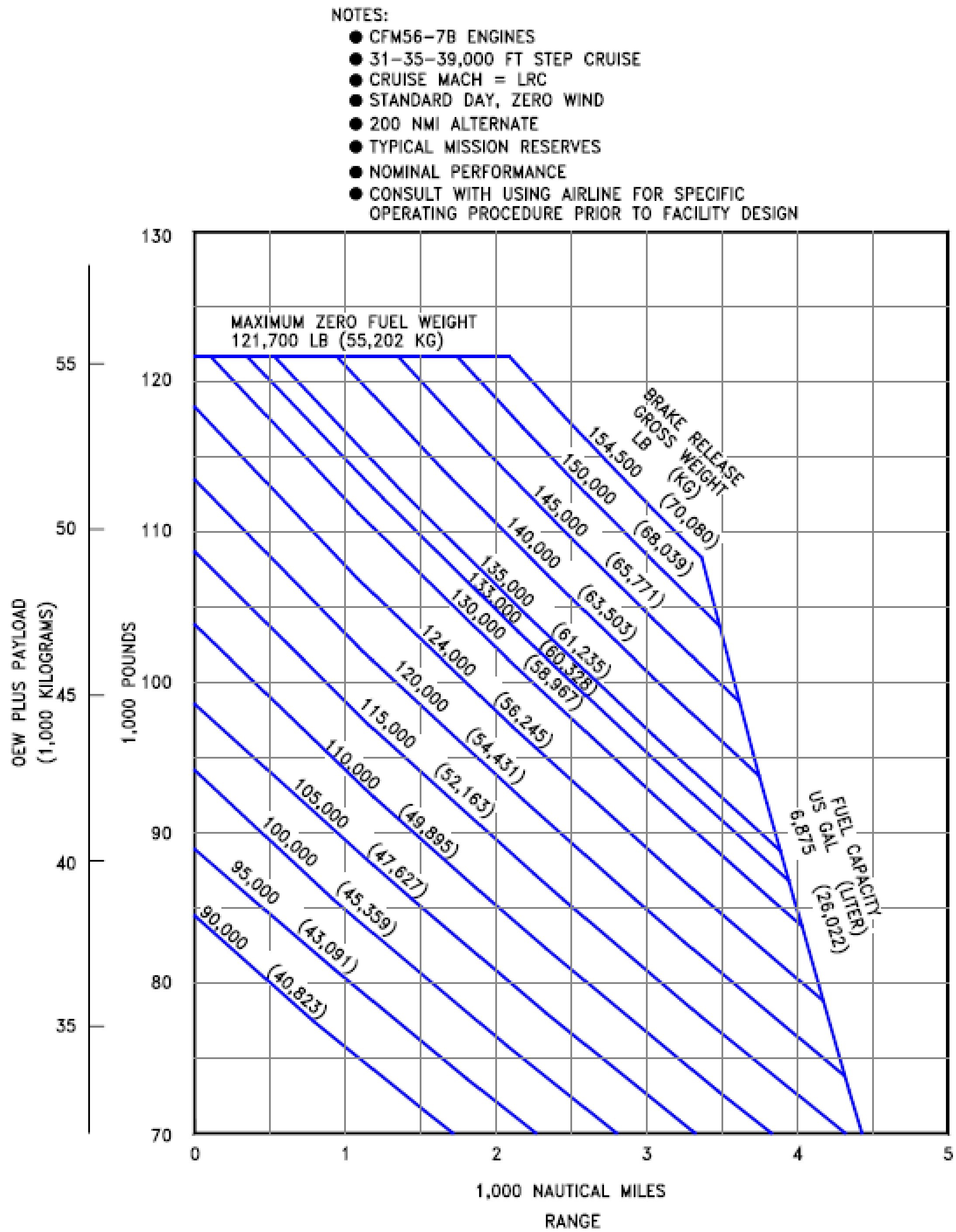


3.2.8 PAYLOAD/RANGE FOR LONG-RANGE CRUISE

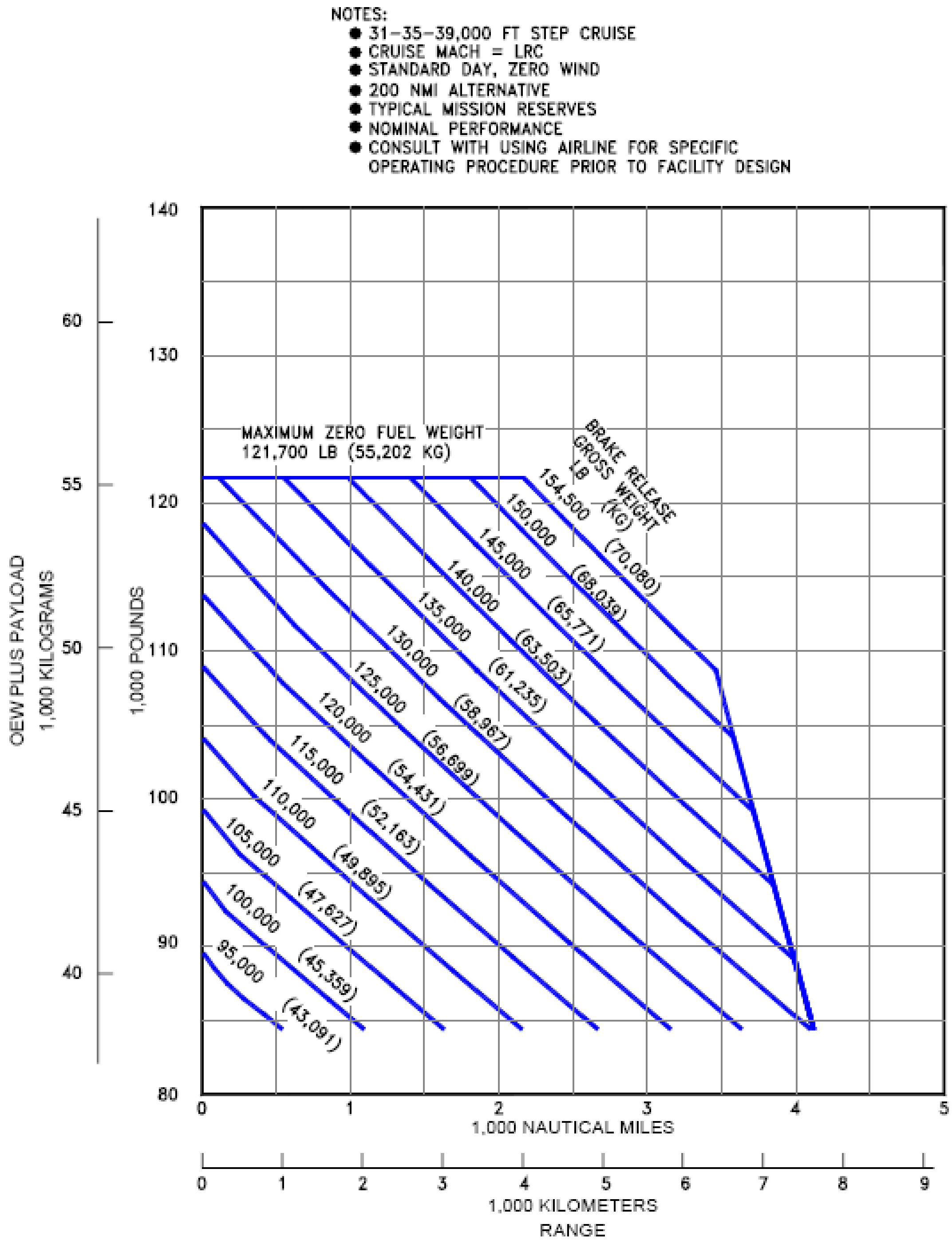
MODEL 737-500



3.2.9 PAYLOAD/RANGE FOR LONG-RANGE CRUISE
MODEL 737-600

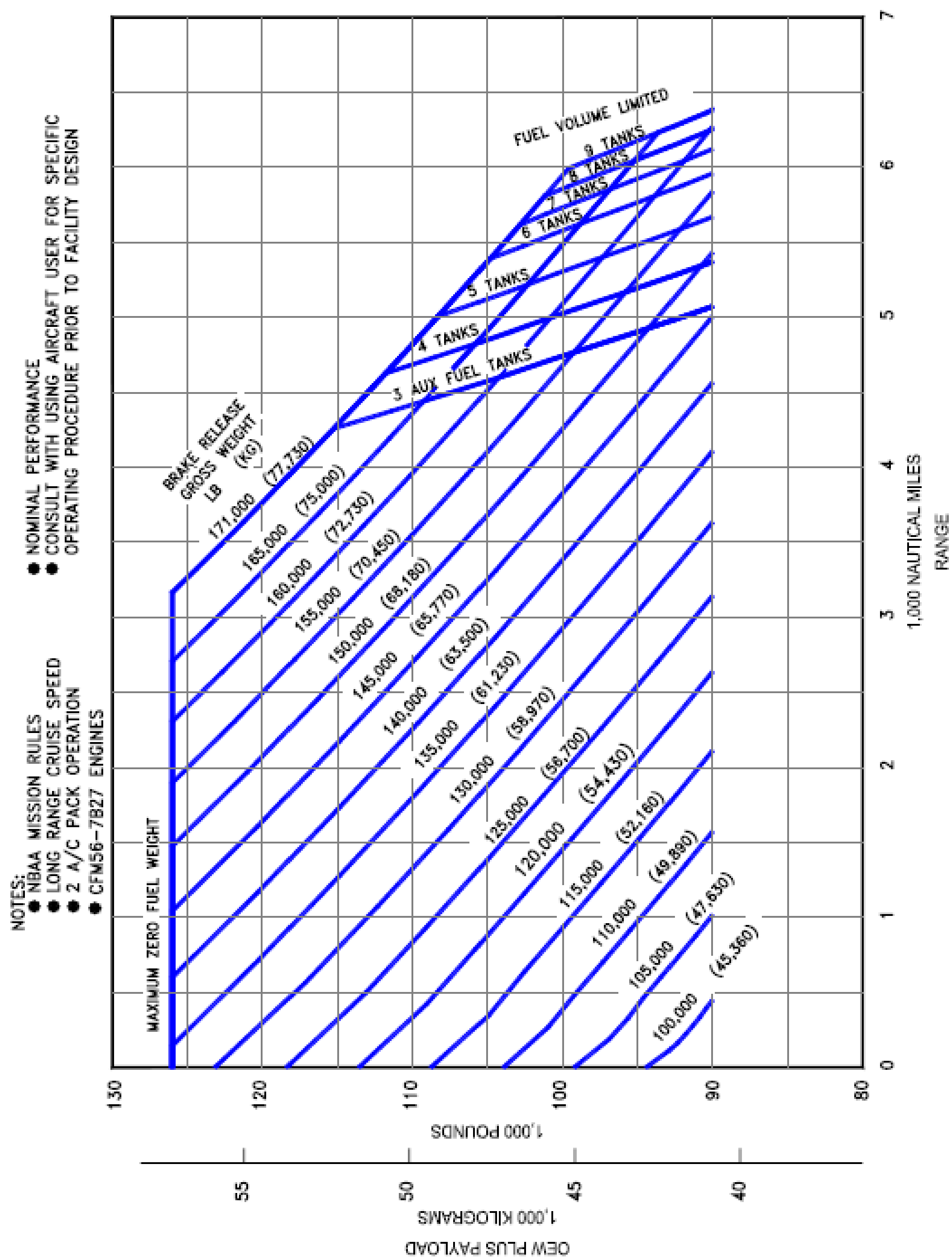


3.2.10 PAYLOAD/RANGE FOR LONG-RANGE CRUISE
MODEL 737-700

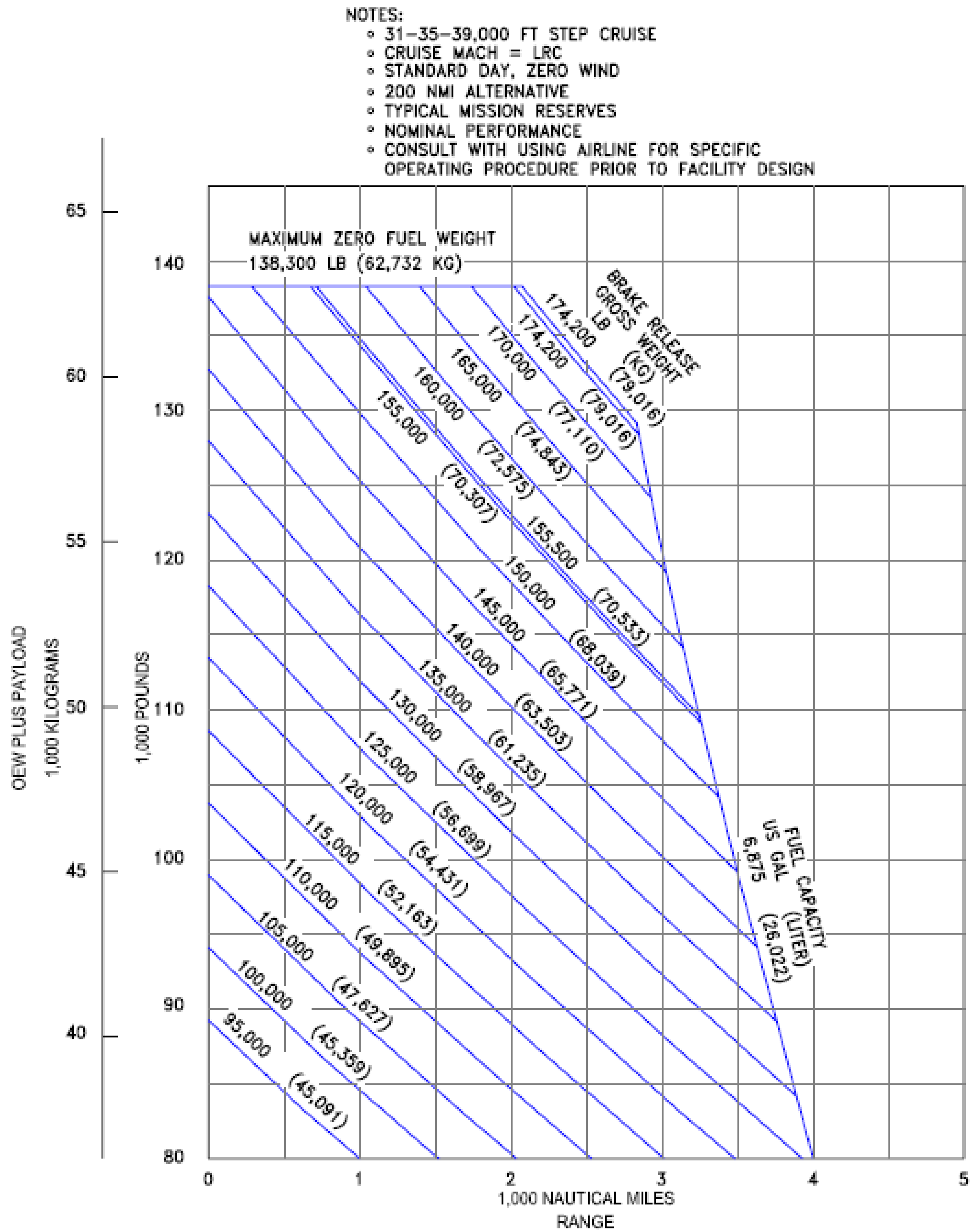


3.2.11 PAYLOAD/RANGE FOR LONG-RANGE CRUISE

MODEL 737-700 WITH WINGLETS

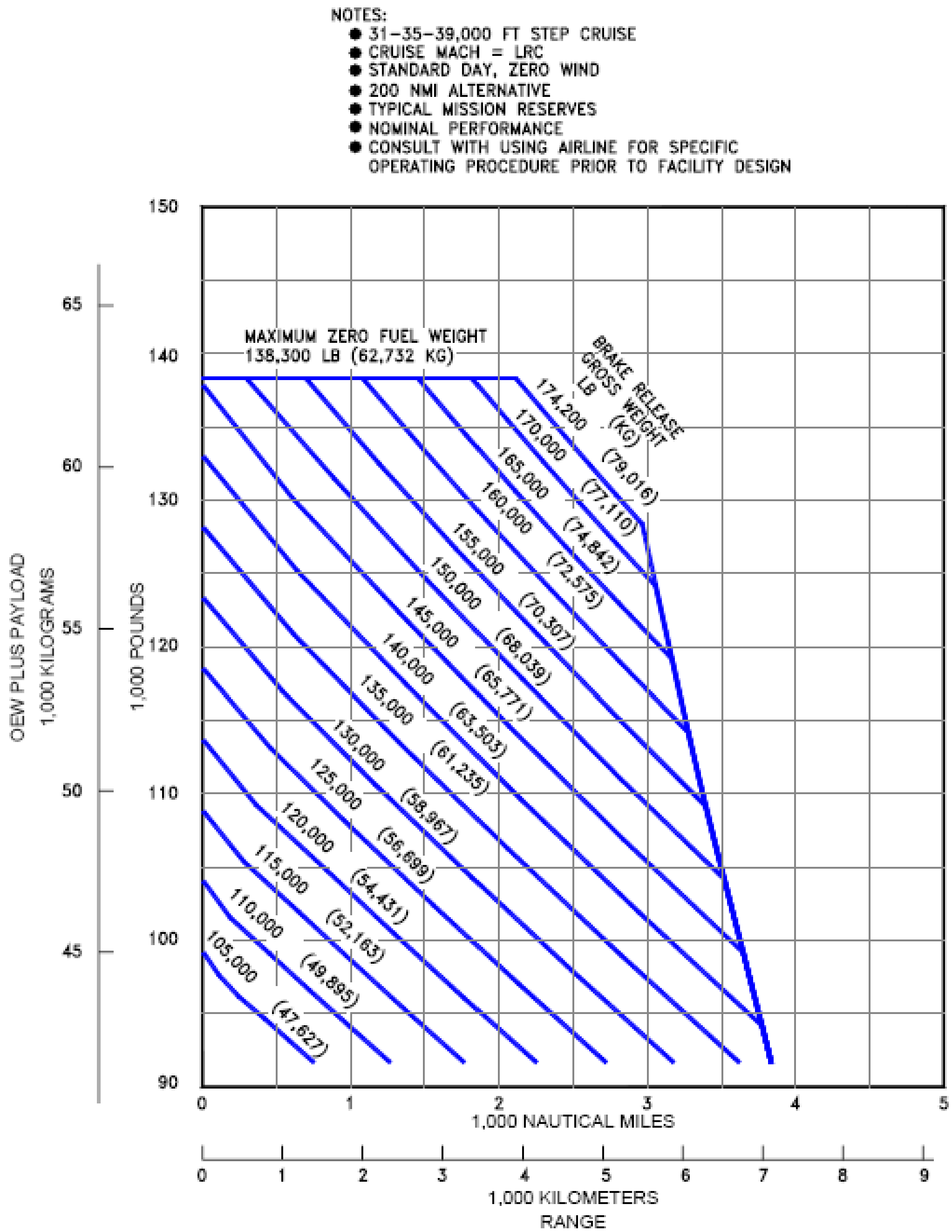


3.2.12 PAYLOAD/RANGE FOR LONG-RANGE CRUISE
MODEL 737 BBJ



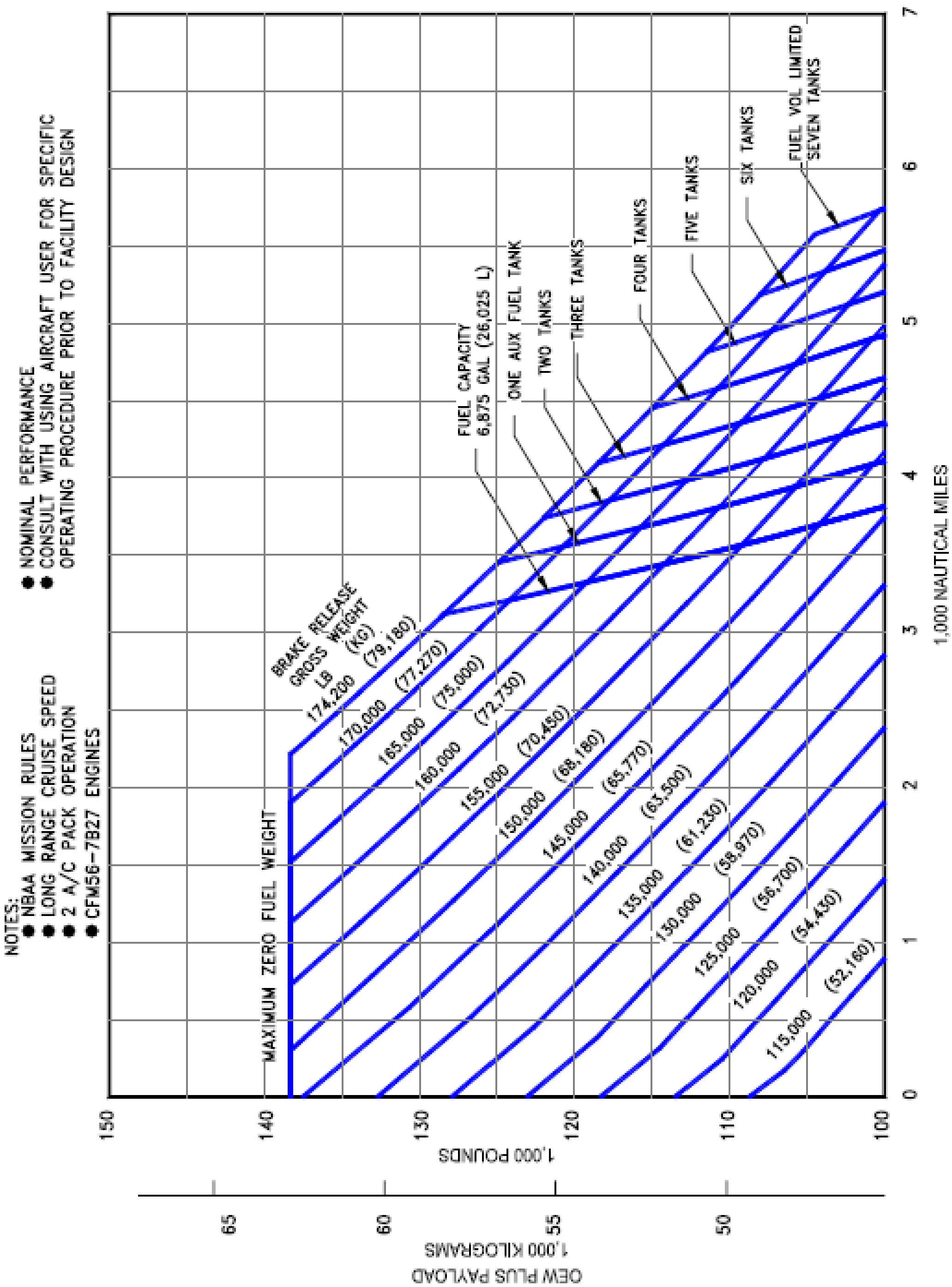
3.2.13 PAYLOAD/RANGE FOR LONG-RANGE CRUISE

MODEL 737-800



3.2.14 PAYLOAD/RANGE FOR LONG-RANGE CRUISE

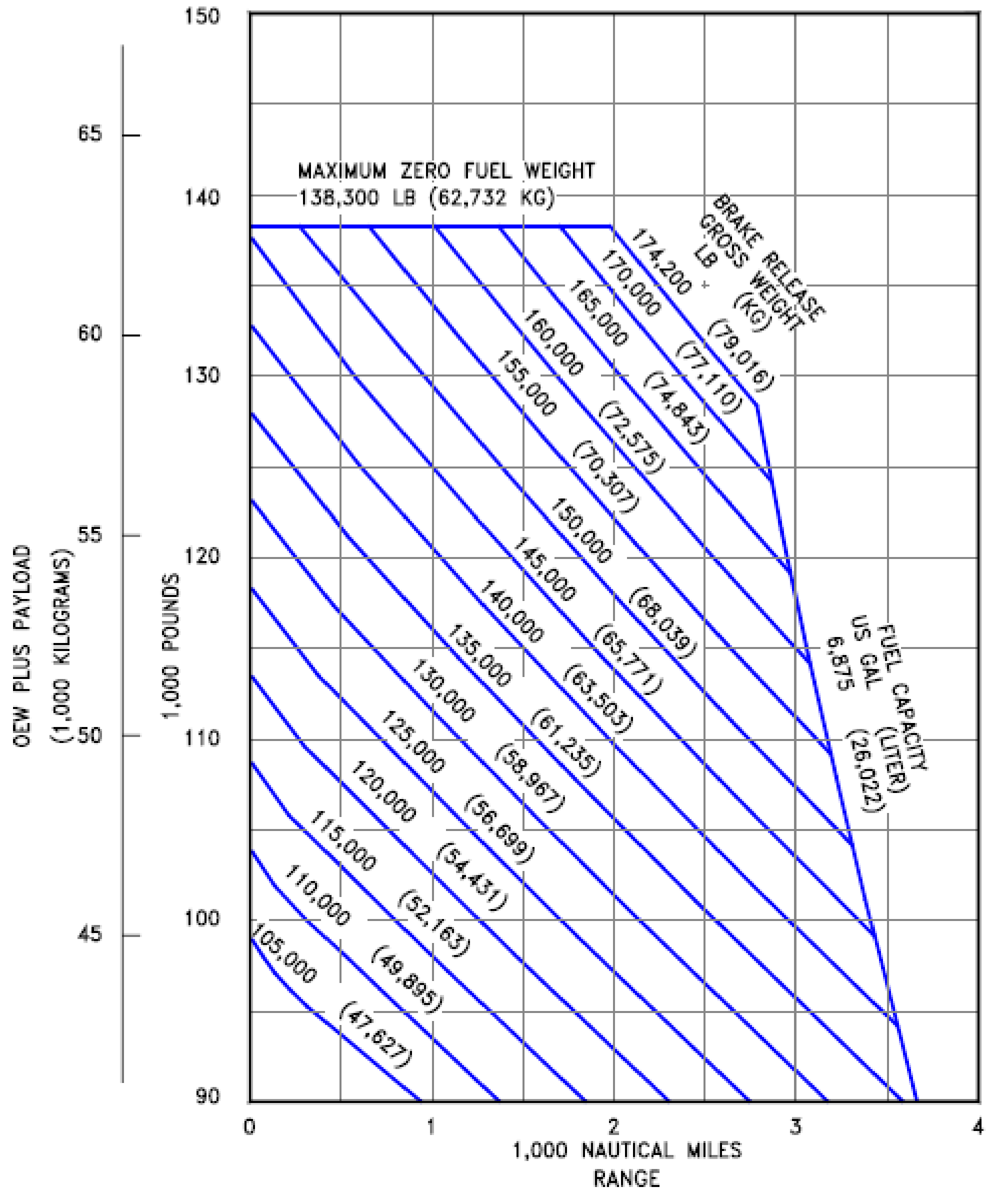
MODEL 737-800 WITH WINGLETS



3.2.15 PAYLOAD/RANGE FOR LONG-RANGE CRUISE

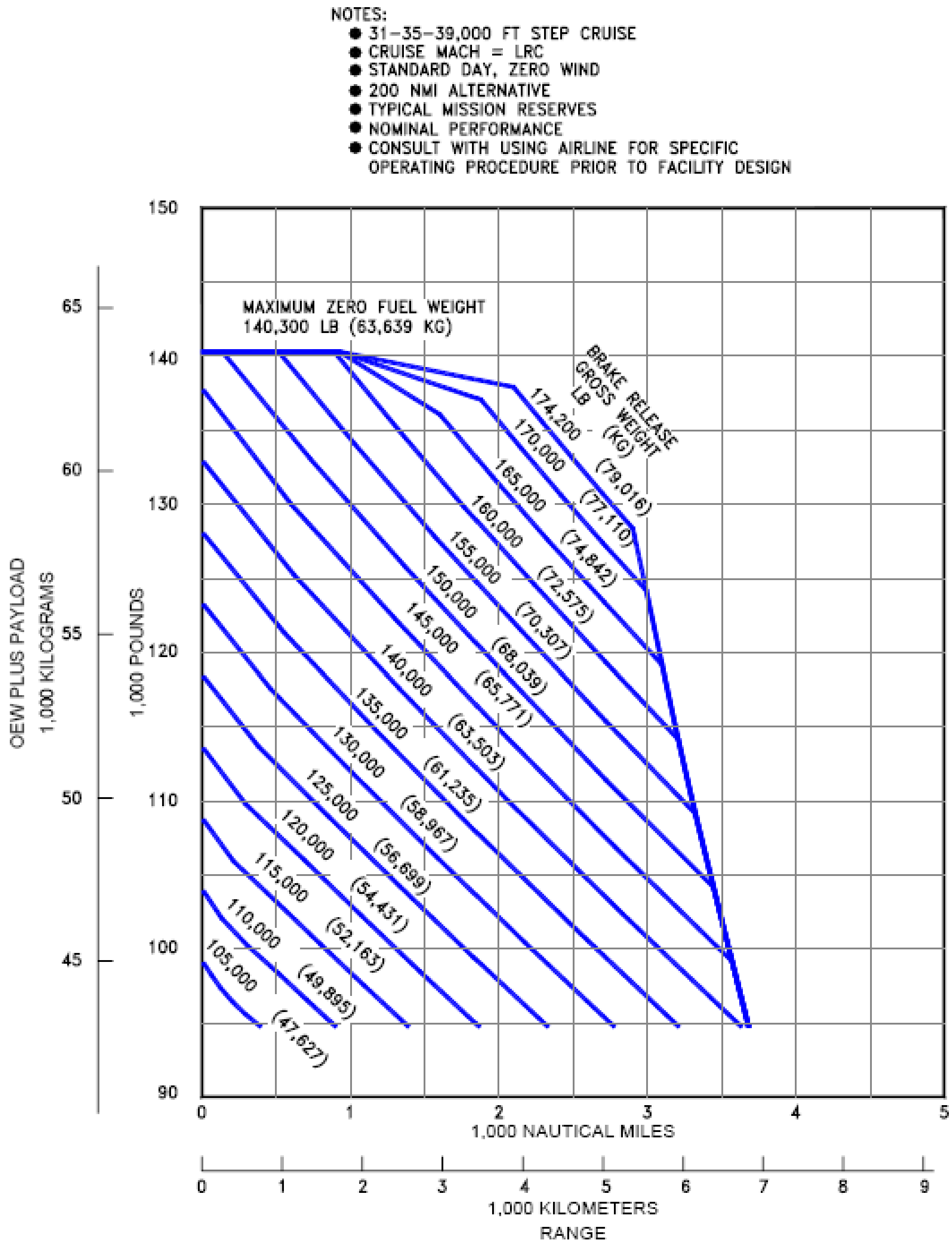
MODEL 737 BBJ2

NOTES:
- 31–35–39,000 FT STEP CRUISE
- CRUISE MACH = LRC
- STANDARD DAY, ZERO WIND
- 200 NMI ALTERNATIVE
- TYPICAL MISSION RESERVES
- NOMINAL PERFORMANCE
- CONSULT WITH USING AIRLINE FOR SPECIFIC OPERATING PROCEDURE PRIOR TO FACILITY DESIGN

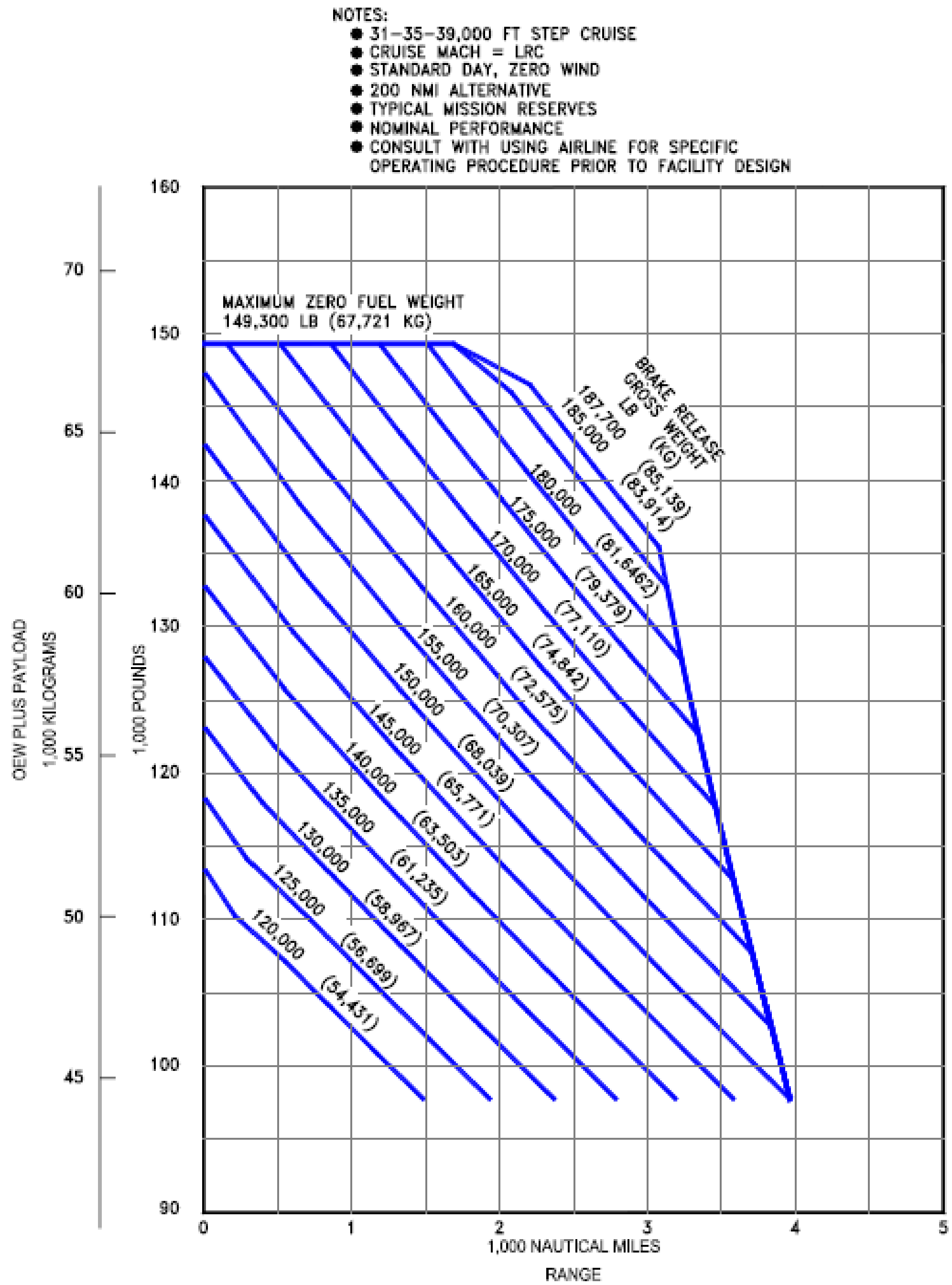


3.2.16 PAYLOAD/RANGE FOR LONG-RANGE CRUISE

MODEL 737-900

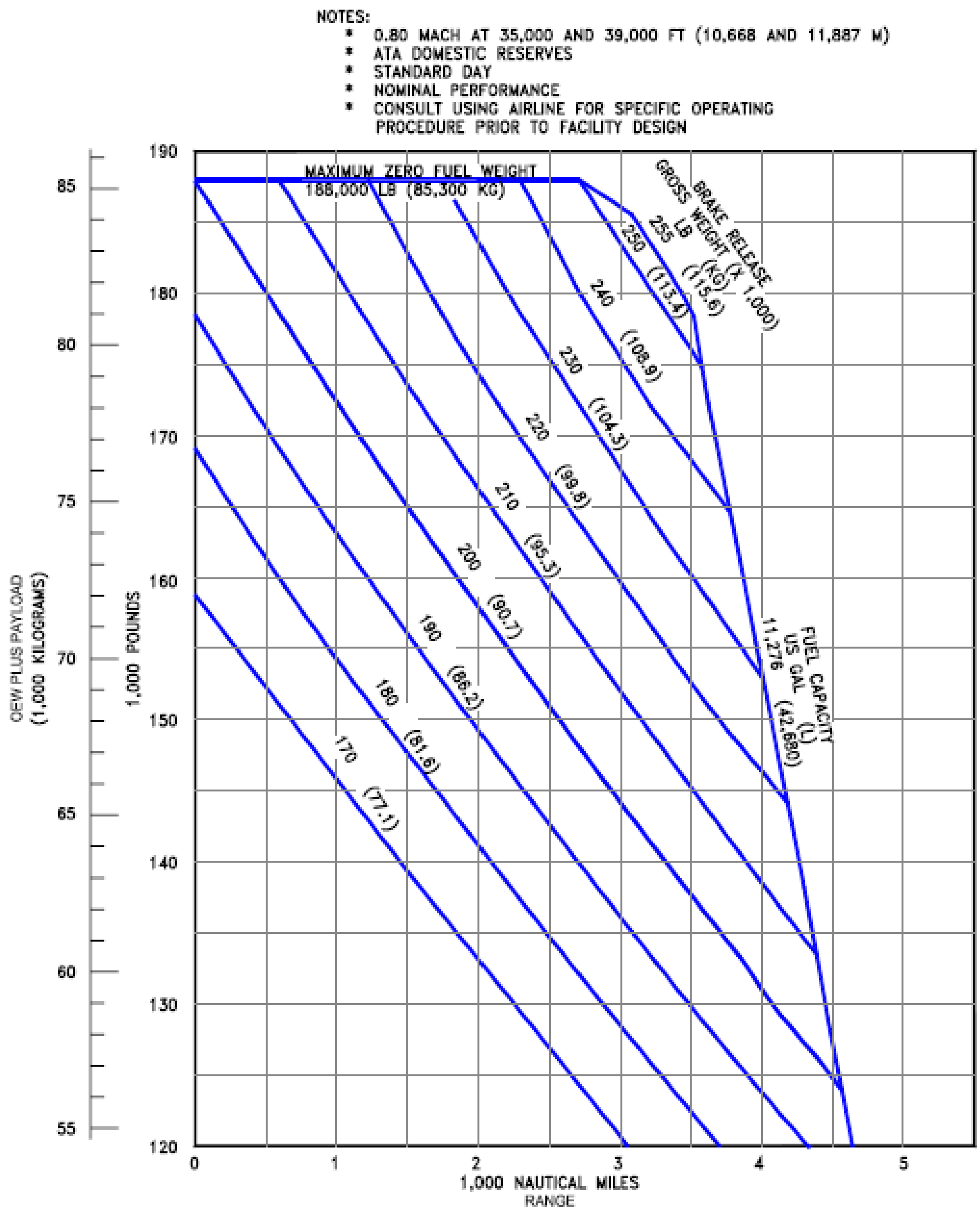


3.2.17 PAYLOAD/RANGE FOR LONG-RANGE CRUISE
MODEL 737-900 WITH WINGLETS



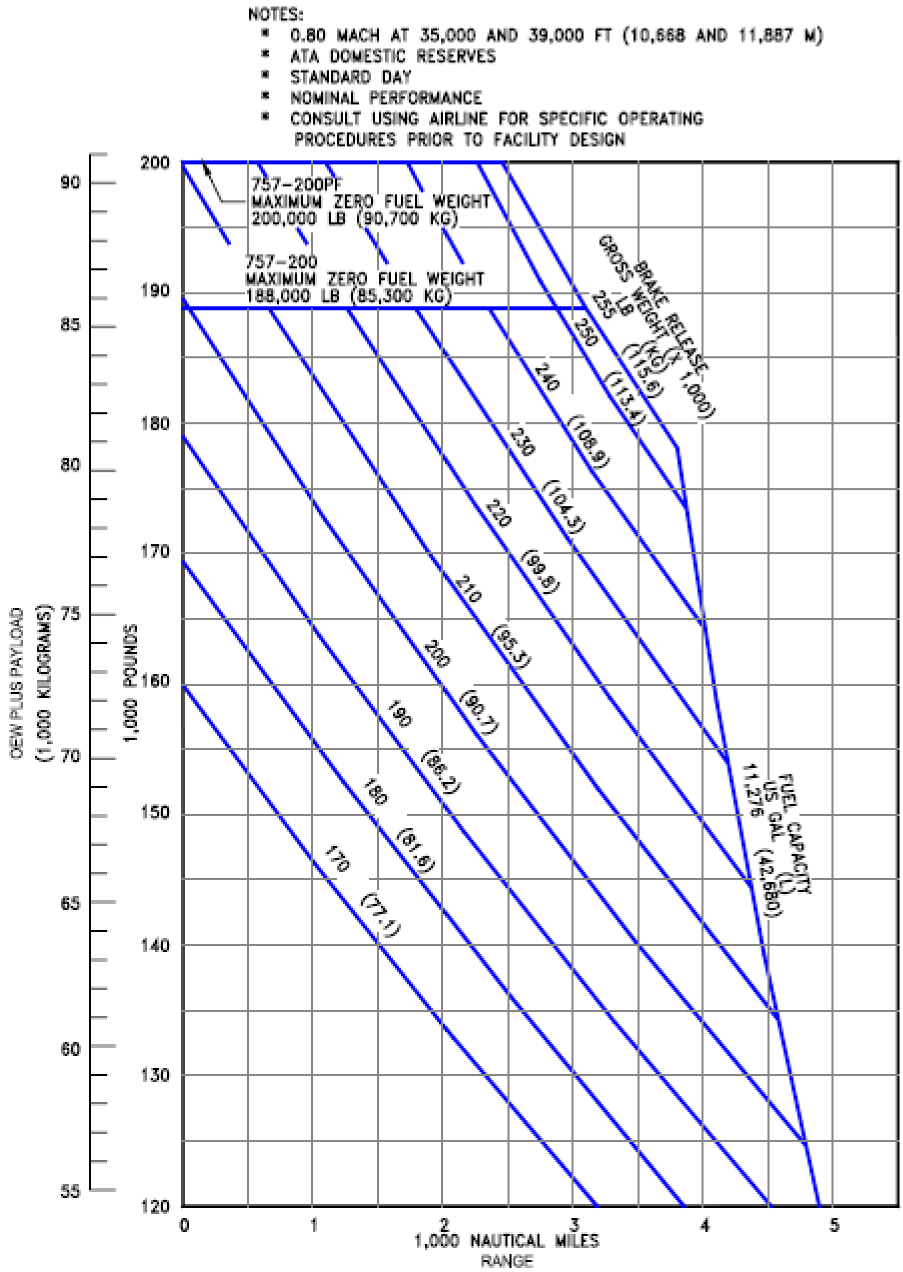
3.2.18 PAYLOAD/RANGE FOR LONG-RANGE CRUISE
MODEL 737-900ER

The following Payload Range charts are derived from the "757-200/300 Airplane Characteristics for Airport Planning" document D6-58327, by the Boeing Commercial Airplane Company, 2002.



3.2.2. PAYLOAD/RANGE FOR LONG-RANGE CRUISE

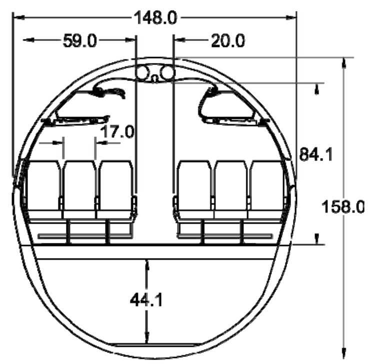
MODEL 757-200 (RB211-53E4, -535E4B ENGINES)



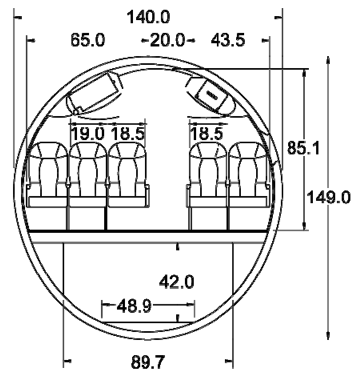
3.2.3. PAYLOAD/RANGE FOR LONG-RANGE CRUISE

MODEL 757-200, -200PF (PW2037, PW2040 ENGINES)

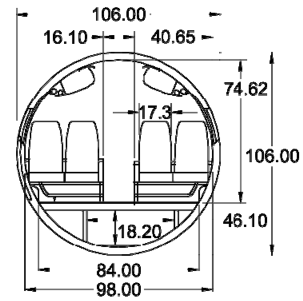
Appendix D – Aircraft Cabin Cross Sections



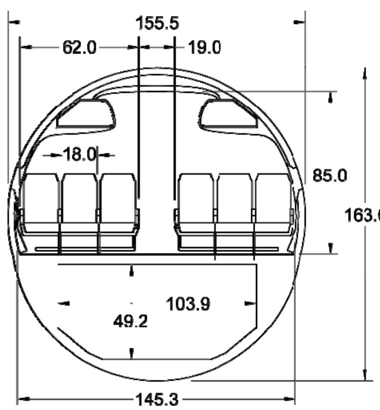
Boeing 737



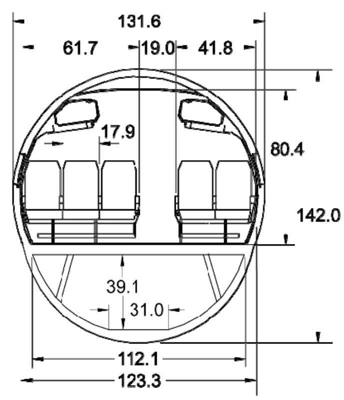
Bombardier CSeries



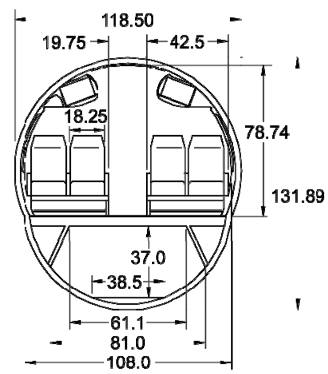
Bombardier CRJ700/900



Airbus A320



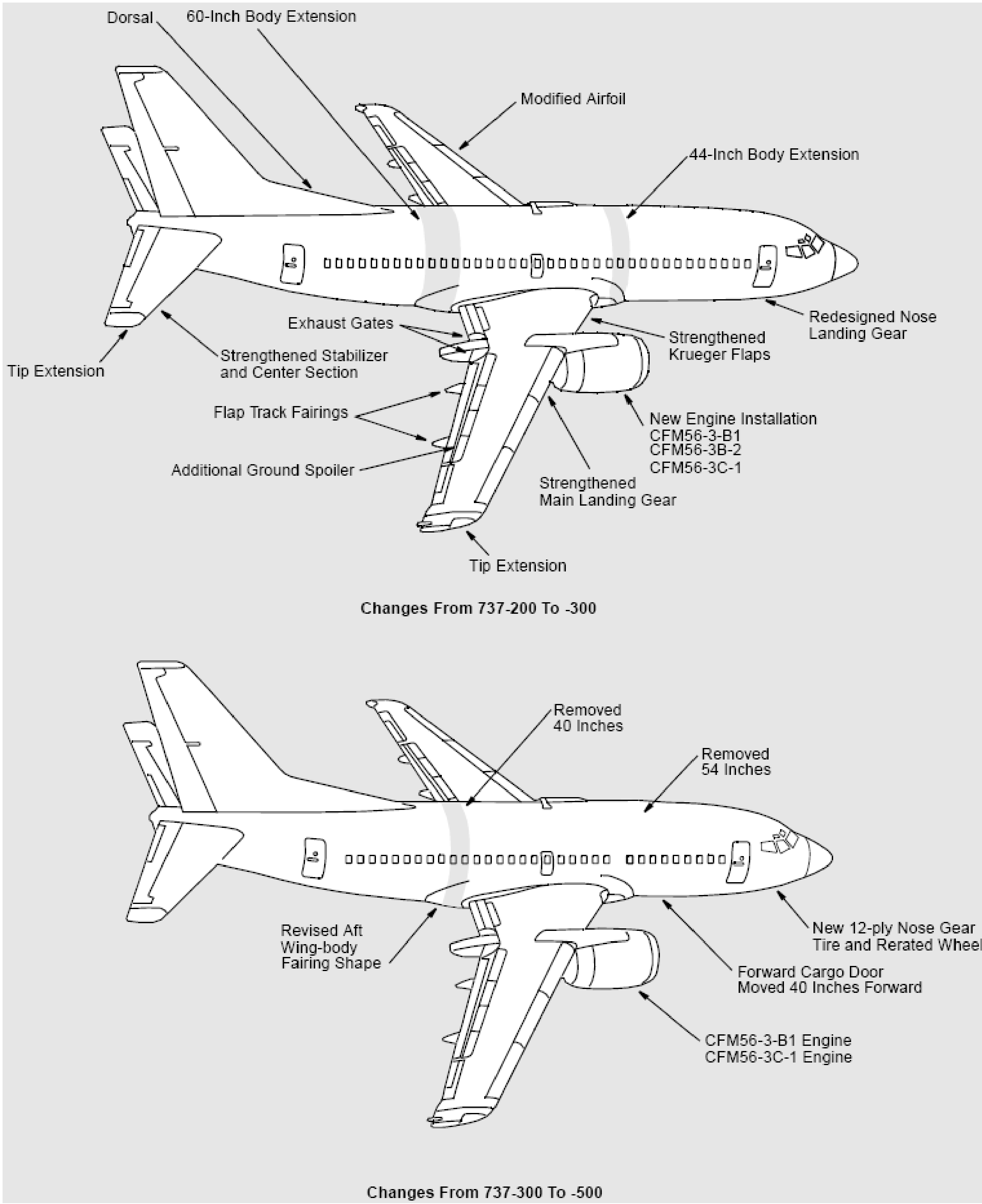
Boeing 717



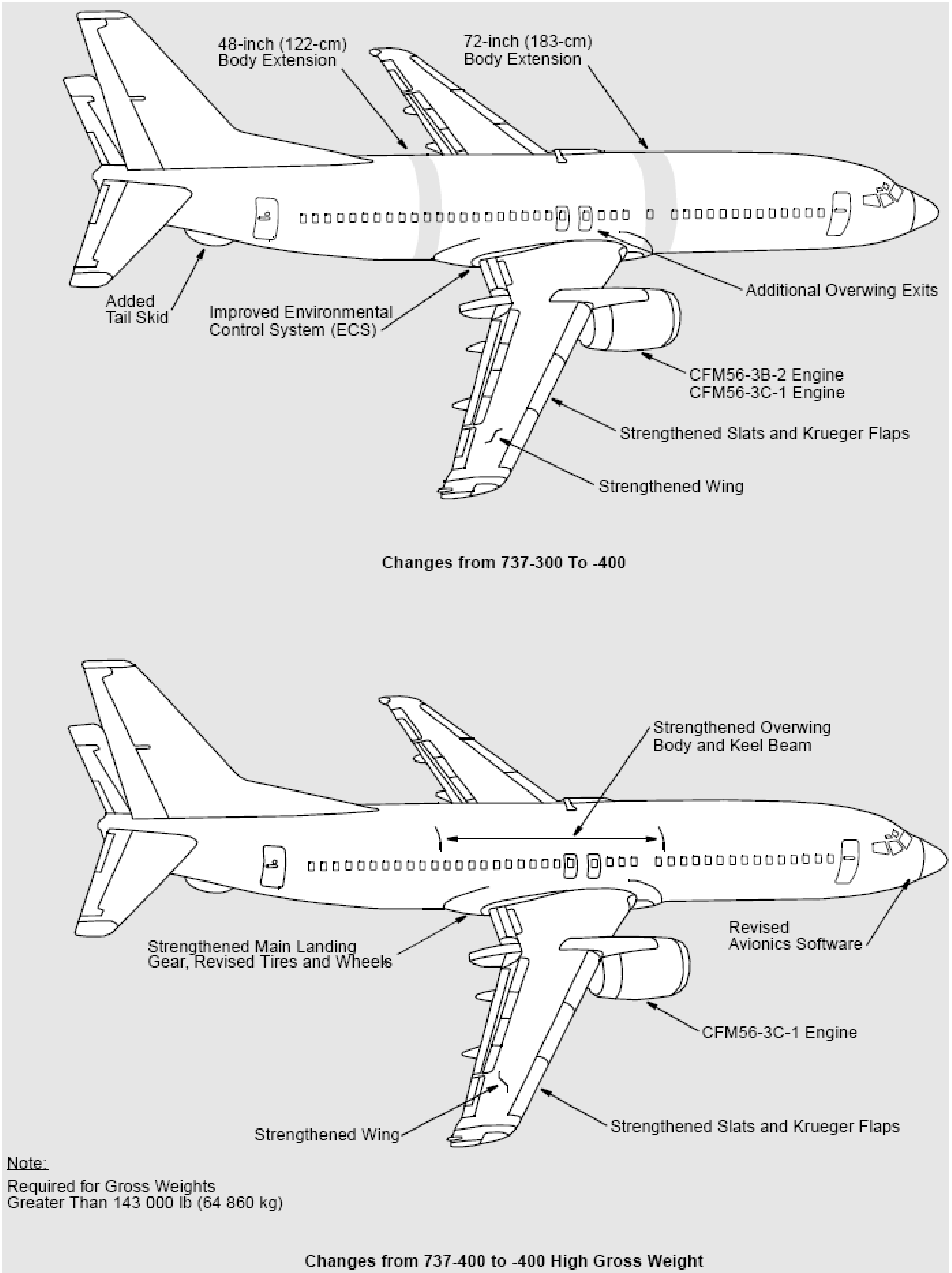
Embraer 170/175/190/195

(Adamson 2010)

Appendix E – Model Changes



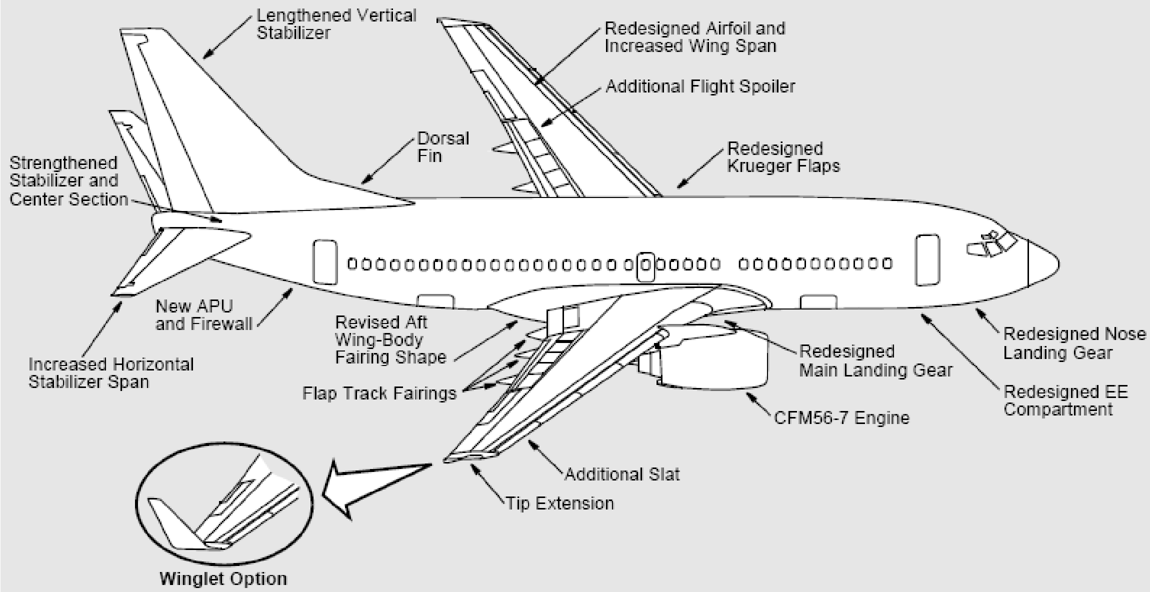
(737-300/-400/-500 General Familiarization Manuals TDOC737-15. Boeing, July 2003)



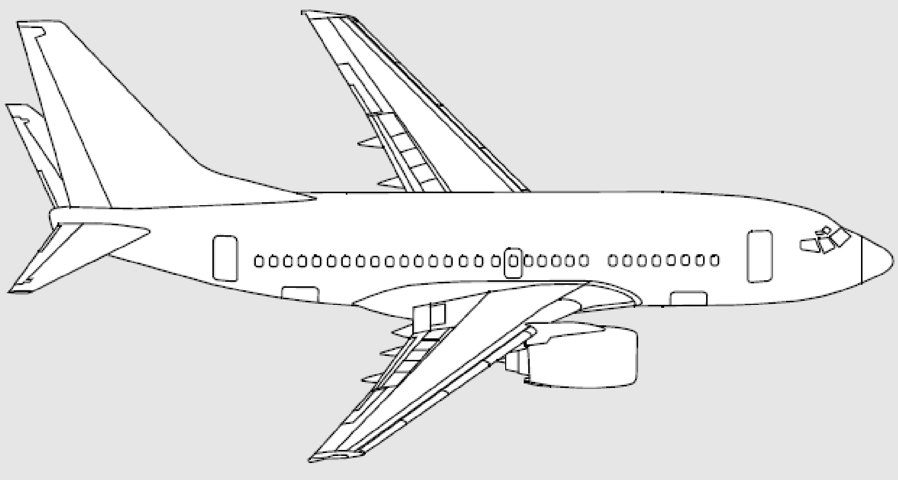
Changes from 737-300 To -400

Changes from 737-400 to -400 High Gross Weight

(737-300/-400/-500 General Familiarization Manuals TDOC737-15. Boeing, July 2003)

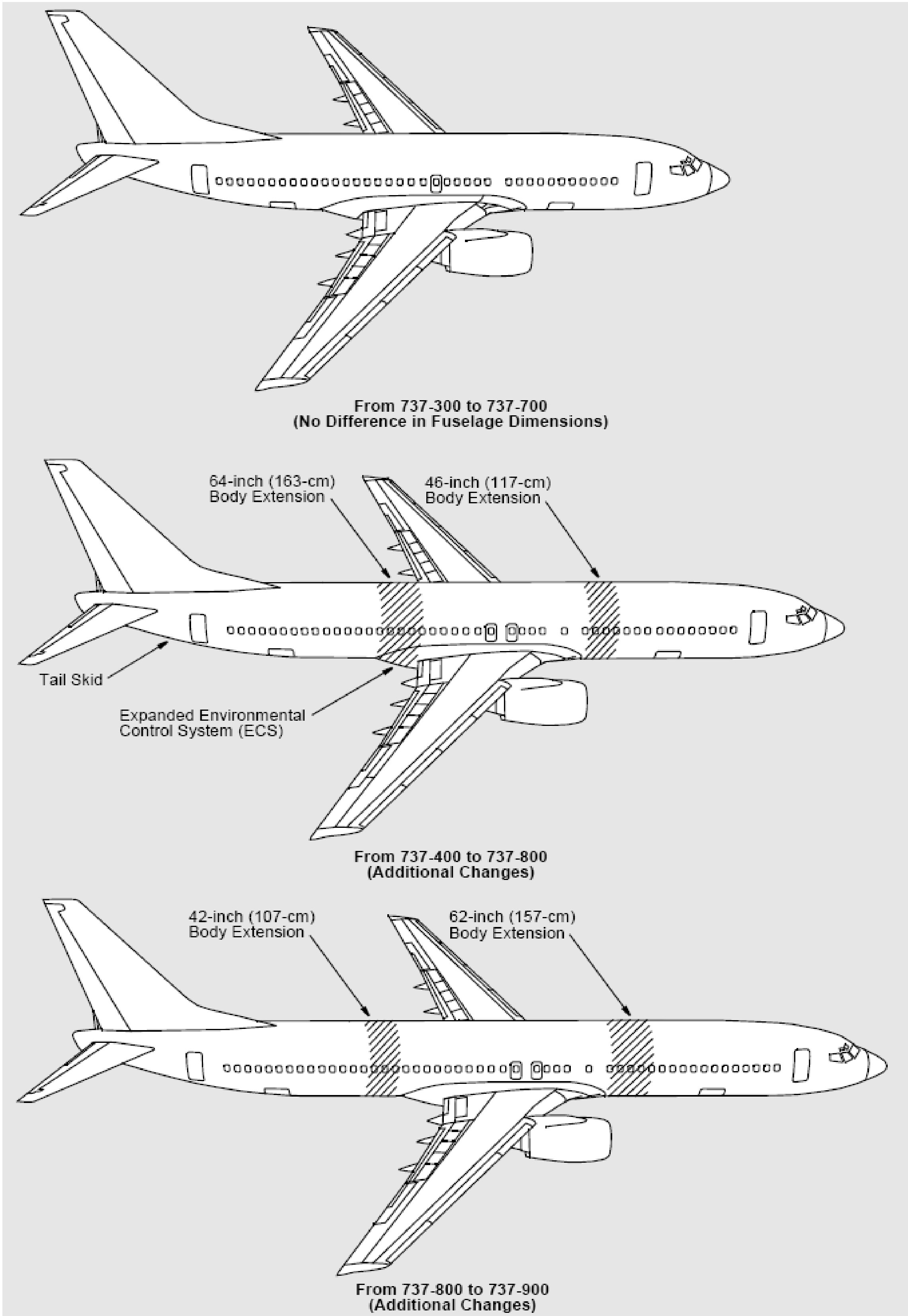


Major 737 Changes
(Typical)



From 737-500 t0 737-600
(No Difference in Fuselage Dimensions)

(737-600/-700/-800 General Familiarization Manuals TDOC737-16. Boeing, May 2003)



(737-600/-700/-800 General Familiarization Manuals TDOC737-16. Boeing, May 2003)