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Success Factors for Digital Mock-ups (DMU)

in complex Aerospace Product Development

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Vollständiger Abdruck der von der Fakultät für Maschinenwesen
der Technischen Universität München zur Erlangung des akademischen Grades eines

Doktor-Ingenieurs

genehmigten Dissertation.

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Prüfer der Dissertation:	1.	Univ.-Prof. Dr.-Ing. Horst Baier
	2.	Hon.-Prof. Dr.-Ing. Dieter Schmitt
	3.	Univ.-Prof. Kristina Shea, PhD

Die Dissertation wurde am 26.11.2007 bei der Technischen Universität München
eingereicht und durch die Fakultät für Maschinenwesen
am 29.04.2008 angenommen.

Acknowledgements

This work is the result of the research I have done over the last couple of years while working in the Digital Mock-up Integration team of Airbus in Bremen, Germany.
I may regard myself as lucky, because even after busy years of intense and challenging professional and research work on the mock-up topic the Digital Mock-up in particular is as exciting as on day one, and the complexity approach has been even more a thrilling and mind-expanding enterprise.

I especially want to thank my doctoral advisor, Prof. Dr.-Ing. Dieter Schmitt, Institute of Aeronautical Engineering, for his support and confidence in my work throughout the years. I am very grateful for both the freedom he granted me exploring the field of mock-ups with a rather unusual approach and for his rigour turning a work strongly influenced by an industrial environment into a scientific thesis.

I want to thank Prof. Dr.-Ing. Horst Baier, Institute of Lightweight Structures, for being the first reviewer and for his advice in choosing the appropriate title of my thesis. Then I thank Prof. Dr. Kristina Shea, Institute for Product Development, for being the third reviewer and for her detailed feedback and improvement proposals. Also, I want to thank Prof. Dr.-Ing. Florian Holzapfel, Institute of Flight System Dynamics, for accepting the chair of the examination board and for the smooth organizational handling of the dissertation process.

I am grateful to numerous colleagues in Bremen who shared their time providing valuable insights from different disciplines' points of view, who supported me with data, background material – in particular on the Engineering Mock-up campaigns which took place long before I joined the company – and who gave feedback and advice at different stages of my work. It deserves particular mentioning that my superiors during that period – Ralf Garbade, Thomas Stockhinger and Marc-Niels Jaeschke – granted me the freedom to arrange my professional occupation with my research the way I found most convenient.

I am particularly grateful to Dieter Weinhauer, a very experienced and now retired aircraft development engineer and manager, who supported me from the very beginning when the thesis began to take shape. I owe special thanks to him for his valuable and detailed feedback and for long-lasting discussions on the various aspects of my work. He greatly enhanced my holistic understanding of the Digital Mock-up, on its place in aircraft development and its potentials.

Last but not least I want to thank my family for their continued – moral – support throughout these challenging yet rewarding years.

Early on I decided to write this thesis in English. Translations I have made by myself, and even though having put greatest care in correctly expressing my thoughts, I can't exclude that errors had gone undetected. If so, I apologize for that and hope that the text will nevertheless be readable and understandable.

Stuhr, May 2008 Walter Richard Dolezal

To my parents and grandparents

for their love and support

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Abbreviations

3D	Three dimensional (3 coordinates of space)
A/C	Aircraft
ACE	Airbus Concurrent Engineering
AGARD	Advisory Group for Aerospace Research & Development
ATA	Airline Transport Association of America
BFC	Better, Faster, Cheaper
BOM	Bill-of-Material
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CAx	Computer Aided x:= E (Engineering), M (Manufacturing)…
CDMU	Configured Digital Mock-up
CE	Concurrent Engineering
CFD	Computational Fluid Dynamics
CFRP	Carbon Fibre Reinforced Plastics
COTS	Commercial-of-the-Shelf
CM	Configuration Management
CSE	Concurrent Simultaneous Engineering
CXI	Complexity Indicator
DBT	Design Build Team
DF	Digital Factory
DMU	Digital Mock-up
DPD	Digital Product Definition
DoD	Department of Defense
ECN	Engineering Change Note
EDM	Engineering Data Management
EDI	Electronic Data Interchange
EIS	Entry Into Service
EMU	Engineering Mock-up
ERP	Enterprise Resource Planning
FAL	Final Assembly Line
FEA	Finite Element Analysis
GAO	Government (or General) Accounting Office (USA)
HMU	Hardware Mock-up
IPD	Integrated Product Development
IS/IT	Information Systems/Information Technologies
LAI	Lean Aerospace Initiative
LC	Life Cycle
LCC	Life Cycle Cost
LE	Leading Edge
LOD	Level-of-Detail
MIT	Massachusetts Institute of Technology
MoU	Memorandum of Understanding
M&S	Modelling and Simulation
MU	Mock-up
NASA	National Aeronautics and Space Administration
NC	Numerical Control

NGO	Non Government Organization
NRC	Non Recurring Costs
OBS	Organisation Breakdown Structure
PDM	Product Data Management
PMU	Physical Mock-up
PS	Product Structure
RASCI	Responsible, Accountable, Supported, Consulted, Informed
RC	Recurring Costs
R&D	Research and Development
ROM	Rough Order of Magnitude
RP	Rapid Prototyping
RSP	Risk Sharing Partner
SAM	Space Allocation Model
SE	Simultaneous Engineering
tbd.	to be determined (or defined)
TE	Trailing Edge
TIFF	Tagged Image File Format
TDM	Team Data Management
US	United States
VDI	Verein Deutscher Ingenieure
VM	Virtual Manufacturing
VMU	Virtual Mock-up
VP	Virtual Prototyping or Virtual Product
VPD	Virtual Product Development
VR	Virtual Reality
vs.	versus
WBS	Work Breakdown Structure

Definitions

Baseline	A baseline is an agreed set of data (3D and non-3D) at a certain time during development that is used as the reference for all design activities. It represents a preliminary status and is the starting point for the next iterations. It is a configuration of a product or status of product data, formally established at a specific point in time, which serves as a reference for further activities. (Airbus, 2003)
Change	Term used to identify a definition evolution with reference to a basic or technical definition of a product. They are managed by means of a modification system. (Airbus, 2003)
Derivative	Development of a existing type (of product) for a specialized role (e.g. freighter) (Airbus, 2003)
Dual-use	These are technologies, manufacturing facilities and products that have military and commercial applications. Commercially produced items (hardware or software) that can therefore be used, with or without adaptations, for military equipment. (Lorell et al., 2000)
Effectiveness	The effectiveness of a system is a quantitative measure of the degree to which the system's purpose is achieved. Effectiveness measures are usually very dependent upon system performance. (NASA, 1995)
Evolution	Changes in the basic or reference functions and characteristics with, as a consequence, an impact on the technical definition of a technical solution. (Airbus, 2003)
Iteration	A repetition and rework activity that encompasses multiple passes for the design to converge to suit an array of sometimes conflicting specifications. (based on Browning, 1998)
3D Master Model	A Master Model is a set of digital 3D data (surface or volume) that is used as the basic reference for design and/or manufacturing. It evolves during development and when fully detailed it becomes the input for production, documentation and verification activities.
Modification	Any controlled change (by the Modification system) to the definition of the aircraft or equipment whose introduction affects airworthiness/certification, operational serviceability, customer or own company contractual/financial considerations. (Airbus, 2003)
Pilot	A pilot is a near term demonstration project. It can be a proof-of-concept and a pre-operational assessment. Done in laboratories or usually in small-scale business units it serves to find out flaws in the behaviour of the system under operational or near operational conditions.
Prototype	A prototype is the first or original example of something that has been or will be copied or developed. It is a model or preliminary version. (Chee-Kai and Kah-Fai, 1998)
Version	A specified customized definition of an allocated aircraft within a given production standard/model. (Airbus, 2003)
DMU Completeness	100% of all digital 3D parts/models linked to the official DMU PS tree in the detail required that makes up the final product minus the sum of all cut backs due to efficiency reasons

Chapter 1 Introduction

1.1 Economic challenges, technological advances and new ways of working

Since the early 1990s high-tech manufacturing industries around the world have undergone substantial changes. Global economic downturn, shrinking defence budgets and stricter regulations e.g. on subsidies[1] have made broader collaboration and financing approaches for future large projects a sheer question of survival. For instance, by the year 2000, a rapid consolidation process in aerospace had only a few global players left. To keep the competitive edge companies had to become more effective and efficient, while offering more affordable products[2] with even higher capabilities than their predecessors.

The changed business environment and its implications drew broader attention to a common phenomenon that till then was rather of academic interest: complexity. It was the often-unpredictable behaviour and results of dynamically changing complex systems that triggered increased interest of a wider public. On the other hand, for developers of sophisticated technical products such as large transport aircraft, complexity was by no means a new phenomenon. Probably it was not described as such. It was dealt with, rather more intuitively than methodically founded. Overall awareness on complexity has grown considerably in recent years, while one could follow the emergence of (software) tools and methodologies to unravel more of its implications.

That era coincided with tremendous increases in software and networking capability and in processing power in the Information System/Information Technology (IS/IT) sector. The impact was twofold: Firstly, all kinds of development activities with its huge amounts of data could from then on be managed in digital form over the entire project life-cycle. Secondly, it helped to bridge the distance gap between the numerous places where the ever more sophisticated products were designed and build. It has been crucial for enabling concurrent working over the entire enterprise, with partners and the supply chain.
One offspring offered particular benefits, as checks with expensive hardware could be drastically reduced. 3D CAD design and *Digital Mock-ups* (DMU) have emerged as one of the major pillars of what became to be called "Virtual Product Development". The DMU in particular has revealed itself as an excellent means of anticipating a lot more questions during development than ever before, at lower costs, in shorter time and with higher quality output. Within a few years the DMU has become nearly a standard in high-tech manufacturing industries. It has also marked the beginning of the downturn of the former exclusive reliance on Hardware Mock-ups in support of product developments.

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[1] For instance in the wake of the General Agreement on Tariffs and Trade arrangements (GATT); the intention was to crack down on seemingly unfair governmental subsidizing of certain sectors, among them agriculture and the high-tech business including aerospace.
[2] That is why successful methods of Japanese car makers triggered the question on their applicability for the aerospace business. Theoretical preparation by various research institutes and the academia in close cooperation with industry (Wildemann, 1993; Bullinger, Warschat, 1996; Murman et. al., 2002) culminated in efforts such as the Lean Aerospace Initiative (LAI).

1.2 Aim and scope

The aim of this study is to *develop a complexity based approach* using "complexity indicators" for the assessment of complex systems and *validate the method* with six mock-up campaigns (two Hardware Mock-ups, four Digital Mock-ups) from large aircraft wing development projects. The *results shall indicate what time, cost and quality impacts the mock-up campaigns* had and still have.
The method is *evolutionary* and has an *approximate character*. But it shall be sufficiently accurate to give clues on the relevant (success) factors to control and steer the 3D development efforts from a complexity and systemic point of view.

The results are naturally 'biased' by a research focus on aerospace. It is not the intention to derive statistically significant data, as for such a purpose a greater amount of complex research & development projects would have to be investigated. Furthermore, mock-up applications and results can and will vary with industry, company approach and different products, all having unique circumstances. Nevertheless, the author believes that basics and methods are applicable – maybe in adapted form - throughout a vast part of manufacturing industry.

1.3 Motivation for this study

There were three reasons for doing this study:

(1) Though seemingly established, the subject 'DMU' is remarkably "under-documented" from a scientific point of view[3]. The development of the digital 3D Boeing 777 was one of the few documented examples in aerospace (e.g. Sabbagh, 1996) that provided first evidence of the potentials on a larger scale. In part this may be attributed to a still comparably young subject. But companies also remain reluctant to give detailed information on full potentials and benefits of its application. It seems as if they see it as a business advantage that shall not be made easily accessible to competitors. It was therefore very appealing to do some work on a still vastly 'untilled ground'.

(2) Both the Hardware- and Digital Mock-ups are "children" of industry. Therefore it is not surprising that in 3D design industry and not the academia drives the frontiers of developmental efforts. Since their beginnings, 3D CAD modelling, DMU simulation tools, processing hardware and the IS/IT infrastructure as a whole have improved greatly. Concepts of integrated digital development grew mature enough to be put into practice. 'Digital frontiers' are now pushed even further fully exploiting the potential over the entire development community and over the whole project life cycle. But still missing are investigations on how mock-ups, DMUs in particular, contribute in meeting *time-cost-quality goals*. The author hopes to contribute in filling that gap so that it serves both sides for mutual stimulation in developing advanced concepts and techniques.

[3] though since starting this thesis some works have been written about it (e.g. by Markworth, 2003) and numerous articles in dedicated CAD/PDM magazines had been published; there had also been from the mid 1990s to early 2000s the European Commission (EC) co-sponsored AIT–DMU Project (AIT- Advanced Information Technology) involving some key manufacturing companies in Europe under the Fourth Framework Programme of the EC: among others it aimed at establishing standards and researching DMU applications.

(3) There is complexity inherent in any developmental efforts of sophisticated products. The idea is placing this complexity right in the centre of this investigation. Adopting a “complexity point of view” enables to assess both technical and programmatic aspects of Hardware- and Digital Mock-up campaigns from a rather new and – at least in general technical publication – not well known perspective.

1.4 Industrial and scientific approach – research methodology

Hypothesis vs. exploratory driven. Hypotheses are very effective when building on research in areas with several theories competing for the best explanation how a system works. Exploratory (or “evolutionary”) research follows a broad, more open-ended approach. It allows the examination of many factors that may affect the system in question. Regarding the relatively unexplored area of DMU and the rather new complexity approach the second road was chosen.

Level of analysis. This is important for having a basis or reference, against which results can be measured and compared. One can either go for (1) individual development *projects* as a whole, (2) for specific development *phases* (e.g. concept phase, definition phase), or have (3) a *life-cycle* view. In all areas research and data are too limited to be taken into account alone. The life cycle approach is in particular question as DMU related life-cycle data of large projects are either too few or not available at all. The simple reason: the DMU subject being too young. In either case it is difficult to find reliable and comparable data. This study therefore compares the same phases the investigated projects have gone through.

Depth vs. breadth. One can usually perform a study in great depth or a large number of them in less depth. While an in-depth study of a single area will result in a full description of the process or system, related areas might be left out that could play significant roles. For drawing broad based conclusions it is necessary to review a large number of (different) projects and compare them. But the more valid statements are sought the more abstract they will have to be formulated. Research will then need to be on a more general (or superficial) level. Though limited in number, the projects were quite diverse in detail so that an adequate compromise of depth and breadth had to be found.

Data collection and evaluation. In the course of this study numerous interviews were held with key actors from Aircraft Design Integration, Planning and Manufacturing to gain a broad understanding of the process and issues involved. For some people the author prepared a questionnaire that proved helpful in reducing misinterpretations. Whenever possible, documented data were sought in support or opposition of the information collected.
Archival and literature research of numerous books, papers, articles in hardcopy or via the internet as well as program/company specific material revealed a poorly documented area. Databases were limited for DMUs, even more so for Hardware Mock-ups (HMU). Key people who worked on the latter provided crucial information, and analysis had to be based on scarce documentary of some departments. These program documents enhanced the understanding and fortified conclusions. Very few case studies were found documenting the development effort of highly complex products and processes (e.g. Winner (2000) on the development of a new US attack submarine). No clear evidence could be found on the quantitive impact[4] of DMU work on time/cost/quality scales.

[4] Glende (1997) for instance provides *relative* indications on the impact of cost drivers in A/C development, but no values at all.

1.5 Chapter Overview

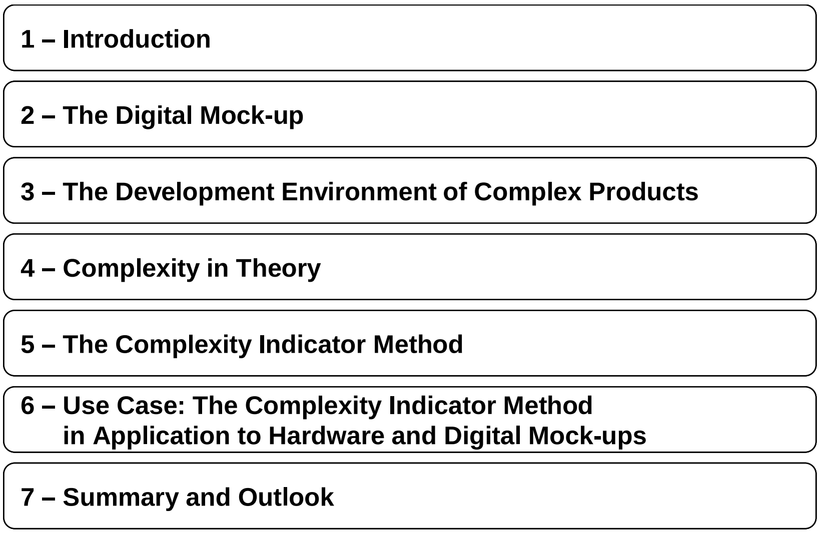

Fig. 1.1 Chapter Overview

Chapters two, three and four lay the foundation for the complexity method and frame the study context.
Chapter two provides a holistic overview on the Digital Mock-up, its dimensions, basic principles and elements and its applications.
Chapter three briefly summarizes today's business context within which complex products are developed.
The theoretical foundation for the complexity method is presented in *chapter four*, with a short but concentrated introduction to fundamental aspects of complexity and how to cope with it.

Chapters five and six comprise the scientific contribution itself.
Chapter five explains, step by step, the new "complexity indicator" method, with its requirements and constraints.
The method is then applied on six mock-up campaigns of Aircraft development in the use case outlined in *chapter six*.

Chapter seven finally summarizes the work, draws conclusions and gives an outlook on possible future developments.

Chapter 2 The Digital Mock-up

From the very beginning, designs where documented as sketches and on (2D) technical drawings. For engineers sketches are often enough to efficiently communicate technical ideas. For a broader technical audience drawing rules were introduced to have a more standardized "language". But for outsiders however, technical drawings are not always fully imaginable, so isometric representations helped grasping the subject. The more general and the more different the education of people, the simpler and more unambiguous the representation of the technical content has to be. That was one of the reasons why (fully aware of this difficulty or not) 3D physical models were built to understand how the product shall look like, how parts fitted together and how they behaved. These mock-ups where real objects that could be touched. They helped bridging some substantial barriers: language, education and professional background.

The *Digital Mock-up (DMU)* is the modern successor of 3D Hardware Mock-ups (HMU; or: Engineering Mock-up – EMU), until the beginning 1990s a well-established practice in industry. Was it first seen merely as means to enable faster and better 2D drawing creation, it now encompasses the whole development and project life cycle. In modern manufacturing industries it is now standard application and seen as key competence to faster design better and cheaper products.

2.1 Definition

The definition for this study shall be the following:

A Digital Mock-up (DMU) is a digital 3D representation of a product together with its product structures and attributes.

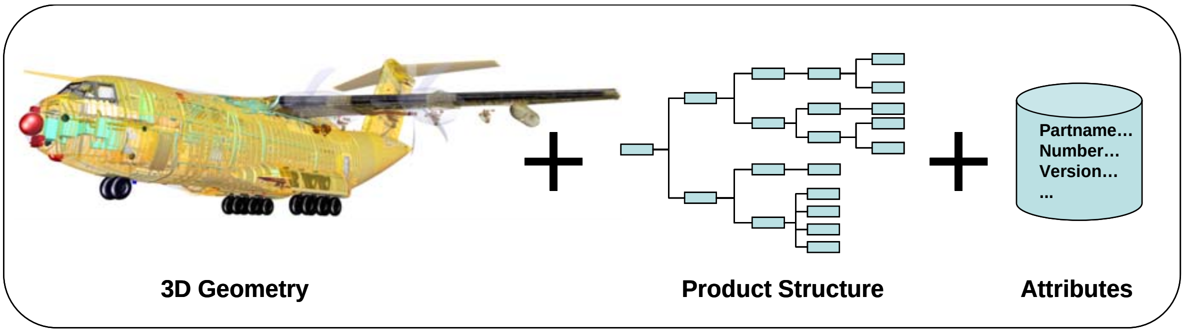

Fig. 2.1 Digital Mock-up of the military transport aircraft A400M

Several other definitions can be found for DMU[5], but the reason for the above mentioned in this study can be found below[6].

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[5]Döllner et al. (2000): *The Digital Mock-up (DMU) is a computer-based product definition of a real product. It consists of documents, attributes and structures.* =>continued on next page

The (usually)[7] CAD generated 3D models are one element of DMU. The others are called *metadata* and comprise the Product Structure together with all attributes. The *Product Structure* (PS) is the breakdown describing the hierarchical dependencies of these models and organizes them. The *attributes* describe what these models are and what their status is.

2.2 A holistic view on the Digital Mock-up

The intention is to provide a complete but not too detailed picture of the various aspects of the DMU. Understanding its multidimensional nature enables seeing the challenges for its implementation but also the full potentials and benefits of its use. Therefore, chapter two is organized according to the three fundamental dimensions seen below. Though treated separately for ease of understanding, they are contemporarily present whenever dealing with the DMU, even if not perceived as such.

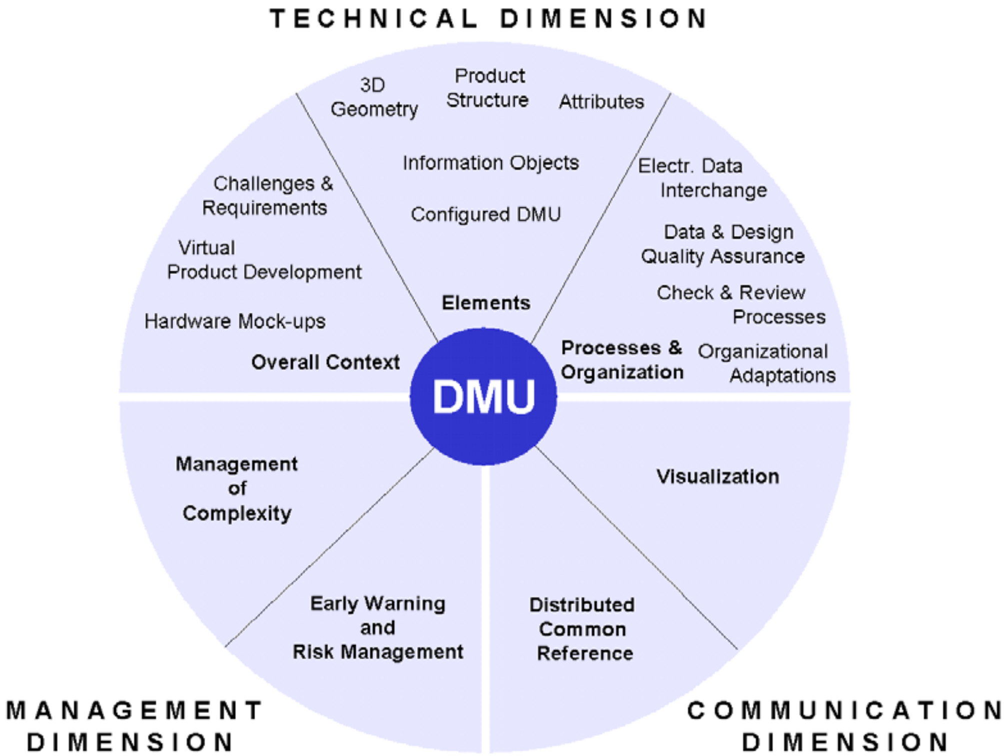

Fig. 2.2 The "DMU wheel" – the three dimensions of DMU operations

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A DMU represents a clearly defined set of data in the product model, whereas the term "product model" includes all of the information gathered during the product development process.
Gausemeier et al. (2000) don't differentiate Digital Mock-up and Virtual Prototype, stating "*it is the basic idea to create computer models for all relevant aspects of the product in development and to analyse them. Thereby can the time and cost consuming constructions of real prototypes be reduced.*"
Berchtold (2000) sees the DMU completely embedded in its development context*: "A 'Digital Mock-up' is a complete virtual working environment for the whole process chain of 3D development and support of complex products with integrated effectivity and variant control."*

[6] The definition chosen here follows the notion of "what it is" and not "what it does", or "what can I do with it". The intention thereby is to reduce confusion due to a vast field of applications DMUs have. However, as other authors point out, it is perfectly reasonable to relate DMU with activities of its application.

[7] It is also possible to generate 3D models with Virtual Reality (VR) software. They are normally built of triangles (polygons) and can be converted to DMU tool proprietary formats.

2.3 Technical Dimension of DMU – Overall Context

2.3.1 From Hardware Mock-up to Digital Mock-up

Up to the 1990s, the construction of Hardware Mock-ups (HMU)[8] had been an integral part of any complex product development. A Mock-up[9] is traditionally a hardware or physical model of a component, an assembly or an entire product. It can be full-size or a scaled model made of paper, wood, metal or actual production hardware (Leitner et al., 1994). All airframe integrators, civil or military, the space-, automobile- and ship-building industries have used (or still use) HMUs to evaluate and verify the design, train personnel or present them to customers.

Major HMU activities involve the assessment of space allocations, detailed part fitting checks, interference and clearance studies, part installation and removal and assembly verification. A HMU was the primary tool for determining lengths of electrical harnesses and for fitting tubes, hoses and other routings into a densely packed structural environment. Maintenance checks could also be run with them. Mock-ups for marketing purposes still represent an important means in the commercial business and are likely to do so for quite some time[10].

Herrmann (1992) lists four types of Hardware Mock-ups for aerospace applications:

(1) The *Design Mock-up* made primarily of wood and plastic in scale 1:1. It is used in structurally complex areas with a high density of systems like in the Cockpit or the Wing-Fuselage junction. The intention is to show design teams, customers and authorities, as early as possible space requirements and constraints for system installation and supportability.

(2) The *Sales Mock-up,* which uses original cabin equipment in a representation of the fuselage as soon as basic parameters such as main dimensions, door positions and galley arrangements are known. Airbus, for example, uses dedicated “Mock-up Centres” at its Headquarters in Toulouse in support of sales campaigns.

(3) The *Production Mock-ups* that serve first of all to optimize manufacturing techniques and can be regarded as first manufacturing trials.

(4) The *Engineering Mock-up,* the most challenging mock-up from a product development point of view has to fulfil a wide range of tasks: It will be used for checking structure and system installation, for system tests[11], maintenance studies, also in front of the customer and for validation with authorities. As a training platform it shall prepare a smooth transition to series production.

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[8] Sometimes termed Physical Mock-ups (PMU). The term “Mock-up” is not yet standardized, so that different spellings exist that are equally valid: Mock-up, Mockup, Mock-Up. It might be confusing to have EMU standing for both “Engineering Mock-up”, as the classical Hardware Mock-up is often called and “Electronic Mock-up”, as the Digital Mock-up is sometimes named.

[9] Airbus (2003) defines *Mock-Up* as “a full-size model built accurately to scale for study, testing or display”.

[10] Airline customers want to virtually “touch and feel” the cabin they are about to buy. No sophisticated DMU or VR system today can provide the multiple impressions human perception is able to grasp.

[11] In this respect Engineering Mock-ups overlap with functionalities usually evaluated using so-called “(System) Test Benches” or “Iron Birds”.

Fig. 2.3 Engineering Mock-ups (EMU) for wing equipping of the Airbus A330/340 Long Range aircraft at plant Bremen, Germany. These scale 1:1 mock-ups of the wings (left in foreground, right in rear part of hall) where used to evaluate fit and form of all installations on leading & trailing edges for structural components (e.g. support structure), hydraulic tubes, electrical bundles, flight controls, actuators and bleed air.

The definitions “Design Mock-up” and “Engineering Mock-up” have not always been consistently used. Maybe the major distinction is that the former was rather used in the very early phases while the latter was build upon a later and more advanced design.

For the military aerospace sector, the US Department of Defence (DoD) has issued specification MIL-M-8650C (US Government, 1976). It covers requirements for the construction of aircraft and related system mock-ups for formal evaluation and preparation of mock-up data. It distinguishes three categories and gives guidelines for mock-up reviews. In one of the first publications on Digital Mock-ups, Rich (1989) also distinguishes three main classes of mock-ups[12], similar to those mentioned in the military specification.

Table 2.1 Mock-up categories

Mock-up category	MIL-M-8650C (1976)
Class I	Constructed of inexpensive materials, proportionally but not necessarily dimensionally accurate. Used to determine shape, allocate space, or used to present a new idea.
Class II	Constructed of good grade materials with overall dimensions as close to drawing as practical. Production materials are used in critical areas and installations are per drawing. Used in detail design and as a demonstrator.
Class III	Constructed of production materials with production tolerances. All structures and equipment should be actual or simulated wherever practical. Used to determine layout of plumbing lines, electrical wiring runs, and to prove out all installations prior actual production.

[12] Rich names another class of mock-up sometimes used. This *“In-Line Mockup”* uses an actual production airplane for development of configuration revisions in lieu of construction of a full-scale model.

Class II and III mock-ups are sometimes combined, depending on objectives. This justifies speaking of a mock-up having Class II and III areas, or different levels of detail in the same mock-up.

Hardware Mock-ups, though having been standard and successful industry practice for a long time have a number of *shortfalls* that are better addressed with their digital substitutes. In fact, they are only an assurance that everything will fit together, in former times based on 2D drawings. No “pre-mock-up” investigations can be run. Update with modifications or duplications are expensive, as always a physical component has to be produced. The response to changes is relatively low (but for minor ones like drilling holes) and there is an inability to reflect real-time configurations. Thus, the mock-up is usually representative only for one aircraft, and is of very little use afterwards (e.g. after certification). Last but not least, maybe the major issue, it is quite costly. There are design, labour and maintenance hours to be paid for, not to forget tools and all the materials. In addition, it consumes precious factory floor space.

2.3.2 Emergence of Digital Mock-ups

The change came with the introduction of 3D CAD modelling systems in the mid 1980s. Though initially restricted in performance and functionalities, they offered the chance to reduce the number of HMUs. Today, Hardware Mock-ups are largely eliminated from Engineering and Manufacturing processes.
As already mentioned, not many DMU applications have been documented so far. Of those few aerospace examples in evidence are the already cited Boeing 777 airliner (Sabbagh, 1996; Glende, 1997), the V-22 Tilt-Rotor (Dougherty and Liiva, 1997), the F/A-22 Fighter Aircraft (Cook and Graser, 2001), the Eurofighter Typhoon (Berchtold, 2000) and the NH-90 helicopter (Leitner et al., 1994; Leitner, 1996; Tauber, 1997). Markworth (2003) specified on the application of DMU in the automotive industry and detailed its introduction at a well-known German sports car maker.
Today, a mix of both mock-ups is in use. In those areas where the focus lies on giving a \`touch and feel\` impression and where \`handling of real objects\` is required, the hardware mock-ups still prevail. But there is a trend with shifting priorities towards the digital world.

Table 2.2 Different application areas of Hardware Mock-ups and Digital Mock-ups distinguishing primary and secondary focuses

	Engineering/Manufacturing/ Supportability	**Training**	**Marketing**
Primarily used	**DMU** for the product itself (airplane, ship, car…) but also for all its production means (factories, transportation equipment…) and verification of servicing procedures	**HMU** e.g. Space Shuttle Training Mock-up, International Space Station facilities, Fuselage/Cabin Mock-ups for workers being assigned to a new assembly line…	**HMU** e.g. to provide customers a “touch and feel” impression, e.g. with fully functioning Cabin Interior – the “Sales Mock-up”; (scaled) Mock-ups for exhibitions
Secondarily used	**HMU** to validate particular risk areas, to cover certification relevant items, prove required functions (system tests) that are not yet reliably possible in a digital environment; examples: Design-, Production-, Engineering MU;	**DMU** supporting faster and better learning e.g. for Space Mission preparation; growing importance as computer performance and computer graphics advance (e.g. Virtual Reality)	**DMU** growing importance for external communication especially when coupled with Virtual Reality techniques; increased reactivity on customer needs and requirements

Current CAD systems allow the modelling of various 3D cases, like flexible representations of parts according to their build-in situation (see Appendix A). Many of these functionalities are customized to clearly express the design or process intent. But there remain a few cases that are not thoroughly addressed. These limit the meaningfulness of Digital Mock-ups in some respects. Near term software developments may therefore focus on, for example:

- Sufficiently accurate representation of deformed parts under various load cases
- Elastic parts (harnesses, hoses, sealing, cloth; elasticity of components: e.g. pre-deformations and relaxations…)
- Accumulation of production tolerances of large assembly representations

Long-term developments should include

- Timely changes of volume of substances (fuel, water, oil, air, greases…); for instance fuel consumption during flight and its influence on the centre of gravity and gust loads on the wing (-shape)
- Dirt, ice, snow (e.g. in cargo area of transporters, landing gear area…) and lubrication to better simulate operational cases with the DMU

To truly check a design on these criteria today either other software tools have to be used (e.g. using Finite Element Analysis - FEA, Computational Fluid Dynamics - CFD, dedicated analysis and simulation tools…) or rely on hardware mock-ups, hardware supported simulations and test rigs. Prior to any decision there will always be a trade-off surrounding two questions: Can (different) simulation tools show with sufficient accuracy how the components behave and are side and cross effects accurately considered, or can a hardware test be done quicker, less costly and with more confidence?

2.3.3 Virtual Product Development

Virtual Product Development (VPD) is the term for developing a product heavily – but not exclusively - relying on digital representations throughout the whole or a part of the project's life cycle. The term "virtual" expresses that it does not yet exist as real hardware, that in fact it is not touchable. Such kind of development makes use of the whole suite of software tools (CAD, FEA, CFD, PDM…) for layout, geometry generation, calculation and analysis, test and evaluation including the management of digital data. This suite enables to concurrently anticipate a lot more considerations sooner for product and process design than in earlier days. Although mostly relying on and working with approximated data, calculations and simulations today come close to verification and qualification test results.

The DMU is a core element in VPD, as it is the culmination of the design intent that gives the product an "early face". If Virtual Product Development is the unifying concept and approach, *Virtual Prototyping*[13] actually is the process of digitally testing and evaluating the virtual representations of the product in all aspects of developmental and operational life. The DMU is therefore embedded in a spectrum of prototyping activities, which aim to mature the product as fast, as less costly and as reliably as possible.

[13] For Coyle and Paul (1997) *a 'virtual prototype' is an integration of data from various sources that define the total product and its environments. It provides a superior means of visualizing any aspect of product design, its fabrication and assembly and the environment it will be used in.* According to Spur and Krause (1997) shall a *prototype* combine all functions of a product and resemble as much as possible the new product.

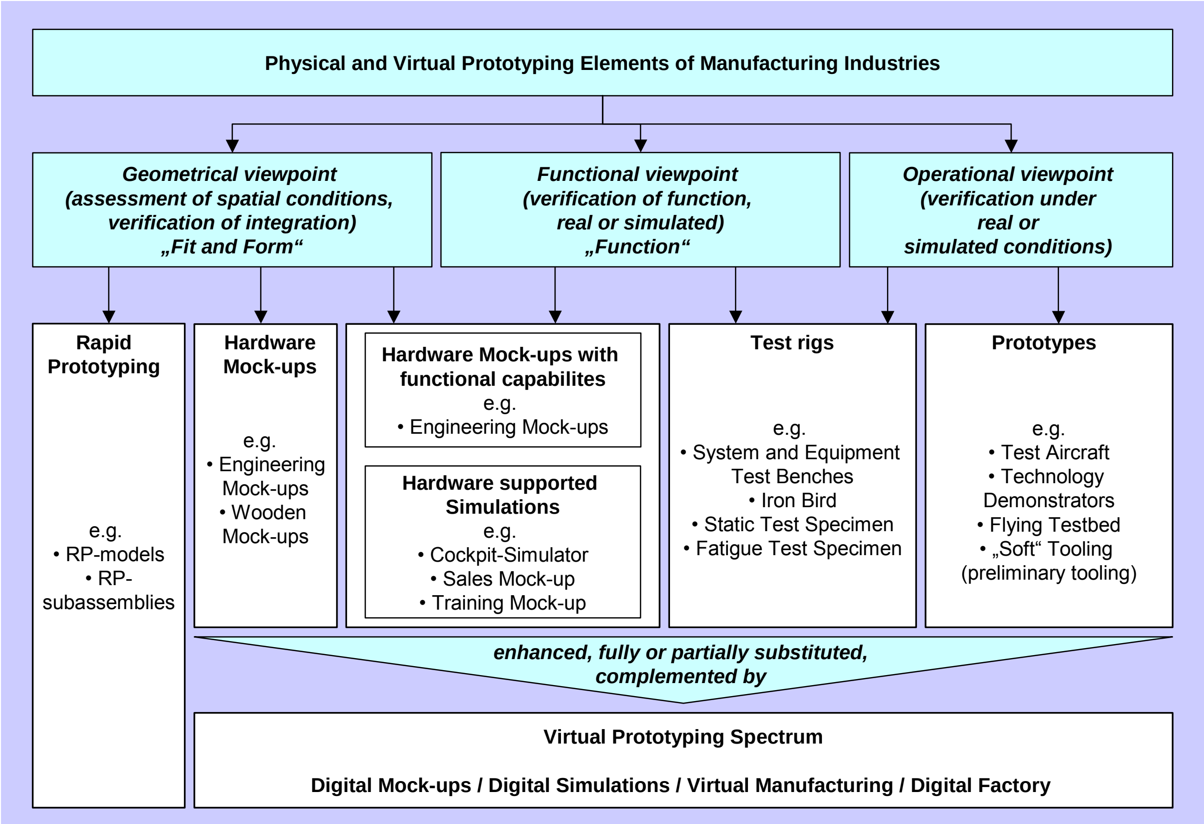

Fig. 2.4 Most common prototyping elements of manufacturing industries

The majority of Digital Mock-up applications, as the classical substitute of Hardware Mock-ups, cover the geometrical and functional areas. The closer one tries to assess the *behaviour and interactions* of the product in its environment the more will efforts shift to the right end of the spectrum.

Commercially available Digital Mock-up, Digital Simulation (simply ‘DMU-tools’) and Virtual Manufacturing/Digital Factory tools have matured insofar as they cover most requirements for geometrical and functional assessment, and, to a lesser extent, operational constraints. Shortfalls have to be compensated either with specific tools (e.g. for tolerancing), own software developments or with physical specimen.

To fully cover the whole spectrum requires all tools in the CAD/CAM/CAE environment to efficiently communicate with each other so that results obtained individually can be compressed to an overall view of the Virtual Prototype.

2.3.4 Challenges and requirements for DMU operations

The challenges of today and the foreseeable future for the DMU of complex products in a demanding development environment can be summarized with a few points:

- Adaptation of business processes to exploit the full potential in all three dimensions, up-, mid- and downstream
- Generation, easy and care-free handling and life-cycle management of large volumes of 3D geometry and metadata (many Gigabyte up to several Terabyte of data)

- Provision of all relevant DMU data/information anywhere in the extended enterprise (= prime contractor(s) plus partner(s) plus supply chain), anytime in high quality
- Mapping of CAE data and information in the DMU environment and vice versa

These points do not address a single topic but challenge technical-organizational improvements in many areas: company/project policy, software applications and IS/IT- and visualization infrastructure, adaptations and re-directions of methods and processes and, of course, changes in people's organizations together with training and empowerment.

The response to that is a list (here deliberately incomplete) of some generic top-level requirements for DMU operations, which are highlighted in the table below:

Table 2.3 Top-level requirements for DMU Operations

Top Level DMU Policy Requirement
• **DMU is the Master:** Any design and drawings shall be based and referenced in the 3D world, throughout the company and the supply chain. Iterations, changes and modifications are done in 3D first, afterwards fed to other applications and processed accordingly. Only minor exceptions can be accepted, as they are deemed technically justifiable and economically feasible.
Generic DMU Data Quality Requirements
• **Completeness:** The DMU shall comprise the complete set of 3D models and associated metadata. This comprises current and historical data, official and non-official in-work and released data, wherever they may be stored.
• **Actuality**: The DMU shall be represented by the latest 3D models and metadata. Changes shall be made apparent wherever necessary as fast and as economically feasible as possible.
• **Consistency:** The DMU shall be the unambiguous resemblance the product. Any processes, methods, rules, standards and guidelines for the provision of good data quality have to be followed thoroughly.
• **Configuration**: The DMU shall be represented in the exact configurational set-up as it is under investigation or as it is ordered by the customer. This encompasses the baseline set together with all variants and options that are valid for a distinct product breakdown.
Generic DMU Design Quality Requirements
• **Specification compliance:** The DMU must flawlessly represent the latest technical specifications, directives and guidelines.
• **Production compliance:** The DMU must be fully compliant to manufacturing, assembly-integration, test and transportation requirements. This shall e.g. be shown in the respective PS breakdowns
DMU Process Requirements
• **Electronic Data Interchange:** The EDI shall ensure the constant provision of DMU data and information anytime, wherever they are needed and in whatever format. The availability must keep pace with growing data volumes, exchange rates, additional participants and diverse contents.
• **Workflow**: The DMU shall be an integral part of the design process with steps followed in a workflow for better traceability of changes and anticipation of impacts, upstream and downstream.
• **DMU Trouble Resolution Cycle**: DMU troubles shall be communicated at short notice to all stakeholders in standardized form. Resolution of the trouble shall be done in an adequate period of time. Tracking and monitoring shall be ensured and statii presented regularly to responsible people for launching corrective actions and for ensuring pre-emptive risk and problem avoidance.
• **DMU Roles and Responsibilities**: Roles and responsibilities for all stakeholders shall be defined. (e.g. following the RASCI methodology)
DMU Technology Requirements
• **IS/IT backbone:** the IS/IT environment (network, workstations, PCs, Operating System) shall have adequate performance and be able to quickly adapt to new situations: higher number of users, handling bigger amounts of data and processing higher exchange frequencies.
• **DMU Software tools:** Software shall be robust and capabilities shall be sufficient to fulfil all DMU tasks throughout the project life cycle, it shall further be flexible enough to incorporate new features.
• **Visualization equipment**: Adequate visualization equipment (e.g. projection means, screens, dedicated graphics processing hard- and software) shall be provided in sufficient numbers to show the DMU in the most convenient way, e.g. in scale 1:1 and as 3D stereo representation.

2.4 Technical Dimension – the elements of the Digital Mock-up

2.4.1 Geometry - Basic considerations for the 3D representation of digital objects

3D solid modelling allows a great deal of insight into the design from the moment of creation. The final model will be an exact digital replica (with the exception of manufacturing tolerances) of the part to be produced. The geometry can have different formats, either being *exact or approximated*, *data volume reduced or not reduced*:

Table 2.4 Data representation criteria

Criteria	Representation (stored in database)
Exact, not data volume reduced:	CAD native
Exact, data volume reduced:	Boundary Representation
Approximated, data volume reduced:	Tesselation, Voxel

The level of detail of models changes throughout product development and depends on particular phase requirements and objectives. The overall aim of the DMU is to allow full visualization of the product in three dimensions at any time, and to be able to simulate and analyse geometric and functional behaviour. The geometrical representation of the components in operation is likely to be different (especially in aerospace) from those during design, manufacturing and assembly ("jig-shape"). This has to be accounted for in creation and analysis and eventually needs to be verified with compatibility checks with downstream areas:

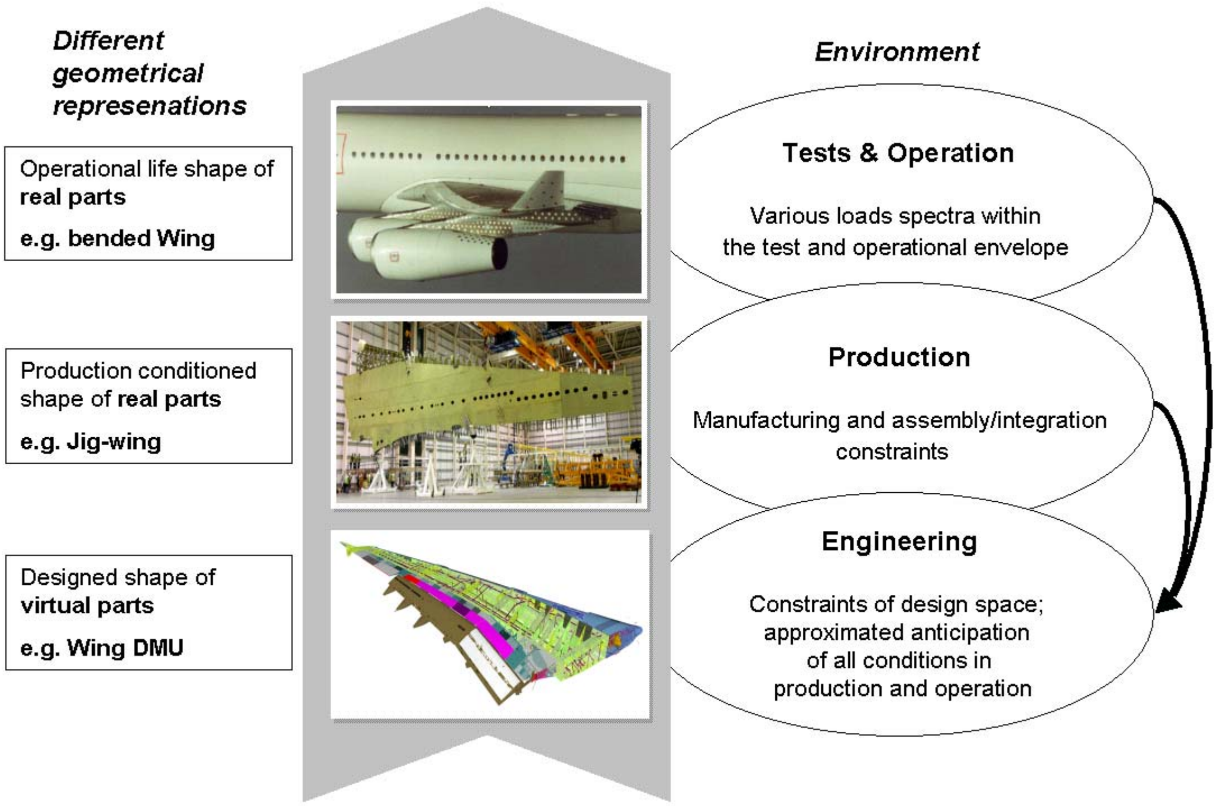

Fig. 2.5 Different environments have different impacts on the 3D representation of parts

The basic representation of most 3D models is that after which they are manufactured. But complex products like aircraft, spacecraft and ships show many cases in which the ideal basic representation differs from the actual build-in situation. The task (representing them adequately on a drawing) is not new, the challenge today is to it with 3D modelling tools in a concurrent environment.

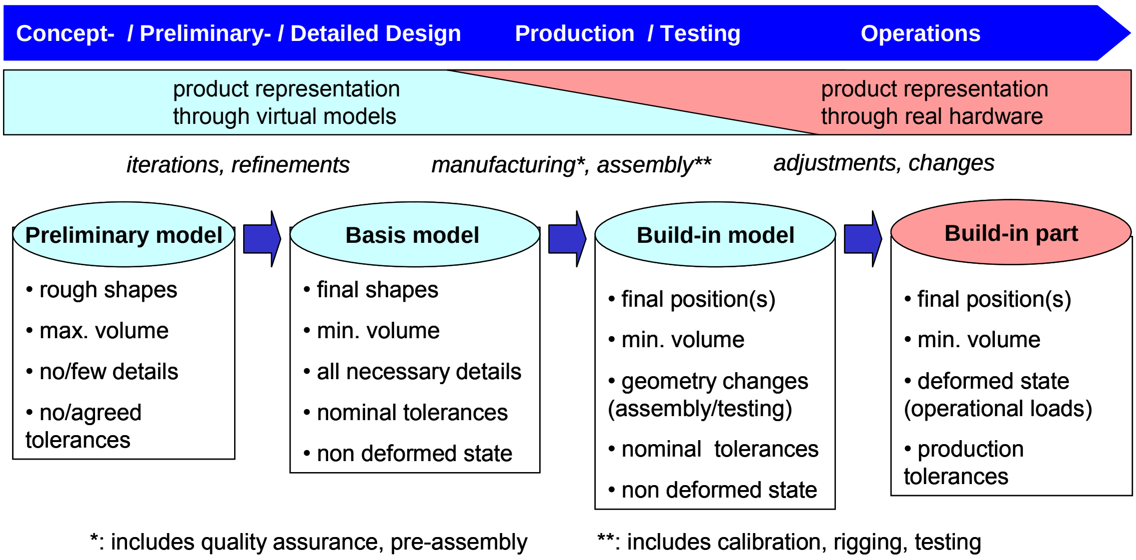

Fig. 2.6 3D models and their characteristics at different stages in development

In every phase there will be trade-offs to what degree 3D models have to be detailed for satisfying requirements of the own discipline and those of other faculties. Simplified representations may well do the job if it is guaranteed that the correct information is passed on. This is also true for performance restrictions of CAD systems having to handle large assemblies and sophisticated representations.

2.4.2 Metadata I – the Product Structure

A Product Structure is, in fact, a *hierarchical breakdown of the product*. Its purpose is both to decompose and to organize. VDI Guideline 2219 (1999) states that *a product structure essentially is a hierarchical decomposition of the product in main- and sub components that is arranged for ease of overview.*
In general, the higher the granularity the easier the handling: Smaller modules/units can be better planed for and their behaviour can be determined in a better way. The breakdown goes as deep as to those single parts, where one can be sure with good certainty that they will sufficiently fulfil requirements. As far as the breakdown is concerned it is essential to illustrate technical and organizational dependencies and interfaces as well as to document processes steps. In the DMU environment the Product Structure is a prime working tool allowing the handling of numerous elements while at the same time allowing easy retrieval in the overall context.

The figure below shows the major influences on the Product Structure, with underlined areas given particular notice in this sub-chapter:

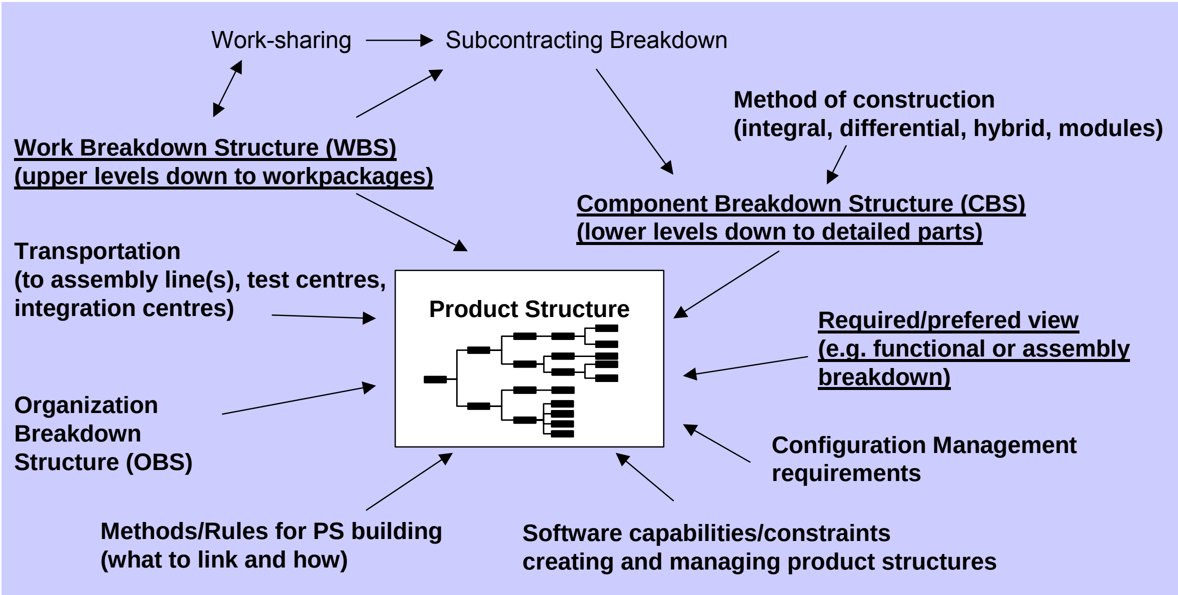

Fig. 2.7 Program specific, organizational-, technical-, methodological and process related requirements and constraints shaping Product Structure trees

In Engineering Data Management/Product Data Management[14] systems (see also Appendix B) data models are defined that connect different documents and other object classes via *relations*. The Product Structure represents the *logical connections* of those segments, which might be physically dispersed and realized by different database systems.

Product Structures during the development project

In the very early phases Product Structures will largely reflect a preliminary Work Breakdown Structure (WBS). Few and simplified models/assemblies will populate the tree. Later stages will see complex branch structures, from which parts-lists and drawing lists will be created to feed the *bill-of-materials (BOM)*[15].
Some companies and (PDM-) software vendors don't differentiate the two terms 'Product Structure' and 'Bill-of-Materials' (BOM). In this study the terms PS and BOM will be denoted separately, for two reasons: (1) the very concept of Product Structures encompasses the power to combine all different views on the product, may it be functional (design) or process-oriented (manufacturing, industrial), (2) a Product Structure is a primary design tool in a Concurrent Engineering environment, and sustained throughout the entire life cycle. The BOM, on the other hand, will manually or automatically be transferred from the PDM system (based on the current PS) to Enterprise Resource Planning (ERP), for which it is a primary breakdown upon which production activities are planned.

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[14] Optegra EPD.Connect™ (from PTC), Enovia VPM™ (from IBM – Dassault Systèmes) and Metaphase™ (from Metaphase Technology) are some examples of EDM/PDM systems with own product structure browsers.
[15] A bill-of-material is a formally structured list for an object (semi-finished of finished product) that lists all components parts with name, reference, number, quantity, condition of supply and unit of measure for each component. It is a product data structure, which captures the end products, its assemblies and their quantities and relationships (DRM Associates, 2002).

Different views of the PS

During the development phases different disciplines have distinctive points of view on the product. For instance, structural design people will see an aircraft quite differently than do system integration people. Supportability sees it from an operational point of view and Manufacturing focuses on process-oriented representations. The idea is to provide everybody with his/her specific *view* of the product, anytime throughout the life cycle. The solution is to extract the product structure (from the EDM/PDM) with parts and assemblies related in different ways. A view is therefore a *filtered* extraction of a product structure from the database according to pre-defined criteria. The challenge is to provide views that correctly reflect the status of the product in (near) real time.

Two of the of most relevant views for 3D design and hence for the DMU are the

- *As-designed* view; it presents the product in a functional breakdown, basically the Engineering view. The smallest functional items make up the core, are brought together in functional areas and culminate in whole functional complexes.

- *As-planned*[16] view; it represents the product the way it is produced and integrated. It is the Manufacturing view and accounts for all stages and assembly operations in which single parts are grouped to pre-assemblies, then to assemblies and finally to the complete product. (Wiendahl, 1997)

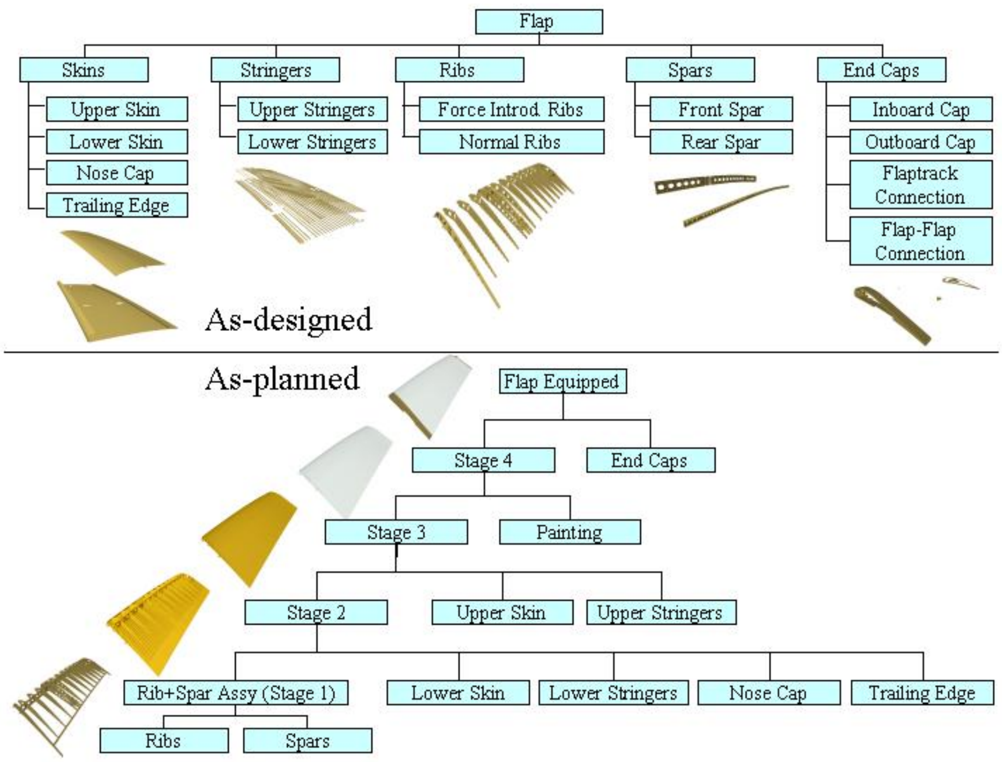

Fig. 2.8 Two Product Structure views for a simplified Flap example

[16] One may call that view also 'as-manufactured' or 'as-produced'. "*As-planned*" refers to *manufacturing planning* how the product shall be decomposed to have all manufacturing operations and constraints accounted for. Its shows how the manufacturing engineer thinks everything shall be put together. A closely related view is the "as-built" which actually reflects the real sequence of operations in the assembly hall. That accounts for unforeseen events (supply delays, assembly errors). If everything goes according to plans the 'as-built' and the 'as-planned' will match.

2.4.3 Metadata II – the Attributes

If geometry gives the virtual product a "face", and if the Product Structure organizes it hierarchically, it's a set of *attributes* that *identify* 3D models and PS elements in the DMU. This is just like a human being is identified by a number of parameters like name, date of birth or colour of skin. Attributes and their alpha-numeric values are vital throughout the entire product life cycle: they not only ensure part identification and allow the traceability of iterations, design evolutions and other changes; they first of all ensure concurrent working of a multitude of people because they virtually "tell" what is going on, where, when and by whom. The relation of the three DMU pillars is shown in the figure below:

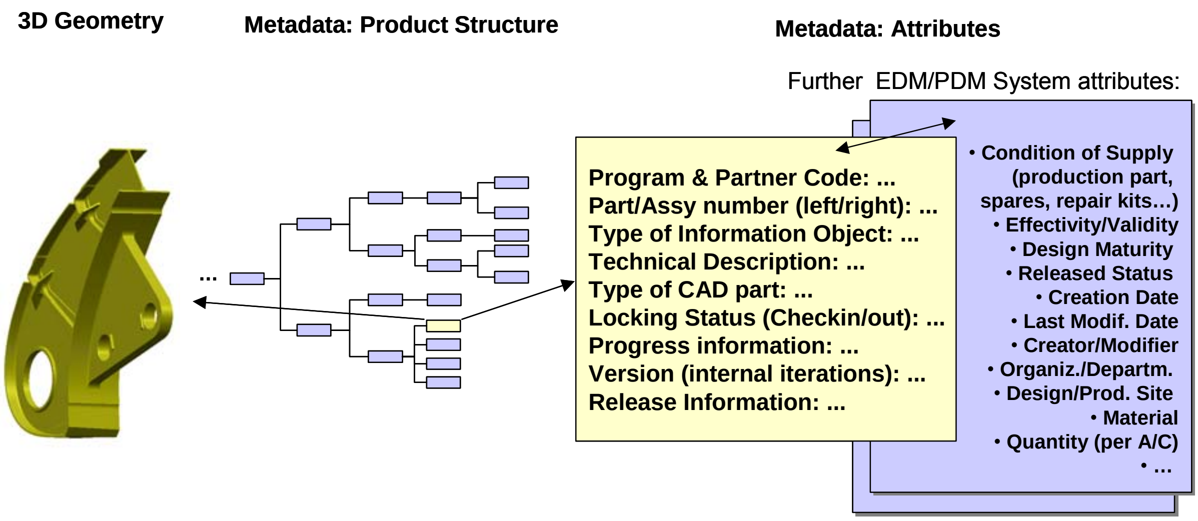

Fig. 2.9 Relation between geometry and metadata on a simplified example

2.4.4 Digital Information Objects

These are different types of DMU representations in certain phases, each with a distinctive purpose and a clear role. Four of these Information Objects are briefly outlined here:

- *The Loft & Basic Geometrical References*: Loft is the outer surface of an aircraft (or ship; also termed "wetted surface", indicating its exposure to the atmosphere) but there can be "inner lofts" as well, e.g. for cabin layouts. Aerodynamic data (e.g. from wind tunnel) are usually the input and smooth 3D CAD surfaces the output. Basic Geometrical References are indications (e.g. planes, coordinate systems) of main structural components (frames, ribs, spars, cut-outs like doors and windows) and the positions of the main sections. For 3D design they are starting points and main references throughout development and input for the preparation of manufacturing surfaces for tooling definition and design.

- *The Interface models*: These are a set of data (3D models; eventually derived 2D drawings and associated documentation) used to validate and fix information at assembly junctions of partners or suppliers responsibilities. Their aim is to early pre-check whether parts and sub-assemblies can be joined (including necessary tooling).

- *The Space Allocation models*: These models are principally used to visualize and validate the global product architecture described by the Loft and the Basic Geometrical References and basic configuration layout options. Operational aspects, human factors studies, transportation, build concepts, public relations and customer demonstrations can be done as soon as models are available. Initially, Space Allocation Models (SAM) “claim” the maximum volume of space that structural parts, systems, machines or any other equipment can have.
  In the beginning models are roughly more than simplified space envelopes. Mechanisms like kinematics are modelled with sweep volumes (in extreme positions: landing gear up and down, panels and doors opened and closed, control surfaces extended and retracted) and stay-out zones. Models have holes to allow systems (tubes, wire bundles) to run through. Opposite hand parts are modelled as necessary (e.g. for left and right wing). Differences between port and starboard will need to be accounted for early on. SAMs allow for clashes, the goal is to validate systems integration as early as possible.

- *The Definition models*: These models are based on the latest agreed detailed SAMs and elaborated to full detail. As such they form the basis for manufacturing and documentation and are those data from which final 2D drawings are created (if required by manufacturing). Being officially “released for production” they are therefore the only 3D models that underlie the strict certification and documentation requirements, and whose changes have to be seamlessly tracked and monitored for product liability reasons.

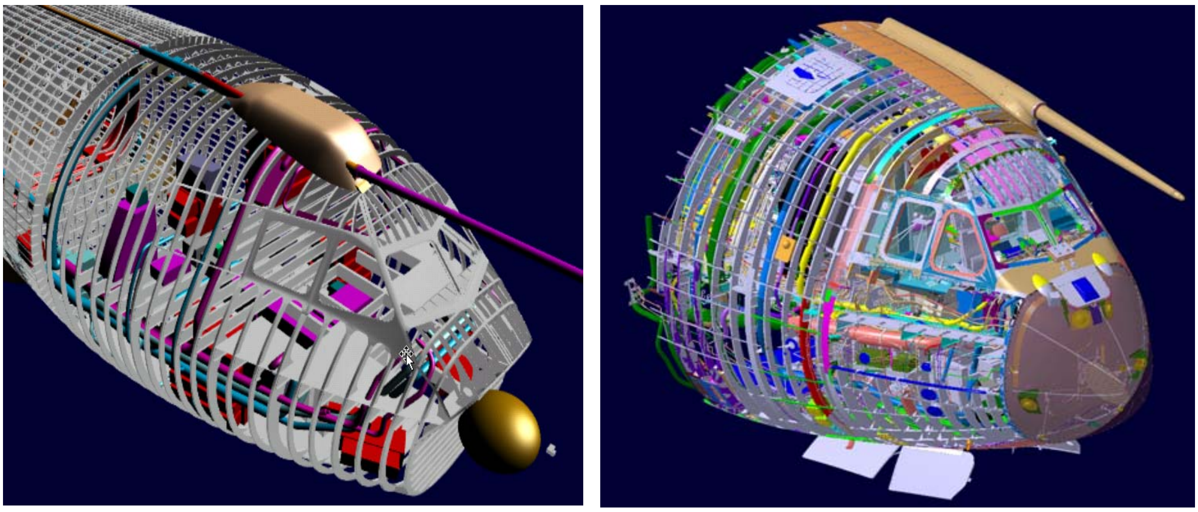

Fig. 2.10 Space Allocation Mock-up (left) and Definition Mock-up (right) of the Nose Fuselage section of the A400M military transport aircraft. Between these snapshots are about five years of development work. While the SAM shows rough geometry of major structural elements and first space volume “claims” by systems and equipments does the Definition DMU represent a densely packed nose section with all sorts of structures, systems and equipments fully detailed ready to be released for production.

Loft & Basic Geometric Reference data, Space Allocation Models and Interface Models are *not released.* They are not official documentary information (they are rather *“frozen”* to serve as basis for further progress on CAD models, NC programmes, stress analysis models…). They all primarily serve as input for the elaboration of the Definition models.

2.4.5 The Configured Digital Mock-up (CDMU)

The CDMU is actually the "marriage" between Configuration Management (CM) and 3D design. The aim is to provide a complete digital product in any variants for any customers, regardless of the design phase and for the multitude of designers who work on them concurrently. In former times usually one standard aircraft was developed at a time[17]. Different cabin configurations came more or less gradually in the wake of new customers. Today, often more than one standard aircraft are developed virtually in parallel, together with numerous cabin and payload variants to satisfy several customers right from the start[18].

The major points for the CDMU are providing the right data for the right configuration, and to have only one representation switched on to avoid geometrical overlapping. This handling of multiple variants and iterations places particular emphasis on a sophisticated *effectivity management*, ensuring that the effective/confirmed technical application is embodied in the DMU. It is making use of a set of configuration attributes, as shown in the figure below:

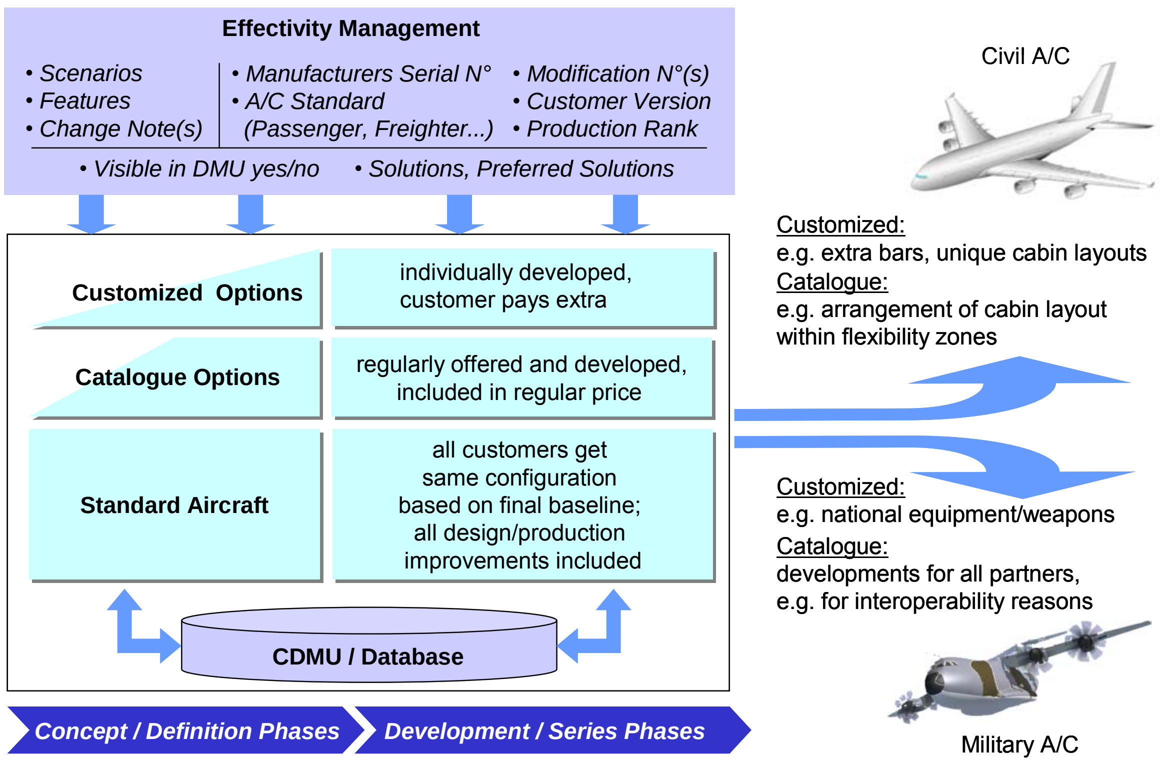

Fig. 2.11 Different product configurations are build upon different CDMU elements, steered and controlled by a few configuration attributes

[17] One exception was the Airbus A330/340 family. Both were developed in parallel with major differences only on wings and propulsion: The A330 is a twin-engine, the A340 a four-engine aeroplane. The wings are practically the same but for engine attachments and systems adaptations.

[18] For instance, the Airbus A380 was originally developed as a passenger version, and even before its first flight the development of the freighter variant was launched (later put on a hold). The military transport aircraft A400M is developed concurrently for satisfying the many operational needs and payload requirements of seven European Air Forces who are the launching customers. In the US, a similar challenge is the development of the Lockheed Martin F-35 Lightning II, being designed in three variants right from the beginning: a Conventional Take-off and Landing (CTOL) variant, an Aircraft Carrier variant (CV) for Navy operations and a Conventional Take-off and Vertical Landing (CTVL) variant.

2.5 Technical Dimension – Processes and Organization

2.5.1 Electronic Data Interchange (EDI)

EDI is the exchange or sharing of electronic data within the product/project development environment[19]. In aerospace (and in other manufacturing industries as well) parts and equipment purchased externally account for 50 to 70% of the value at prime contractor level[20] (Cook and Graser, 2000). This underlines the importance of partners and suppliers being closely connected to the prime, as they contribute a great deal of value to the final product. A high level of EDI integration (see Appendix C for more details on EDI) is therefore of vital and increasing importance for companies, as without no effective Concurrent Engineering can be achieved. Figure 2.12 shows in principle what data/information needs to be exchanged or shared:

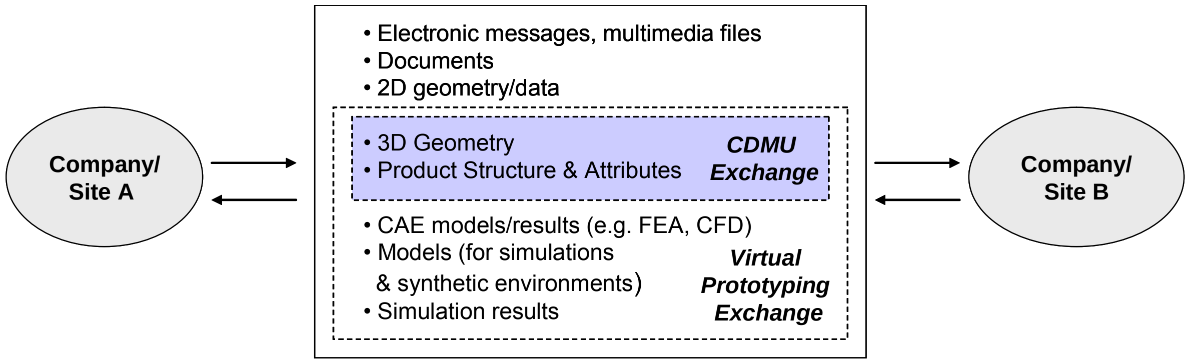

Fig. 2.12 DMU data exchange in context with other data and information types

2.5.2 Data and Design Quality

In a concurrent environment the DMU is created by many people and used by many more: numerous disciplines inside and outside the design community work with the DMU, extract information and reference it. Undetected or ignored problems can rather quick become serious issues that will need costly fixing. It is therefore of profound importance that quality non-conformities be kept as few as possible, through pre-emptive implementation of high quality standards and norms, their relentless enforcement over the extended enterprise and, if occurring, their swift detection and resolution.

DMU Data and Design Quality are actually two sides of the same medal: *Data Quality* focuses – as already mentioned in the requirements catalogue above - on completeness, actuality, consistency and configuration *of the data itself*, based on its technical content. *Design Quality*, on the other hand, aims for a DMU correctly *reflecting the very design intent*, with all requirements and constraints of all involved disciplines sufficiently considered.

With so much at stake, maintaining a high level of DMU quality is in the interest of everybody, it is the obligation of every stakeholder: in particular Management, IS/IT and Quality Assurance departments and not only the design communities as creators of the data.

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[19] Further (similar) definitions can be found in Weid (1995). Most build on elements such as ‘inter-company exchange of messages’, ‘business data’, ‘standardized format’ and ‘computer-to-computer dialogue’.

[20] The situation is similar in the automotive industry also having a high degree of design and manufacturing taking place at suppliers (Markworth, 2003)

2.5.3 Check and Review Processes

The *check process* encompasses continuous quality tracking and monitoring tasks, DMU trouble detections (e.g. "clashes") including documentation ("trouble report"), validation activities and any other investigations. The figure below shows – from an Engineering point of view - a spectrum of checks plus most common trouble types in the respective areas:

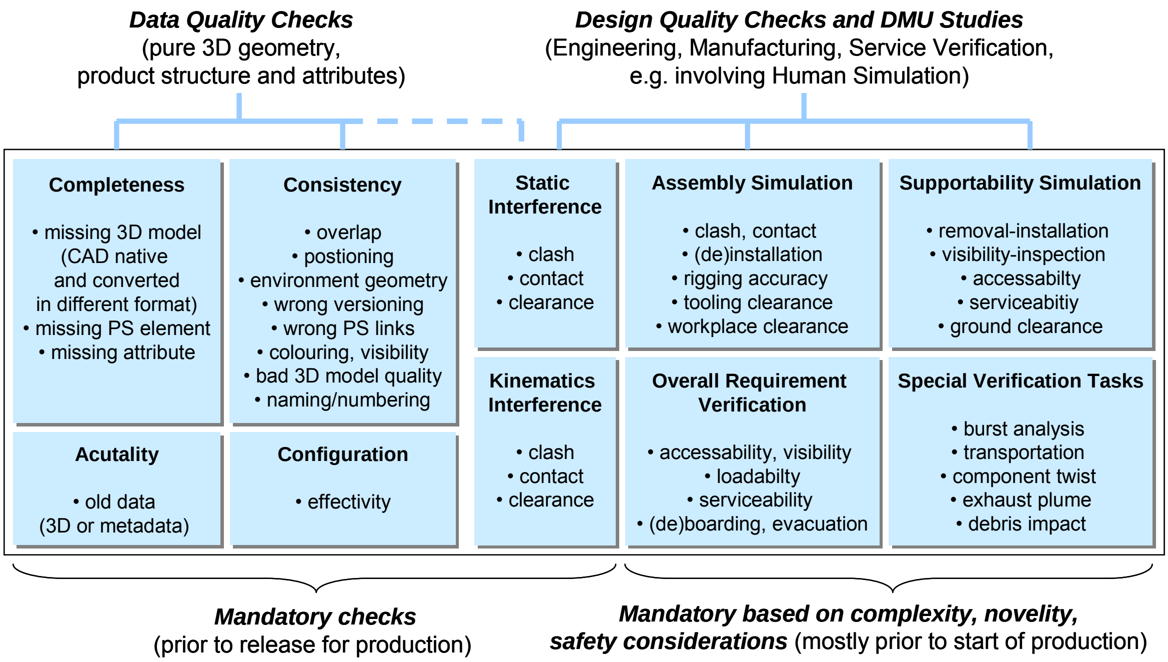

Fig. 2.13 Spectrum of most common trouble types; static and kinematics interferences are very often "symptoms" following poor data quality: old model clashes with new one, missing or wrong effectivites, wrong positioning…

On one hand there is *discrete* checking with virtually stopping 3D design activities at a certain point in time. After the checks problem areas are resolved and design goes on till the next check (as done for the Boeing 777, see Sabbagh, 1996).

Continuous checking doesn't stop the design for checking's sake but continuously takes samples[21] ("snapshots") of the DMU. Design could have solved the problem in the meantime, but experiences on previous A/C programmes indicate however, that troubles resolved before being documented and communicated are minority cases.

Greatest emphasis must be laid to the phases when every 3D model is still in work, and that it is validated prior release in all required aspects. Any (serious) trouble detected after part production or (sub)-assembly has begun triggers corrective actions, which are twofold: First, a *short-term resolution* has to be found for already affected areas. As parts are usually produced in batches, it's likely that they will already be in production, impacting more than one A/C. At the same time a *long-term* (or lasting) *modification* has to be elaborated, and determined when to phase it in, and whether previous A/C have to be re-equipped with it.

[21] To be fair the snapshots are also discrete views taken at certain points in time. The difference is that design isn't stopped for broad checking activities.

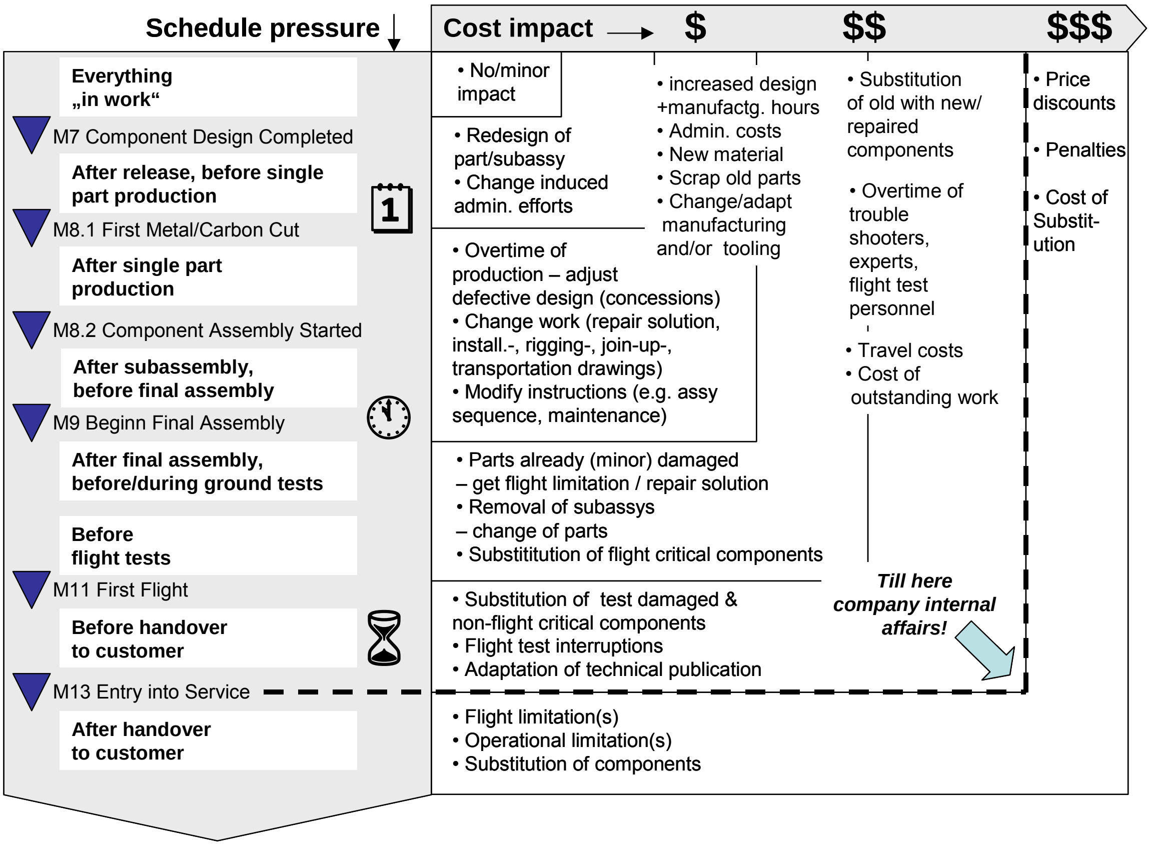

Fig. 2.14 Time and cost impacts of unresolved DMU troubles and consequences

The *review process* is closely related to the check process and is a primary quality improvement and sustainment measure. Whatever type of review (e.g. formal Preliminary and Critical Design Reviews, everyday technical reviews or dedicated DMU reviews), the supporting activities are always the same: the reviews have to be *prepared* with the right data, reports, statistics and background information; they have to be *run*, e.g. doing online fly-throughs, showing critical areas, and they need to be *followed up*. The follow-up is particularly important to track resolutions, feed statistics and report on progress or non-progress, e.g. for troubles existing for a longer time and to escalate them to higher hierarchical levels should there be disagreements on resolution.

2.5.4 Organizational Adaptations

New methods, tools and technologies will never be exploited to their fullest potential if not matched by adequately organized, trained and empowered people over the entire extended enterprise. Digital Mock-up integration is today seen as an Engineering *core competence* and capability requiring careful selection of the ratio of in-house vs. external DMU specialists. The DMU is the *responsibility of every stakeholder*. But it has proven beneficial that dedicated “DMU people” act as facilitators until the DMU is common knowledge and established and routine practice throughout the development community. Airbus, for instance, has since 1998 established a considerable number of “*DMU Integrators*”.

They usually work embedded (co-located) in multidisciplinary teams (e.g. Design-Build-Team DBT) and support them with a broad spectrum of dedicated DMU activities: Product Structure build-up and management, trouble detection and reporting, quality tracking and monitoring, quality validations, reviews, data exchange and subcontracting support. They help in aligning team-specific ways of working – that often have very diverse requirements and constraints - with general and project specific DMU principles, standards and methods. This fosters standardization and harmonization across teams and functions and optimizes DMU exploitation. Furthermore they actively participate in acceptance tests for new software tool and methods' releases and formulate new requirements out of daily operational pitfalls (e.g. on tool functionalities, method and process adaptations, IS/IT infrastructure improvements…). Their role is therefore not only one of enablers of the Digital Mock-up but actually being the "link" between design and IS/IT communities.

2.6 Communication Dimension – Visualization and Distributed Common Reference

Visualization is a central aspect of working with the DMU: it actually shows how the 3D design is looking like. It instantly reflects what is generated or changed, and the 3D models can be inspected dynamically in all directions, turned around, rotated, "looked behind", high-lighted and flown-through. As we human beings strongly rely on our visual perception the pictures thus pass straight into our minds and stimulate our imaginations. Visualization presents the design intent in an efficient, precise and unambiguous way that is only matched by the real hardware. People from all disciplines with all kinds of different technical, educational, cultural, or language backgrounds can communicate on a common and easily understandable basis. They can discuss and negotiate with a big advantage: they see the same thing, have the same picture in mind, and hence reference the same. This drastically reduces misinterpretations and speeds decision processes.

May it be standard PC or workstation visualization screens on one end, or highly sophisticated large scale 3D stereo projection equipment with advanced tracking and manipulation devices plus powerful graphics processing machines on the other end of the visualization spectrum, they all bring the virtual product to "life". For some purposes like Marketing, DMU representations can be made more appealing with textures, light and shadow effects and animations. While this is a great instrument to influence and impress people it may, on the other hand, wrongly foster the conclusion of a more advanced design and project status than it actually is. The DMU supports the "what you see is what you get" approach, but it needs a trained eye to see the facts for not being lulled into a false sense of safety.

In large and multinational projects work usually takes place on many and often highly dispersed locations. Furthermore, the single units develop only parts of the whole product. But despite of that the virtual product has to fit together, guaranteeing everybody the same reference. This aspect of communication shall be called here "Common Distributed Reference". It draws heavily on the above-mentioned Electronic Data Interchange process, as the *relevant* contents of distributed databases have to be exchanged or commonly shared. That means that it is not so important to make the whole DMU readily available to everybody but rather to have everybody work on the same reference, no matter how small the pieces are. One will always be able to placing them correctly in the context of all other parts in the DMU.

2.7 Management Dimension – Early Warning and Risk Management & Management of Complexity

The Management Dimension is the most abstract of all three dimensions of DMU. But it is the one with the greatest leverage for project success. The DMU is, in this context, to be regarded as a primary *controlling instrument* that provides an encompassing picture of the actual development status. The visualized DMU itself, any kinds of trouble and quality reports and all reviews can be used to assume the management function in order to control and steer design progress into the desired direction. The reliance on traditional management reports, often filtered through multiple layers, is reduced by the possibility of a direct look on the actual facts onto the database.

The first management aspect shall be named *"Early Warning and Risk Management"*. The figure below uses the analogy with an airborne military early warning aircraft to demonstrate how that aspect can be seen:

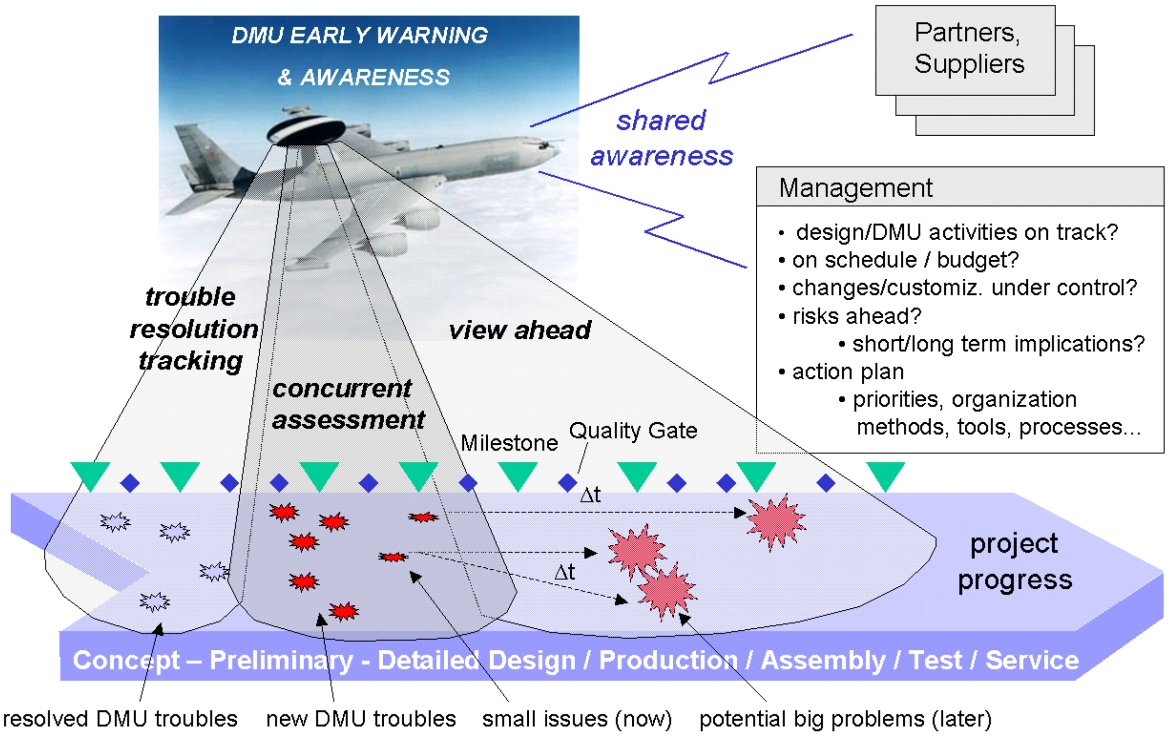

Fig. 2.15 The DMU early warning and awareness function: all three "surveillance cones" act together for trouble detection and mitigation and risk avoidance

The concurrent assessment provides the timely information on the status of the DMU as outlined in the check and review processes above. Once evident, troubles and issues need to be tracked and monitored to ensure that they are resolved. Otherwise errors and quality non-conformities could perpetuate creating a "snowball effect" of troubles with many people using flawed data. The *view ahead* actually is an attempt to anticipate future developments and risks based on a good degree of engineering and management judgement. The DMU enables to imagine many more cases where often small and seemingly neglect-able issues are placed within a larger (geometrical) context so that the real problem becomes apparent. That is then a starting point for pro-active risk management and for corrective actions.

All views can be shared contemporarily among management and with partners and suppliers. That creates common *awareness*, which not only increases reactivity on unforeseen issues. It fosters mutual trust among project members and stakeholders and helps shaping the best approach for successful project execution.

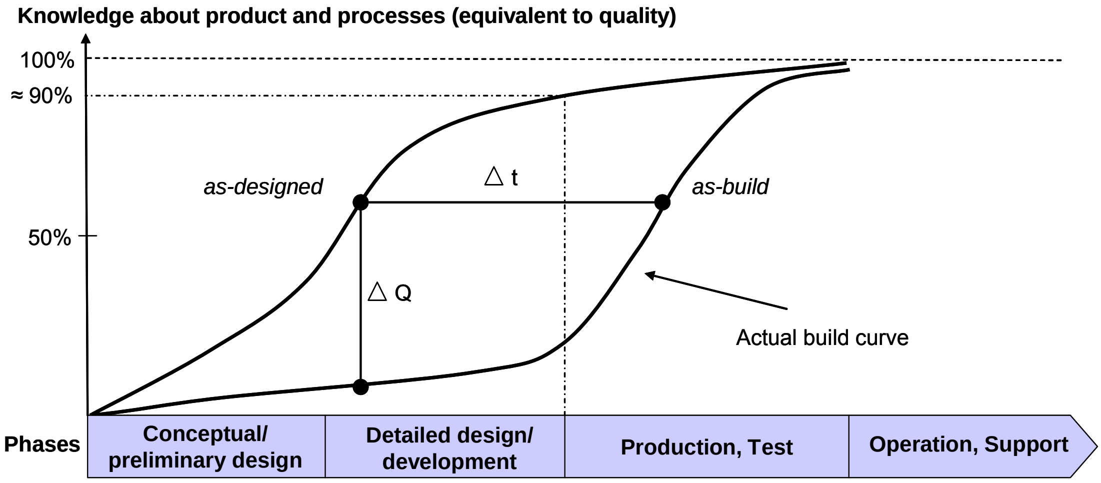

Fig. 2.16 The time and quality advantage brought by 3D design

The essence of 3D design and therefore the DMU is shown in the figure above: 3D models are generated much earlier ("as-designed"), long before real hardware items are build ("as-build") resulting in (1) a *time delta* for evaluations of possible and probable implication and (2) a *leap in product knowledge – a quality delta* - very early, just when it is needed, e.g. for life cycle cost decisions. It allows what may be called "sanction-free trade studying" as iterations neither cost much money nor will anybody get physically hurt. The time advantage is of major interest for management: a large delta allows greater reactivity, e.g. for sorting out unanticipated issues or for increased customization, and gives time to mature the product by deeper/broader analysing cross and side effects of the emerging design. The smaller the delta t the more risky management decisions become.

Last but not least, the *"Management of Complexity"* aspect shall round up the dimensions. Without prematurely delving too much into the complexity subject detailed in the following chapters it shall be understood that DMU probably is *the major development instrument to master complexity*. As complexity is described (among others) by its *"variety"*- the number and difference of system states that elements involved may assume – the *DMU gives order* to the thousands or millions of parts that in the end will represent the final product. Three reasons shall explain why the DMU is a tool to keep complexity under control: (1) Though it may sound trivial, but e.g. a concept shape of a wing will become a detailed wing, and not a fuselage or something else. This reduces the possibility of elements to turn out as something completely different and undetermined. One simply knows what will come out, what to expect. (2) It is virtually impossible to anticipate all events (e.g. disturbances) that will challenge the project's progress. The DMU – though evolving itself – reflects the results of the many design considerations in a dynamically changing environment. It shows impacts of one's own design on the "neighbours", thus creating the basis for spatial and functional arrangements and deconfliction. It thus provides and represents a unique reference to anybody involved, wherever located. (3) The DMU enables concurrent working on heavy customizations in a short time. This reactivity - as outlined above - paired with keeping the overview on the design makes up the essence of complexity control that is possible with the DMU.

Chapter 3 The Development Environment of Complex Products

3.1 Characteristics of complex products and their developments

Complex products – and their not less complex development in particular - are subject to a substantial paradigm change: Because of continuing cost pressure and overall reduced innovation cycles they have to be developed faster, perform better and be increasingly customized to satisfy the demand of the market and individual customers, and all that at an affordable price. These factors not only increase product and development complexity but actually bear products that are superlatives in many ways: they fulfil their tailored missions under special conditions and are often restricted by demanding constraints and environments. Embedded in "super-systems" with whose elements they strongly interact and depend on, they often function with clockwork precision and deliver unparalleled customer value.

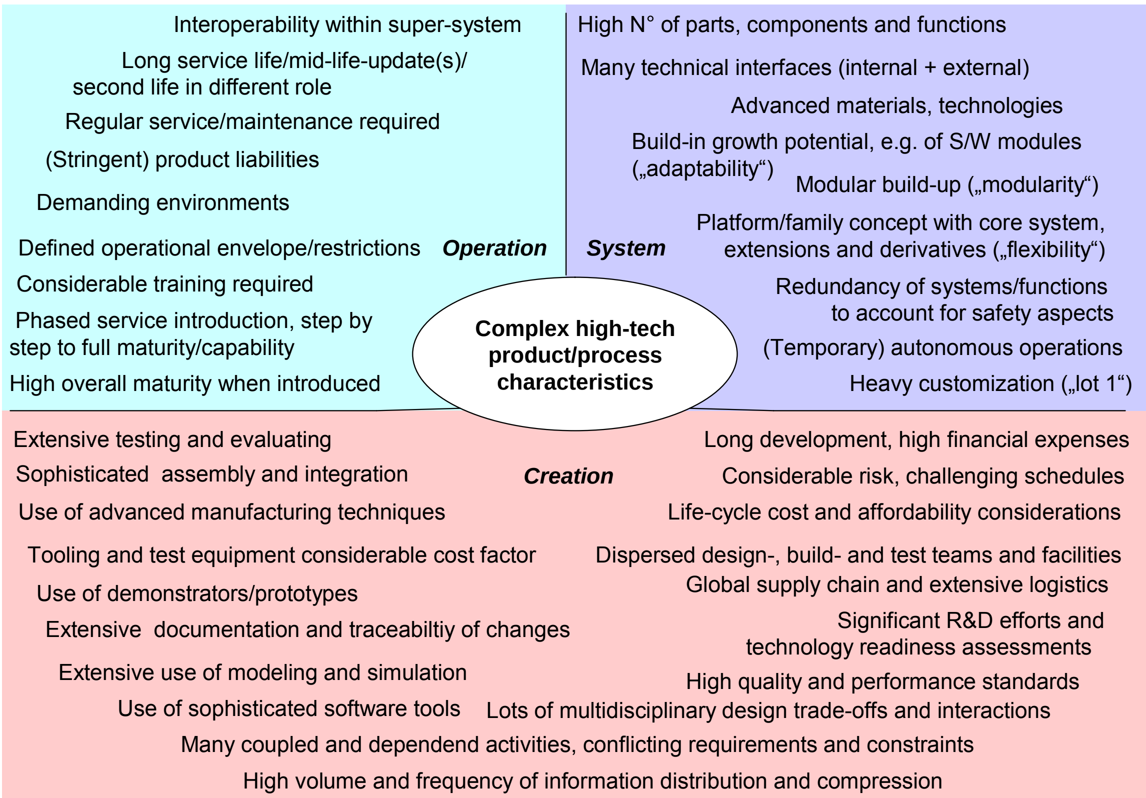

Fig. 3.1 Common characteristics of complex products/processes and their developments – typically not only for the aerospace industry

Examples of the products concerned are shown in Figure 3.2 below. The myriad of aspects to be considered by a great many people within the project makes development a complex undertaking. The environment in which that takes place and how it contributes to complexity is briefly outlined in the following sub-chapters: the *systems environment*, the *market situation*, the *management challenges* and the *megaproject*.

Fig. 3.2 Examples of complex products

3.2 The product in a highly dependent environment – the systems view

The NASA (1995) definition of a system is '*…a set of interrelated components which interact with one another in an organized fashion toward a common purpose. … Every system exists in the context of a broader super-system, i.e. a collection of related systems. It is that context that the system must be judged.*' Dörner (1989) defines a system as '*an amount of variables that are connected with one another through a network of causal dependencies*'. Decisions may be taken based on different aspects for the whole system and not just single events. For handling highly depending systems he sees too many schemes and regulations as too dangerous[22]. Acting must be adjusted on contexts, and must adapt itself as soon as these change. Taking the aircraft example, there are components in numbers in the range of > 10^6, with advanced functionalities and sophisticated relations across the many technical interfaces. Whereas the aircraft's operational environment is both challenging and constraining, the development/project environment is characterized by a spectrum of direct and indirect, strong and weak influences from numerous stakeholders (= system elements) within and outside the system giving it considerable and often undetermined dynamics.

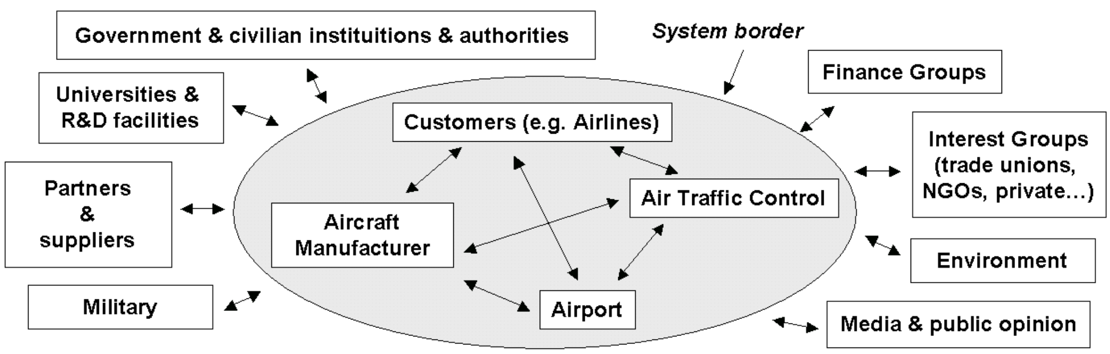

Fig. 3.3 System relations among majors players of the aviation system and cross border influences

[22] Note: this is in some contrast e.g. to reality of development projects of large aircraft. Complexity there is inevitably given; it can't and may not be ignored. Safety and security constraints (e.g. from authorities) account for a great deal of project complexity and difficulty. Regulations and schemes are numerous and there are likely to be a considerable number of them defining ways how the many people and elements interact.

3.3 The Market challenges

The civil market (= commercial and scientific) is largely a buyers' market, highly dynamic with fierce competition, constant cost pressure (e.g. due to price degradations), a drive for relentless innovation and short development cycles. The business is a global one, and so are partners and suppliers. Military markets - though having been more domestically focused for a long time - have become strongly international as well. National laws still restrict them considerably. But unlike most commercial products, military projects are (historically) driven by detailed performance and technical requirements provided by the respective Defence Departments. In some sectors like software or processors the civil markets are now the technological drivers, which leads to cross-insertions of such technologies into military products. What all market types have in common is that product solutions are more and more customized, meeting the very detailed and diverse demands of the customers. Phase effects like the cyclical ups and downs every 9-11 years (Murman et. al., 2002) typical of the aerospace business, have affected the global industrial and scientific base in form of mergers and acquisitions, but also in some companies leaving the field.

Table 3.1 Sample comparisons of some market characteristics of commercial and military markets, based on Lorell et. al. (2000):

	Type of Market		
Characteristic	**Military Aircraft**	**Commercial Aircraft**	**Mass Product (general)**
Output Quantity • Total production • Rate of production	 Small Very Small	 Small Small	 Large Large
Nature of Demand • Number of buyers • Who defines the product?	 One (or very few) Buyer	 Few Buyers* Seller, with significant buyer input	 Many buyers Seller
Demand stability	Highly uncertain	Cyclical	Fairly stable
Nature of Technology • Technological challenge • Learning effects	 Very high Important throughout production run	 High Important throughout production run	 Generally low Modest at mature production
Performance and Service • Level of performance • Variability of performance • After-market service	 Stringent Non-tolerant Extensive	 Stringent Non-tolerant Extensive	 Non-stringent Tolerant Limited
NOTE: The description of markets is highly generalized. Many exceptions exist (e.g for car makers). Characteristics may easily change under new conditions, such as urgent needs or in a war, e.g. for output quantity on the military side. ** Although there are well over 100 airlines, a few of the largest effectively determine the success of a new aircraft model.*			

A few large vendors, offering the same products to civil and military customers, characterize the market for CAx/PDM/ERP applications. Most named aerospace firms nowadays make use of commercial developments for managing their product life-cycle data. These applications are usually strongly customized, posing continuous compatibility challenges, especially in heterogeneous tool environments.

3.4 The Management challenges

‘Management’ can be understood as the “*transformation of resources (e.g. knowledge) into values (especially customer value)*” (Malik, 2006) and as *“shaping and controlling complex dynamic systems in complex and dynamic environments”* (Gross, 2005).
For the development of complex products the management tasks remain challenging throughout the project’s life. Much is at stake, as often prosperity and future of the whole company depends on project success. Top Management will need to ensure, first, to define the best time to launch the project as soon as all critical criteria have been met *(“robust launch”*), and second, to swiftly execute the job while balancing the time-cost-quality triangle.

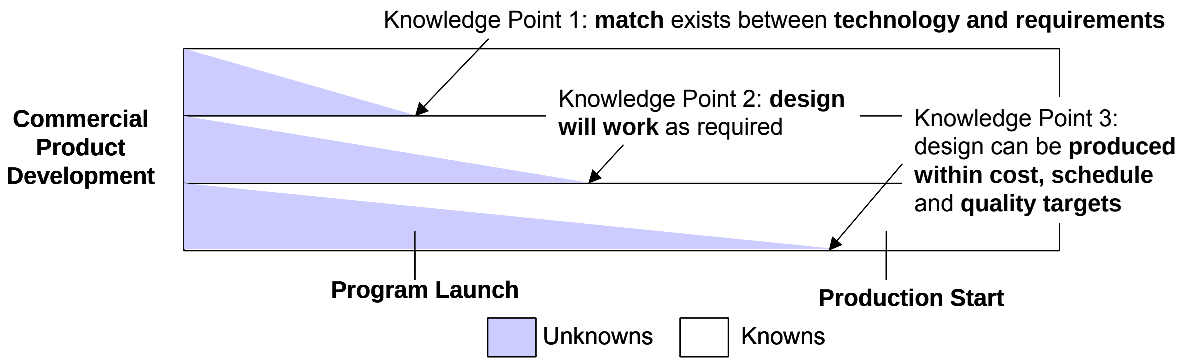

Fig. 3.4 Ideal commercial “knowledge points” during development (GAO 1998a). For military projects these knowledge points may well go to the right as requirements and technologies change (“creep”), leading to schedule slippages and cost overruns

Launching a complex project is a risky decision. In spite of all preparatory work, studies, analysis, assessments, prognosis and simulations there will always remain a considerable degree of uncertainty. The culmination is the official “Go-Ahead” (Schmitt, 2000) when (Top) Management has sufficient confidence that it has correctly assessed the situation, involving green lights from

(1) the *market* (launch customer, product specification, guarantees, contracts…)
(2) the *business* (cash flow, work sharing, program planning, financing…)
(3) the *technical area* (configuration freeze, product definition, systems specifications, technological readiness/maturity…)

Considerable emphasis must also be given to a company’s organization, and the processes, methods and tools to execute the project. They should either be proven or mature enough to cope with complexity. Ramp-up problems and continuous operational shortfalls beyond the usual friction are poison for project success.

Post-launch challenges start with mobilizing all necessary means to successfully execute the project. Lying ahead are years to develop, build, test and evaluate all different pieces of hard- and software. Great emphasis will need to be laid on ensuring that everything fits together and/or communicates appropriately. It means consolidating the dense partner and supplier network and keeping the teaming with changed compositions and headcounts. It is essentially an *“orchestration (or synchronization) of systems and people”* while continuously acting and reacting on internal and external issues to keep the project on track towards common goals.

3.5 The Megaproject Challenges

'Megaproject' is a rather new term. It is a synonym for highly complex and usually very large projects, whether in the high-technology sector or elsewhere. It indicates that the project encompasses considerable financial investments and commitments, has many people/ organizations directly or indirectly involved and directly or indirectly affected. Managing it is a delicate task and technological challenges and risks are generally high. One could say that a *megaproject is an extraordinary undertaking requiring extensive resources for a long time while facing considerable risks throughout the endeavour.*

Flyvberg et al. (2003) talk about the *megaproject 'paradox'* pointing to a "*calamitous history of cost overrun*" for infrastructure projects. The high-tech arena, where this study focuses on, also sees frequent megaprojects. They don't meet expectations either, some in terms of performance, many in the fields of schedule slippage and cost overruns. Examples of the latter are the F/A-22 Fighter for the US Air Force, the Eurofighter Typhoon, the US Navy Seawolf Submarine, the V-22 Tilt-Rotor and the International Space Station (GAO 1994a, 1994b, 1996a, 1996b, 1997a, 1997b, 1998b, 2002a, 2002b).

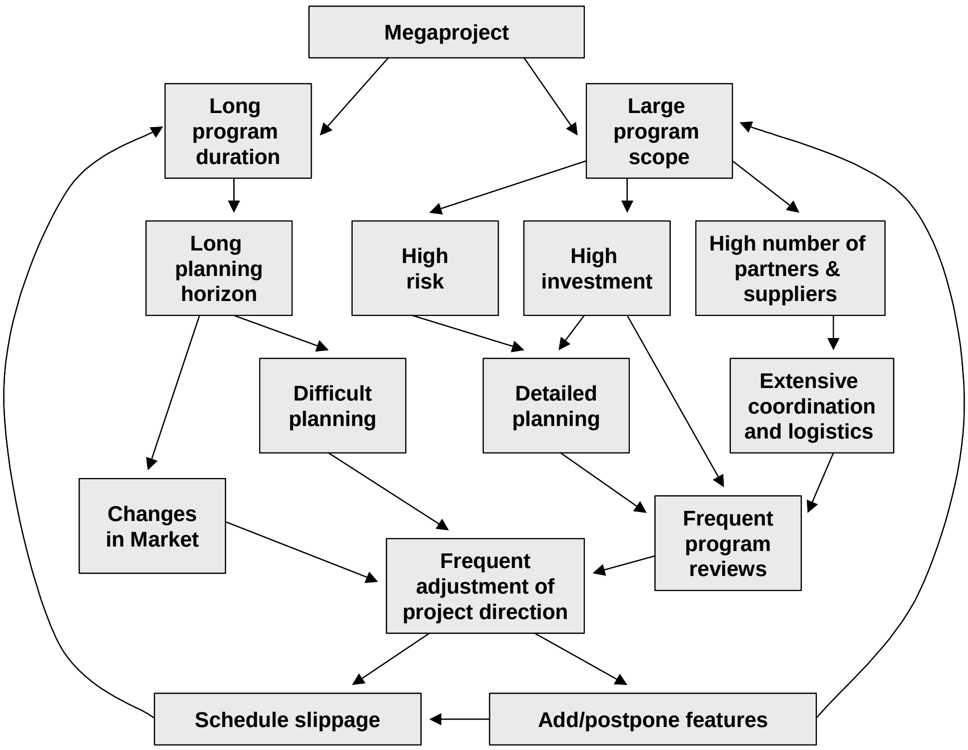

Fig. 3.5 The self-reinforcing nature of megaprojects (based on Smith and Reinertsen, 1998): it is a kind of vicious circle that companies have to break to succeed.

Some comments: For some types of businesses 'changes in markets' occur quite slowly if at all (but nevertheless they do). A science project that has no counterpart or alternative won't be faced with that kind of trouble. On the other hand, changing military threat environments will trigger a change process with politics and the armed forces, being reflected in the acquisition of weapon systems of different types, different quantities and adjusted specifications.
The two major characteristics of megaprojects, long program duration and large scope, shall now be outlined a bit more in detail.

Table 3.2 Impacts of too long cycle times for development: numerous authors conclude that in a competitive environment they are counterproductive if not poison for success. (Wildemann, 1993; Ehrenspiel, 1995; Hundal, 1998; McNutt, 1998; Smith and Reinertsen, 1998; Gausemeier et al., 2000)

	Military Cycle Time	**Civil Cycle Time (commercial and scientific)**
Examples	• Fighter aircraft with better capabilities are being fielded by an opponent, urging own development to counter the threat; • Operational life of weapon system will expire, replacements have to be developed in time not to leave a security or capability gap;	• Market conditions reveal chances to gain market shares by launching a new product family or a derivative and potential customers find the idea appealing; • A favourite planetary constellation in future shall be exploited for a science mission, so the optimum launch window largely determines the response time;
Impacts of too long cycle times	• The systems don't meet current needs when fielded or are fielded with dated technology • Slow response time to emerging threats and known safety problems • Financial stretching, minimum resources and requirements creep • Cost increases of development project and through forced operating of dated and lower performance equipment • Enemy perished due to new political climate /new world order – project endangered of being cancelled (McNutt, 1998)	• Competitor is quicker and gains higher market share, has more sales volume, runs through the learning curve faster, has decreasing production costs and can give price reductions • Time to react on threats and opportunities is reduced, less time to observe market, unique scientific opportunities are lost • Resources are bound that could be used somewhere else, efficiency targets can't be reached, cost increases • Longer way to product and process maturity • Project endangered of being cancelled – severely damaging a company's financial stand, loss of reputation and image

Nota bene: Development cycle times can also be deliberately set *too short*, posing serious problems as well. The product is not as mature enough as required e.g. the design could not have been traded off extensively or test and evaluation has fallen short: this exemplifies too high expenditures for too low a quality.

Technical and financial risks and an extensive partnership constitute the large programme scope. In spite of a robust launch the project can be faced with undetermined technical and technological difficulties. That will raise the need for more analysis, more tests and more prototypes and above all, more time to do that. It will increase costs making higher expenditures necessary. Investors could back off and additional resources may be stretched thin elsewhere. All this undoubtedly contributes to uncertainty and complexity, but on the other hand, megaprojects usually cannot and will not be executed by a single company. Teaming with crucial partners is deliberately sought, to simply spread the financial and technical-developmental burden. Often, as in multinational development projects - in particular in aerospace - several countries with their respective industries are involved thereby setting the complexity frame right from the start. The work-share usually reflects each partners' contribution, is highly complicated and often sub-optimal from a pure developmental and logistics point of view. The final project price tag might be higher, but respective players need to spend less and need not overstretch their resources and capabilities.

Chapter 4 Complexity in theory

4.1 Introduction to complexity – what it is, where it comes from

Complexity is a unique factor in business, social and private lives. It appears whenever parameters exceed deterministic levels seemingly manageable by human beings. *This study assumes complexity as a fundamental property of every development endeavour, especially that of sophisticated high-tech products*. The founding framework is briefly outlined in this chapter. The aim is to become familiar with definitions, fundamental thoughts and approaches for mastering complexity.

Today's businesses in particular are characterized by shorter product life cycles, tighter budgets and increased competition pressure. This generates symptoms that some authors describe as *"complexity trap"* (Gomez, 2005; Pruckner, 2005). Higher business dynamics normally would require more time for thinking about the right decisions, but exactly that time is less and less available. No matter if there is too much data and information or too less, according to Pruckner *missing relevant information* is a key factor. This leads to overstressed and overloaded people feeling "trapped". Out of that stems a *"credibility trap"* (Gomez 2005) where people make unjustifiable simplifications, neglect harmful side effects and exemplify incompetent and abusive management and leadership.

According to Malik (2002) "*with 'complexity' one understands the fact that real systems can appear in an immense number of different states. Even in still relatively simple cases the complexity is mostly higher than one is able to imagine'*. Often accompanied are words like 'complicated', 'obscure' and 'non understandable' to describe problems of great complexity.
It is of profound importance to understand complexity both as an *objective fact* (e.g. following Igenbergs, 1998) and a *subjective perception* (e.g. compare Dörner, 1989).

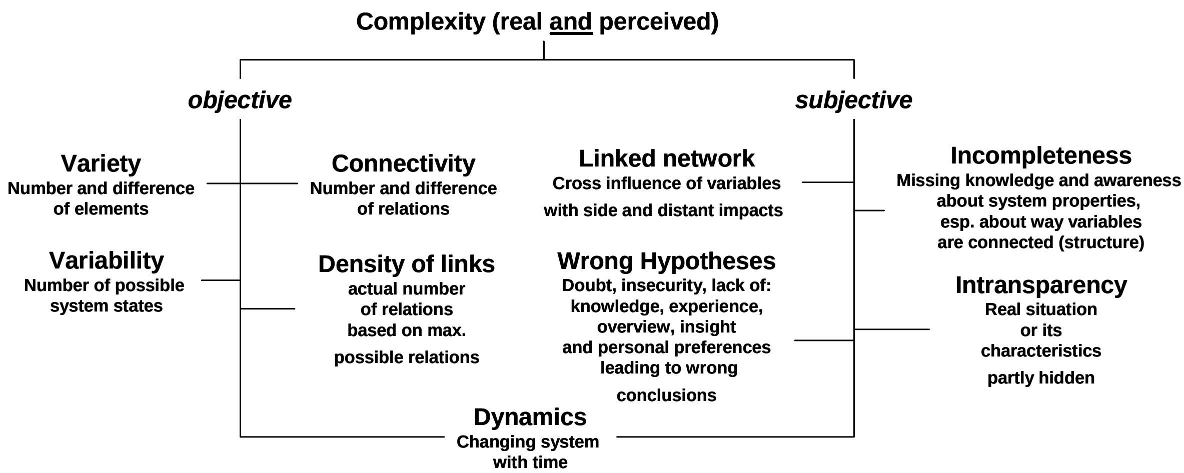

Fig. 4.1 Objective and subjective complexity classifications combined

Williams (2003) describes a similar global approach: Referencing some other researchers he distinguishes the two factors “structural complexity” and “uncertainty”. The first encompasses the scope of the project/product with its amount of elements and their interdependencies, thus creating complex interactions. The latter refers to uncertainties with respect to aims and methods. Uncertainty is hereby understood in a wider sense: elements that derive out of lack of knowledge but also stochastic elements resulting out of probabilities.

For Malik (2002, 2004) the prime indicator of complexity is *“variety”*. From a holistic (= objective and subjective) perspective it encompasses the *“amount of possible and different states that can be shown or assumed by a system”*.[23]

Complex systems can be complex social systems, technical systems or a combination of both. In contrast to simple or complicated systems (as classified in the figure below) they show some distinctive characteristics that differentiate them from others: they are largely indeterministic, their exact behaviour (of its elements and as a whole) is difficult to predict and they exemplify self-dynamics that usually can’t be influenced on a direct way. One may never have enough information to analyse them the way one is used to analyse other (simpler) systems. Nevertheless, one can deal with them, but approaches, means and methods will be different. The new paths allow deriving the relevant information, controlling the system and steering it into a favourable direction. The figure below can be regarded as a template for categorizing systems, a crucial first step of any analysis.

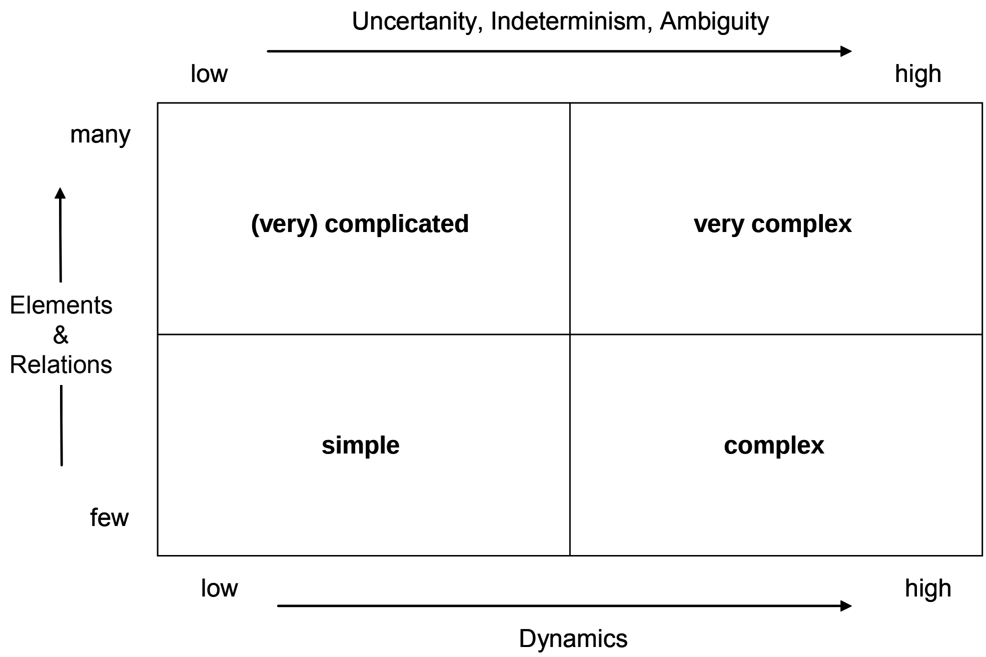

Fig. 4.2 Different notations of systems in relation to some crucial characteristics. In what field a system is in depends on circumstances and the eyes of the spectator and his/her experience with the situation.

[23] The definition of variety doesn’t appear to be consistent with the before mentioned combined classification. Authors like Igenbergs (1998) use terms like ‘variability’ or ‘connectivity’ for a more differentiated mathematical description from a Systems Engineering point of view. In the context of this study however, variety is to be understood as the unifying measurement for complexity, may it stem from objective or subjective assessments.

4.2 The objective and subjective sides of complexity in more detail

4.2.1 Structural or objective complexity

The objective view in principle addresses elements and their relations, so the term *'structural complexity'* is often used (Williams, 2003; Kirchhof, 2003), pointing to its inherent structured nature. To tell complex from complicated or very complicated systems it is important to realize the context: e.g. whether elements are known and relations are deterministic and proven. A large factory plant in which many people are working on numerous sophisticated machines, with clear input, transformation and output of resources will be classified 'very complicated' rather than complex. On the other hand will comparably few advanced electronic modules with many technical interfaces be a rather complex task to develop: a lot of tests and evaluations will need to be done (plus software updates and component replacements) to account for technological advancements and to reduce uncertainty and ambiguity of behaviour in concert with other system elements.
The fact is that real systems continuously change because of preconditions and environment alterations (e.g. fluidity of boundaries) so that certain states are more probable than others. This implies that out of all *potential configurations* the system might adopt there will be a *selection* of the favourable ones, hence also an avoidance of unfavourable ones. This strongly influences and determines the "shape" or appearance of actual structural complexity.

4.2.2 Functional or subjective complexity

The subjective side is also known as *'functional complexity'* or *'behavioural complexity'* describing the behaviour in dealing with complex systems. Difficulties to perceive and understand the system (especially its structural complexity), shortfalls in realizing and judging problem situations, in deriving options and actions, and difficulties in planning and controlling activities are just a few contributing factors. Other ingredients are an unknown number of variables, different representations, hidden portions of reality, information overload, unclear and multiple goals, dynamics of system parameters and the linked nature among them.

Subjective complexity is rooted in essential issues of human behaviour. The most important considerations are outlined below. These are strongly interconnected and overlapping activities, occurring contemporarily.
The first concerns *perception*. Hereby, observers choose (seemingly) problem-relevant information out of all presented ones. It is done more or less unconsciously putting everything together in a mental model, reflecting the observers' knowledge and experiences about external realities. Not known or irrelevant factors are filtered out. What happens is that situational variety is reduced. The consequences are that the same situation can be covered by different models that deliver different views of the system. Because of such a mental reduction of complexity, models can never claim being entirely completed, valid and true. Fig. 4.3 highlights the phases of model construction.

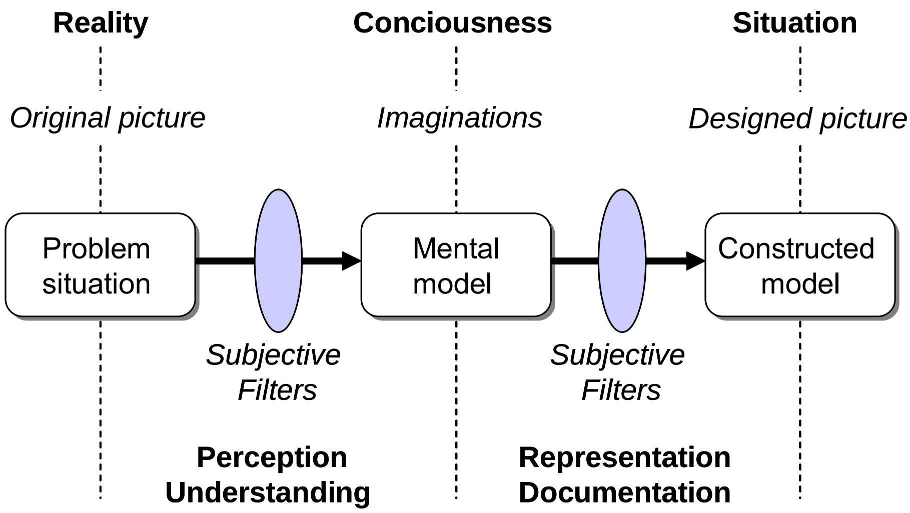

Fig. 4.3 Phases of model construction (Kirchhof, 2003)

Another issue focuses on *decision making*. Deciding means selecting what information is deemed important and which actions shall result from it. The process relies on so-called *schemes*. These are a set of rules that allow ordering and interpreting new experiences and findings. Schemes are grouped in three categories: First, there are *constraints*, which have a restricting impact on possible representations of a system. Among them are rules, norms, standards, laws, commandments, guidelines and principles. Constraints also define the degrees of freedom one has for decisions and actions. Then, there are *pattern,* which put together different dependences, thereby reducing complexity and presenting a simplified view of a seemingly chaotic system. They support general understanding about statii and proceedings as well as the complete and integrated perception of systems. Last but not least *models*, as above mentioned, show the strong interactions between the process of perception and that of decision-making. (Kirchhof, 2003)[24]

The third view is the complexity concerning *actions*. They derive from a range of action alternatives and action pattern and are based on how these are perceived and what subsequent schemes come out. Action pattern can be strategies, single activities or controlling measures. Each action has direct or indirect impact on other system elements (actors, products, processes, the environment…). The consequences may feedback on actors and their perceptions.

These views are vital for understanding and mastering complexity as they reduce it through *selections*. They also strongly emphasis complexity as a phenomenon which is heavily influenced by what we as human beings are consciously and unconsciously aware of.

[24] Another view is that schemes can also be deemed as *filters* and *restrictions* to possible actions and perceptions grown out of experience and learning. Kirchhof (2003) further differentiates: *individual schemes* of the single person and his/her very personal decision findings and action rules, behaviour pattern and personal goals; and *collective schemes* applied by actors of organizations and regarded as basis for decisions like organizational structures, company goals, laws and work instructions.

4.3 Mastering complexity

4.3.1 Ways to cope with complexity

How complexity can be coped with is directly related to what appears to be a fundamental law of nature, formulated by British cybernetics researcher W. Ross Ashby. Known as the "law of requisite variety" or simply "Ashby's Law", it says that *"only variety destroys variety"* (compare e.g. Malik, 2002, 2004; Kirchhof, 2003; Gomez, 2005). It essentially means that for bringing a complex system under control one needs a control system with at least equal complexity (or variety).
The figure below shows a general situation and what actually is required for coping with the variety of it:

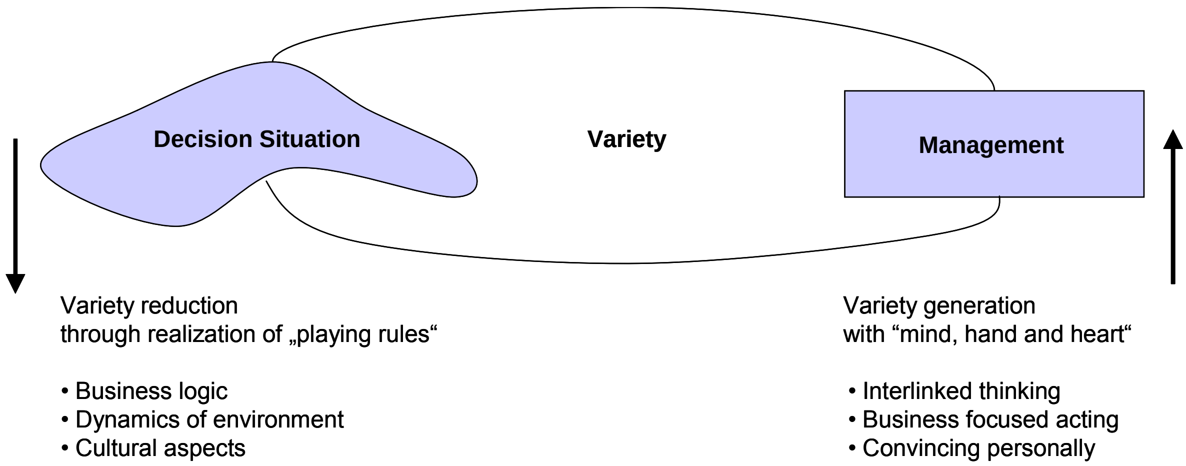

Fig. 4.4 Coping with complexity means both increasing variety on the management side and decreasing it on the side of the situation one is in (Gomez, 2005). He points out that the decision situation is usually far more unknown compared to own management capabilities. That is why the left area is shown in cloud-like form against the box of a rather well known management framework.

Increasing variety means increasing one's capabilities dealing with the situation, having more options and being able to do better selections. There are more chances available to bear a system of higher order, something that is considerably more than the sum of its parts. But it can also mean more elements and relations to deal with, a higher need for balancing more and maybe contradictory goals as well as higher uncertainty and ambiguity.
Reducing variety aims at deliberately finding out the "playing rules", creating ordering structures, reducing degrees of freedom of the system (and hereby increasing its level of exactness and definition) and decreasing existing relations. One can build sub-systems, focus on part-environments and fully draw on schemes. Then one can modularize, standardize and sequentialize. It helps reducing the selection pressure for being able to react on certain situations with a limited number of system configurations.
The delicate task is to know where and what to increase and to reduce. It will usually be a mix of both that needs to be applied for coping with complexity.

For Malik (2002) there are two general ways manipulating variety and thereby coping with complexity: through creation of *order* and through *problem solving*.
'*Order*' is defined as a state of many elements of a different kind, where one can make correct *assumptions* for the rest (of elements) based on knowledge of their time and/or space parameters, which have a good chance of turning out right. Terms often used for that are "structure", "pattern", "configuration" or simply "system". Order, on one hand, can be *made and deliberately planned*. Such an "organisation" requires a rather clear goal, and people performing concrete tasks whereby serving a common purpose. As such it is imposed as a kind of force from outside. On the other hand order can be *grown, spontaneously developed*. Created through regularity in the behaviour of its elements, it comes from inside, is self-regulating and self-organising. No clear goals are pursued; individuals are following own goals in addition. Such an order is more abstract and may cover an uncountable number of circumstances.
Problem solving concerns the areas of controlling, steering and guidance. There are two competing approaches. One focuses on making purely rational decisions. It requires a clear analysis of the problem with good insight into cause-effect relations, an unambiguous and stable ranking of goals and assesses all means necessary to accomplish them. It checks all possible alternatives and then chooses that with highest prospects for optimum accomplishment.
The other is based on a whole different mindset, in fact quite the contrary of the just mentioned. It tries to eliminate whole classes of alternatives out of an undefined number of them (through trial and error) to home in on those, which seem to be relevant (*evolutionary* method). On what parameters (kind and amount) a final decision is ultimately based is not known from the beginning and will only be elaborated over time. More than one goal needs to be taken into account simultaneously. Consequences of decisions cannot be entirely anticipated, so that unintended side effects must be considered. Decisions are embedded in a continuous flow of events. They are only temporary 'good' or 'right' and might even be outdated at the time of realisation.

4.3.2 Object and Meta Levels

Both ordering/organizing and problem solving take place on two levels, denoted object and meta level. The *object level* is the level of all activities directly producing *output* or the *content* of something. The objects are items or entities and are often visible, countable, can be calculated and are easily imaginable.
The *meta level* on the other side comprises the *inherent relationships*, *behaviour and (playing) rules* that apply for everything that is actually happening (as well as potentials, capabilities and properties). That level is not readily obvious and deserves special attention.
As conditions of (complex) systems continuously change, adaptations primarily happen on the meta level, demanding a *shift* of the evaluation focus away from purely assessing the object level (Malik, 2002). Furthermore, it is generally easier to cover a complex subject in an encompassing way by its meta level (the behaviour and mechanisms leading to behaviour, the playing rules…) than trying to "count" each and every item on its object level that might be relevant, but never really getting to the point of sufficient relevancy (actually not knowing what and where that point is).
As general guidance for dealing with complex systems Malik (2002) recommends solving problems in a decentralized way on the object level with contemporary control by a central meta system. This enables a uniform direction with the greatest extend of adaptability and flexibility.

Chapter 5 The Complexity Indicator Method

Before delving into the method, here a reminder of what this study aims to provide: to reveal the time, cost and quality impact of Hardware Mock-up and Digital Mock-up campaigns with a case study from wing integration activities of large transport aircraft development projects. The results shall be achieved with the help of a new complexity based method for the assessment of complex systems, for which the case study shall be its validation.

The method itself makes use of so-called “complexity indicators”. It is explained in two sections of this chapter: First, in chapter 5.1 the objectives, requirements and constraints for the method are laid out and some background information is given. In the second part, chapter 5.2, the method and its steps are explained in detail. The description of the steps is intended to serve as a guideline or handbook for applying the method on multiple and different kinds of complex problems.

5.1 Objectives, Requirements and Constraints of the Method

5.1.1 Background

Although the scientific exploration of complexity has been around for some decades, investigations on practical applications with *quantative* examinations remain rare.
This study is inspired in particular by an investigation on the schedule and budget performance of NASA satellite programmes under the “Faster-Better-Cheaper” (FBC) initiative (Bearden, 1999)[25]. Bearden studied 43 satellite missions and devised a relative “complexity index” from 21 technical parameters[26]. He then plotted schedule and budget as functions of complexity and compared successful, impaired and failed NASA missions and, as a baseline, traditional missions of the Department of Defence and the Department of Energy.

The results showed a concentration of failed and impaired missions in the region of high relative complexity together with short development times. The Spacecraft costs side was not as strong a factor as time, as those same FBC missions were scattered over nearly the whole range (of costs), indicating that both expensive and cheap missions are subject to full or partial failure. By comparison, successful Spacecraft developments under the traditional paradigm also having high relative complexity indices were balanced by comparatively higher costs and longer development times.

[25] The magazine *Aviation Week & Space Technology (AW&ST)* brought articles about the subject in its May 26 and June 12, 2000, issues. The study is a rare exception as it provides quantative evidence of complexity.
[26] E.g. satellite launch mass, solar array area, battery capacity, pointing accuracy, propulsion type, thermal control type…

Bearden's study approached complexity from a purely technical point of view, but admits that

> "When examined after the fact, loss or impaired performance is often found to be the result of mismanagement or miscommunication. In combination with a series of 'low probability' events, these missteps, which often occur when the program is operating near the budget ceiling or under tremendous time schedule pressure, results in failure due to lack of sufficient resources to test, simulate or review work and process in a thorough manner." (Quoted by M. A. Dornheim in Aviation Week & Space Technology, June 12, 2000 issue)

Neither programmatic nor human issues concerning complexity were taken into account, as well as the study didn't reveal relations and interactions among the factors.

5.1.2 Objectives of the Complexity Indicator Method

The prime objective is – similar to Bearden's aim - to be able to *better tell the status of a project (or complex system in general)* from a complexity perspective against schedule, costs and quality in order to derive adequate control measures, allow better planning and ensure project success.
It is an *integrated approach* (and not solely a technical one) that shall provide a better *orientation* and maybe *new insights* on complex system issues and an enhanced understanding of interactions among the relevant factors. It aims to reveal whether one is still on track and to open up *new alternatives* of action.

The method is deliberately kept *simple* (accepting some issues not being addressed, as detailed further below in sub-chapter 'Limitations'), trying to avoid dependence on sophisticated software tools for evaluation. Standard office software shall be sufficient. The method and its rational behind are in the centre of concern, not tool developments and excellence in applying them. But the method is not intended to be *easy*, as this wouldn't respect the nature of complex systems and the challenging questions that arise out of their behaviour.

It is first of all aimed at practitioners[27] for rather quick assessments of their development project situation, and for anybody else to use it as "first shot" for deeper analysis. Visually speaking, the goal is to hit the target, not to aim for the centre circle at all costs. But the target is the right one, even from a considerable distance. Depending on the level of detail chosen for the investigation the objective is to analyse the macro-structure of the complex issue, to become familiar with overall dependencies and interactions. Once the complex global context is confidently understood, one can delve into details and fine-tune his/her actions, eventually by applying more sophisticated methods and tools.

[27] Especially experienced practitioners can contribute with crucial in-depth system(s) knowledge that is vital for setting the right context.

It is an *open* method allowing the addition or removal of Complexity Indicators (CXI), and it may be done by a single person or as team effort (although there is a recommendation for the latter as individual biases and deficiencies are minimized). This underlines the evolutionary and iterative approach that strongly emphasises human ways of problem solving.

Finally, the method aims to be a *standardized* procedure to facilitate exercising it through on a broader range of different problems.

5.1.3 Premises

Complex systems are subject to ongoing transformations, internal and external stimuli and feedback processes from external environments. Development (mega-) projects, are essentially complex socio-technical systems themselves, and are therefore constantly evolving. Due to that dynamics our knowledge about it will never be perfect. Hence, assessments of present states will always result from non-perfect observations; obtained parameters are – to a degree – not correct, as there will be measurement errors. Even a very well defined initial state is likely to result in a multitude of possible future outcomes. The rules, conventions and characteristics may neither be defined, known, agreed nor invariant from the onset. This gives an enormous amount of possible constellations and sequence of configurations. This is fundamentally different to mathematical-physical questions where clear initial and boundary conditions give exact and always the same results.
Thus, the only reasonable approach to assessing a project is therefore *to approximate as meaningful as possible and as closely as adequate.*

An initial premise, though it may seem common sense, is actually *recognizing a problem as complex*[28] – hereby knowing what that means – is the first crucial step for the method. Only then the roads to a whole lot of new alternatives open up, away from linear cause-effect thinking and acting. This also dismisses the use of outdated procedures, which are inadequate for solving complex problems.

Another premise is to *resist* the temptation of increasing evaluation efforts longing for analytically *exact* values of complexity (or variety). Due to a shear infinite list of real and probable influence factors and due to the unpredictability of human behaviour, it is per definition impossible pinpointing the complexity phenomenon, neither for even a single point in time nor for a period. But it is nevertheless possible - and one foundation of this study - to evaluate *approximated* values from relative complexities. This is actually the only possibility to compare complexity levels.

Following the simplicity objective may complexity indicators be removed if nearly the same conditions can be taken for granted for all projects. This is also true for those factors that *demonstrably* play(ed) *inferior* roles (natural small-scale project variations, "background noise"…)

[28] Many problems may be served perfectly well with traditional, well-established methods – given the circumstances.

The farer investigations go back, the higher uncertainty will become. Reaches into the future are even more speculative as events have simply not yet taken place. For past projects there is a chance to find out facts, but the actual real conditions leading to them - as they are now apparent - are far more difficult to assess. In many cases, just too few or no data at all[29] will be available. The level of detail of investigation will usually be coarser and so will be complexity categories. Any results therefore need to be interpreted with caution, especially if far reaching conclusions shall be drawn. Good data on one project but databases far from sufficient for others may require simplifications for comparability purposes.

Each project has *unique circumstances* and it is important to account for them. This makes comparisons difficult and only supports the approximated approach, thereby accepting certain uncertainties in results.
Very unique events that happened in only a few projects will need to be placed in context properly. That may mean adopting a classification scheme from non-existent complexity to existing complexity. Cases like these need be accounted for, because leaving out such events would possibly mean playing down some crucial elements in the development of these projects[30].

5.1.4 Hypothesis

Bearden's study is based on the assumption, that an overall (technical) complexity can be related to schedule and budget performance of satellite projects. With the information on whether these satellites performed as planned, were impaired or were even complete failures he could give some first statistical evidence that there actually is a relation between complexity, budget and schedule. It is serving at least as an explanation (not to say prove) for a mission success statement.

This thesis goes further. It assumes that there is not only a fundamental relation between complexity and the factors of the 'magic triangle', namely time, costs and quality (here, performance shall be included in 'quality'). It also states that – with caution - this may be true for any complex system, of which development projects of sophisticated high-tech products are only one application. Here in this study though, it is the central issue, and that is why the approach will be validated with an example from aircraft development.

The relation of complexity and time, cost and quality shall now be explained more in detail. It is based fundamentally on the law of requisite variety, as already mentioned in chapter 4 (see especially figure 4.4).

[29] Often, in older projects far fewer things are documented than anticipated. If not official regulations (e.g. by authorities) rule that data be kept for a period of time, older documentation is discarded (after certain periods) to open up room for new one. Even if relevant data were kept in storage, it is particularly difficult for researchers to draw realistic and above all true conclusions, because the story behind is virtually impossible to anticipate.
If written evidence is lacking one will have to rely on personal remembrances – with all pros and cons.

[30] Imagine projects having interrelations with politics. Investigating pre Sept. 11th, 2001 projects will not have that date and its implications as external stimuli. But researching ones that were still ongoing at that date, and which were affected by it will certainly have to include that factor in one way or the other.

Ashby's Law states that there must be requisite variety for bringing a complex system under control. This also implies that the more complex the situation (or system) the more complex the control mechanisms have to be. One can actually assume that in general this law will be obeyed:

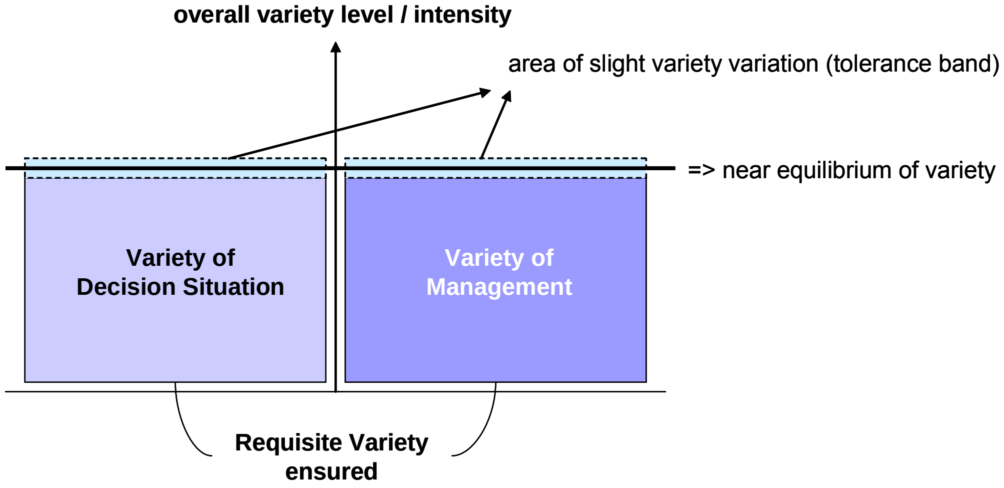

Fig. 5.1 Requisite Variety for a complex situation: here 'Management' shall be the name for all developmental efforts from all disciplines involved: in particular Engineering, Manufacturing and Quality but also IS/IT departments and Program Management.

A project is unlikely to be launched out of nowhere; there is always a context. People will do preparatory work to evaluate how to master the project: They will observe the market, evaluate customer needs and wishes (often together with (potential) customers themselves), they will elaborate a business plan and estimate how to cope with challenges within a time-cost-quality frame.

The coupling of time, money and quality with complexity is revealed if some aspects are considered: For reducing variety on the decision situation side and increasing it on the management side respectively, one needs time (e.g. for training) and resources (people, budget). One needs to figure out what the challenges and problems are. One has to reduce uncertainties and ambiguities for the road ahead. One has to design, test, analyse, evaluate and trade-off to find out more about the product, the interaction of its components, achievable quality and performance levels and for incorporating any kind of feedback.

The overall level of variety (one may also call it 'intensity') depends on the complexity of the situation and its adequate response by management. There can be slight fluctuations of variety, but in general, variety increases and reductions will converge around a near equilibrium. This is the case where it can be assumed that – given a certain complexity level - overall time, cost and quality targets can be achieved.

The situation starts to differ if we assume mismatches on corresponding variety levels, if one side has higher complexity than the other:

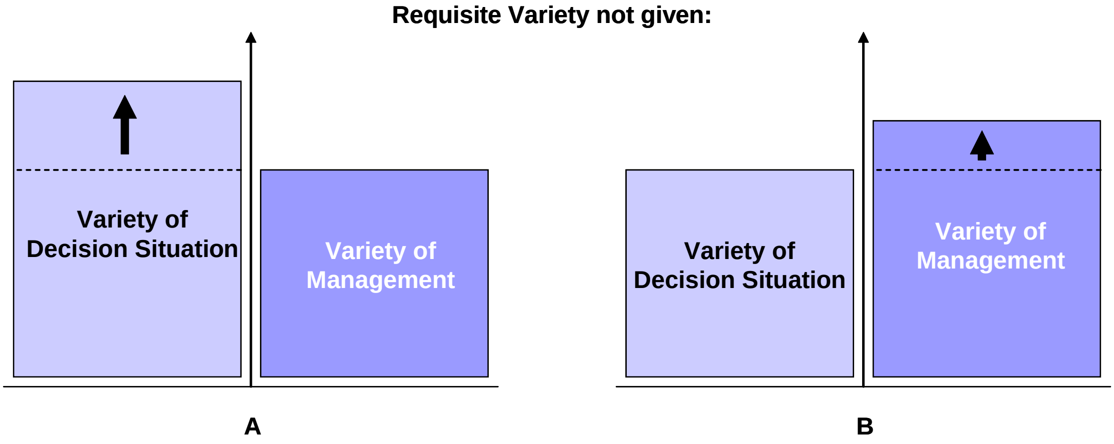

Fig. 5.2 Examples of variety level mismatches

In case A the variety of the decision situation strongly increases. This can be a hint that the playing rules have not been understood, cultural aspects had been underestimated or the environment changes too fast for management to follow.

Case B exemplifies too much management (possibly too much administration, "over-engineering"…) over a situation that is already sufficiently under control.
Variety mismatches can, of course, be a combination of contemporary reduction and augmentation of either side.

An important consideration in this respect is the question of duration: short term fluctuations of variety (even if they are considerable) are more likely to be coped with than long term violations of the law of requisite variety. The former case might be easier mitigated with adequate measures, while the latter would indicate to fundamental problems that are more difficult to deal with. This doesn't mean that a project is about to fail. It may be best compared to a "warning light": it indicates that there is likely to be a problem. It deserves special attention and eventually needs corrective/control measures. If ignored it can become worse, run out of control and inflict sustainable damages to the project: schedule and budget overrun and quality/performance shortfalls.

Either case is likely to impact financially, on the schedule, with quality and performance deficiencies or as mix of it. For high-tech products, the problem usually exemplifies as budget and schedule overruns. Quality and performance cuts are less likely to happen, either for competitive reasons, human safety aspects or due to contractual restrictions (penalties). But there can be mutually agreed phased increases in quality and performance *after* entry into service.[31]

The question now is how to know that the law of requisite variety is violated and what kind of mismatch do we have? This can only be answered approximately by (1) comparing the situation with the same situation of a similar (often past) project, and/or (2) to perform several investigations and analyse potentially dangerous changes from one assessment to the next.

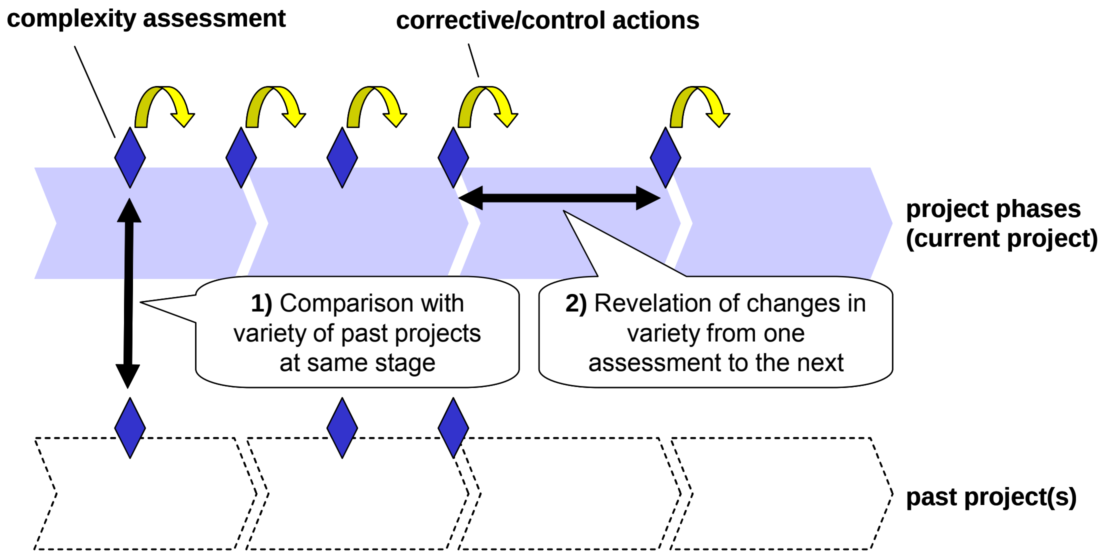

Fig. 5.3 Multiple assessments of complexity to analyse changes on the variety levels

Knowing the variety situation of the project in relation to schedule, budget and quality gives an *orientation* what to do to perform better. Corrective measures can be launched in the sense of a control system. The effectiveness of these actions can then be verified – after some time – in the wake of a new assessment.

[31] E.g. for military aircraft it is common practise to actually contractually define a phased introduction into service, with milestones "Initial Operational Capability – IOC" and "Full Operational Capability – FOC". Given the very long development and test cycle times it makes perfectly sense for an Air Force to start operating a new aircraft and training its personnel as soon as basic missions can be flown, instead of waiting until the aircraft is mature enough to execute all planned missions.

5.1.5 Requirements and Constraints

A major requirement for the execution of the method is setting the *right level of detail*. “In the end, one always has to find a useable degree of complexity somewhere between the atom and the universe to describe a system” (Vester, 2002). Given the evolutionary and iterative approach this question might not be answered right from the start.

Different projects shall be assessed with the *same set of criteria and relevant indicators* to allow for comparisons. This can imply trade-offs on indicators to find those being valid for all of them. Interlinked parameters, the intensity of relations among them and non-linearities are to be considered to the degree practicable and economically feasible. But exactly here lies a fundamental restriction: a posteriori - and a priori even more - it is nearly impossible to assess, which, how many, when, where and with what intensity non-linearities occurred or will occur within the projects. These usually took/take place unconsciously for participants, who simply had/have to live with consequences.

Taking isolated measurements shall be avoided. They can be outdated the “next moment”, thus become wrong. If accidentally or deliberately used as fixed values, errors could perpetuate. Measurements therefore shall always be taken *within the context* of project circumstances.

Soft factors like business culture, language and personal attitudes might need to be taken into account as well. In traditional investigations they usually remain unrecognized even though they contribute a great part to the behaviour of the system. Actually, they can be far more essential for understanding how the system works (Vester, 2002).

The method requires clear statements what the *basic assumptions* are and which factors are taken into consideration as CXIs. A clear distinction of what is known - and can therefore be taken for granted - and what is unknown is equally important to separation of causes and effects. It further requires a definition of the scope and especially what is *out* of scope.
Defining *success criteria* are the finalizing step for a general success or failure judgement.

All indicators contain compressed information, but need to be sufficiently exact to track variations. They need to be presented for providing a good overview and for showing transparency. They also must be understandable and easy to use, ensuring effective evaluation. Set-up and calculation must obey economic criteria as well and shall not require extensive resources: manpower, time, money, IS/IT equipment.
Last but not least, the Complexity Indicator system must be *flexible* to adapt to new circumstances.

5.1.6 Theme and Justification of the Method

As stated above, the method is evolutionary and hence highly iterative. Complexity driver areas need to be elaborated from a holistic point of view. The number and details of Complexity Indicators will probably need to be defined in several feedback loops. The idea is first to converge to the *relevant* and hence influencing complexity driver *areas*. Then, possible indicator candidates are identified and analysed whether they belong to the object level or meta level. A discrete number of them are considered based on critical judgement. They describe the system sufficiently enough and only those are chosen which fundamentally affect the system as a whole or its sub-systems directly or indirectly.

For these indicators, a discrete and not too high number of *states* or *subdivisions* are defined. These subdivisions, expressed with sufficient exactness, describe with high probability – as far as humanly and technically possible to tell - the realities the system can assume. Each subdivision is then assigned a numerical value, which indicates its contribution to complexity. The sums of indicator-subdivisions form the overall variety (intensity) level, which is then put in relation to time, cost and quality.
To unveil more of the roles of complexity indicators and the nature of their interactions a deeper analysis with Cross-Impact-Matrices and Connectivity Analysis can be performed.

There are actually two sides from which this method draws support and justification.
As already mentioned, for Malik (2002) the very cause of complexity lies in the interaction of a great number of different and mostly independent variables. He dismisses two traditional approaches not coming up to the complexity phenomenon: one is the seemingly scientific reduction to a few “typical” variables; the other is summing up the many variables to collectives and evaluating them with statistical techniques. In both ways the very characteristics of complexity get lost.

But what remains is a decisive characteristic, in fact a starting point, namely the number of *possible configurations*, which result out of the interplay of a great many variables. The only thing one thus can do is to *regard the types of configurations that can form and to order them with a meaningful classification scheme.*
Vester (2002) expresses a similar view: “In many complex situations one may not only regard a few of its characteristic features (and deciding to act upon them), but to *regard the very specific “individual” configuration of characteristics* that may be followed by a very individual and adequate sequence of actions”.
Both views provided vital insights and guidance for the elaboration of the method.

In order not to mix up with “product-configuration” and possibly confusing the reader on double usage of the same term the word *“subdivision”* will be used in the following method in lieu of “configuration” in the meaning of Malik and Vester.

5.1.7 Alternative and Complementary Methods

A few other methods addressing complexity and which aim at revealing the critical areas for projects shall be mentioned here. They can be highly sophisticated, often heavily relying on computer hardware and software tools. The increased effort executing them can be worth doing to get some specific answers: For instance, it may be possible to better point out effects of small changes and non-linear relations. The computer/software support allows the variation of parameters for running through simulations quickly and having a multitude of policies checked and verified in comparably short time. Actually asking "what if"-questions in a set of scenarios may be more worth than getting ever more detailed answers to ever more detailed – and often just theoretical – questions. In highly undetermined situations executing the models is then a goal in itself.

There is the vast and growing area of *Modelling & Simulation* (e.g. see Cloud and Rainey, 1998) that helps the understanding of the interplay of a great many parameters based on mathematical models. It can be used in a wide variety of applications such as exploring alternatives of products (or "systems", to be more general), for analysing measurements, assessing designs, predicting performance, training operators and for education and marketing purposes.
Vester (2002, 2007) for example applies the *Sensitivity Model* to cope with complex questions, to learn thinking in networks and to help finding new ideas for sustainable solutions. It not only reflects the dynamics determining how a system develops, but is able to describe the cybernetics that prevail within those dynamics. Making cause-effect relations visible this method enables to influence these relations by setting new courses, to improve the constellation of the system through self-regulation and to examine how the system behaves as a result.
Another technique is known as *System Dynamics* (Williams, 2003, provides a short introduction, see also Maurer, 2007). It primarily aims to model feedback and feed forward relations. These feedback loops then enable to assess the system's basic dynamic behaviour over time.
Maurer (2007) also provides an overview of *matrix-based approaches* for system modelling and analysis. One commonly used method is the *Dependency* (or '*Design*') *Structure Matrix – DSM*. It examines relations of the *same* type (e.g. technical features, product components, requirements…). For an in-depth discussion and application of DSMs relate also to Browning (1998). If one wants to analyse combinations of elements of several and *different* kinds (e.g. technical features vs. customer requirements…) then *Domain Mapping Matrices (DMM)* are applied. The Cross Impact Matrix as exercised through in this study belongs to this type as it analyses (or is intended to analyse) dependencies of various kinds of elements, e.g. stemming from product-, process-, project-, management-, organization-, market- and system-inherent complexities.
A similar approach that makes use of cross-impact analysis is known as *Scenario Technique*. The goal there is to find out a few likely futures ("scenarios"), to be able to examine the steps that led to that future. It is a tool for strategic planning to serve as a decision basis for the present (see e.g. Strohmeier, 2002, for the application of that technique in aircraft concept design).

5.2 The Complexity Indicator Method in Detail

5.2.1 Overview

The three phases and their steps will subsequently be explained in detail.

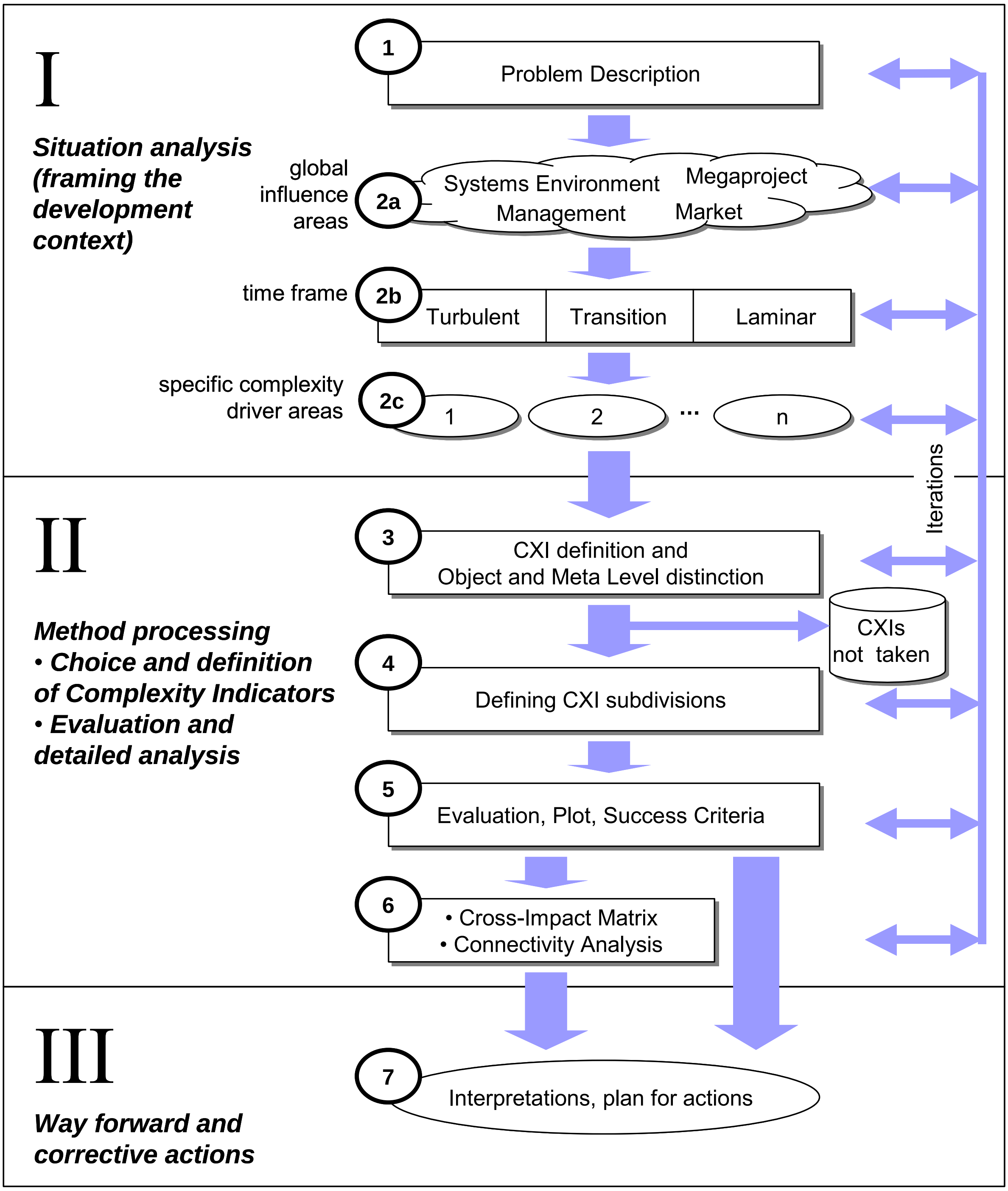

Fig. 5.4 Complexity Indicator Method overview

5.2.2 Phase I: Situation analysis – Step 1: Problem Description

The purpose of this first phase is to restrict the investigational subject to a meaningful area, for projects this will likely be the close development environment (Malik, 2002). The required level of detail is not known a priori and may only be found out in the wake of iterating the process steps (Dörner, 1999). It is fundamentally important to understand that the method shall not be executed in a way that requires finishing one step before going to the next. It will be necessary to work through several steps and iterate until one is confident with the choices made.

What is actually happening is a reduction of the variety of the decision situation. It enables the elaboration of the *relevant* complexity drivers.

The very first step is to state what the problem really is and to find the right method in dealing with it. Is it truly a complex problem or is it "merely" complicated? Is it complex only for me or do others share my point of view? Complexity definitions and classifications as stated in chapter 4 (especially figures 4.1 and 4.2) can help finding out if the problem can really be called 'complex'.

And if it is complex, how much or to what extend(s) is it complex? Rather less complex or highly complex? Design and integration of wing movables of large transport aircraft are certainly less complex than design and integration of the whole wing, let alone the entire aircraft. Setting the right contextual frame is crucial avoiding wrong expectations: what the method may reveal for the whole product (or project, or system…) may not be entirely true and applicable for its sub-components and vice versa.

5.2.3 Step 2a: Selecting global influence areas

In practice, steps 2a, 2b and 2c are likely to be done contemporarily. That they are dealt with in separated steps shall merely help converging top-down on those complexity driver areas that are deemed relevant.

2a presents the global view on complexity driver fields, headlined by the four challenges mentioned in chapter 3. The question is "Which areas do have or could have influence on the complexity of the situation?" This perspective shall help to understand the complex problem as something that might be influenced by external and not always obvious factors. Areas have to be analysed on a case-by-case basis, hence not every headline needs to be manifested in a specific complexity driver area. But one should not exclude these factors prematurely. The method may subsequently filter them out. One should beware not to exclude anything right from the start. The method could otherwise be degraded either to a pure academic exercise without practical relevance or worse, be the basis for wrong conclusions. The representation of influence areas in the figure below is by no means exhaustive:

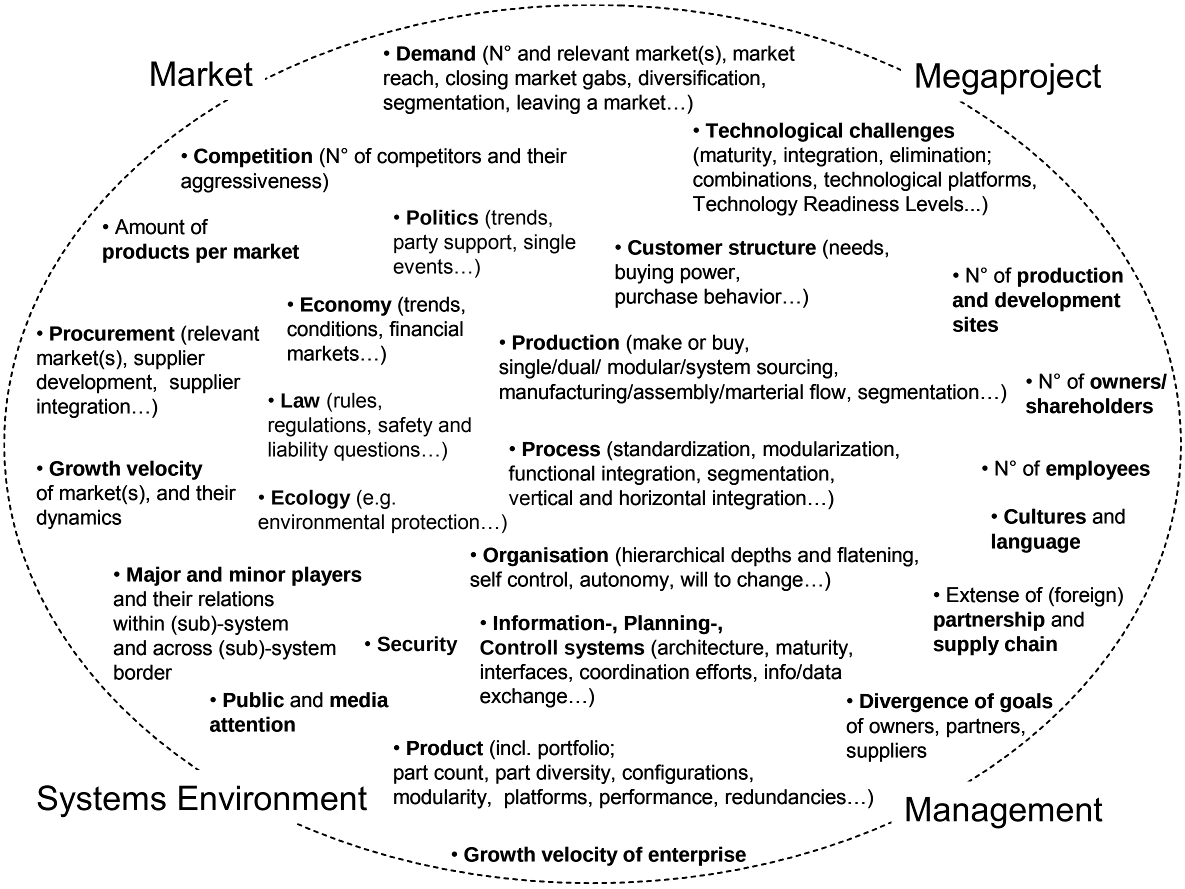

Fig. 5.5 Generic influence areas on complexity

5.2.4 Step 2b: Framing the choice from a timely perspective

The very distinct characteristics of certain periods (e.g. development phases) are often the cause for different complexity levels. To place the evaluation correctly, one has to consider them. There can be numerous designations how different phases are named. Here, for a general application, phases are divided into three generic classes (the characterizing names are lent from fluid dynamics, easing the analogy with a small but wild stream becoming a large river):

- In the *turbulent* phase(s) most things are uncertain and in flux, few core people work on the project and many and considerable changes occur: the whole project is in elaboration. One tries to reach a match between conflicting generic goals, e.g. for the general configuration, the specification, the business case or the terms of reference. With reference to figure 3.4 it happens roughly until 'knowledge point 1' (match between technology and requirements) is reached. It is the time around the establishment of the project idea and the feasibility and concept studies.

- The *transition* is the time when the project gears up (got the official "go"; approximately around pre-design) and "the rules of the game" are laid down. It is characterized by ramp-ups in workforce, increases in data volume and detail and in opening up many communication and reporting lines. Many new players (partners, suppliers…) enter the field, thus that phase is characterized by a high increase gradient of both element-amount and relations.

- In the *laminar* phase(s) everybody generally knows what to do, with whom and where. Schedules are detailed and usually no larger scale changes occur. Everybody is determined to meet time-cost-quality targets. That's about the time of detailed design, production, testing and integration and preparing for operations.

The table below gives some examples on characteristics of the three phases.

Table 5.1 Development characteristics in different phases - example

Area	Characteristics in Development Phases		
	turbulent	**transition**	**laminar**
Time Scale (relative)	Long	Short	Long
Product related			
• Design Data	Few (coarse) data sets	Strong increase in amount & detail	Many data sets
• Product configuration	In flux	Largely baselined	Frozen
• Requirements	In flux	Baselined	Frozen
• Technologies	Evaluation / Selection	Introduction	Implementation
• Processes	Build-up	Largely established	In-place
• Tool Set	Evaluation / Selection	Initial applications	Vast applications
• Changes	Many, also large scale	Many, usually in short time; smaller scale	Usually few / Minor
Execution related			
• Administration, Documentation	Small	Strong increase in extent and frequency	Extensive
• Organizational Structure	Core Team	Structural evolvement	Vast, detailed
• Control Mechanisms	Simple, few but strict	Strong increase in extend and reach	Fairly rigid, sophisticated
• Partnership, Supply Chain	No / Few major players	Major players selected	Vast, across all tiers
• Work-share	In flux / Open	Largely agreed	Finally agreed
• People, Workforce	Few	Ramp-up	Many
• Communication, Reporting Lines	Few, in build-up	Considerable increase in frequency and volume	Many; established; running in parallel
Other			
• Leverage in Life Cycle Issues	Greatest/Major	Medium	Minor / Few; Often: No / Insignificant

Nota bene: classifications are mainly notional; Boundaries are fluent so that characteristics may flip sides accounting for unique project circumstances; furthermore, within the same project teams may find themselves in different phases at the same time. Finally, intensities are likely to vary: In the early project phases a derivative will be far less "turbulent" compared to a completely new design.

5.2.5 Step 2c: Identifying specific complexity driving areas[32]

There can be n different "recruitment areas" for complexity indicators. The first issue to be addressed is *relevance.* Only those areas are considered that actually and obviously contribute to complexity. Here it will also be stated what conditions are taken for granted (if not already done so). This reduces the complexity right from the beginning, sets the right scope and frames the situational context.

The investigational *level of detail* is set here to extract only those indicators around the same level. Too global assessments paired with too specific ones may spoil the evaluation.
For an integrated view one might need to consider *hard and soft factors* from *internal and external* of the project. As for complex products one specifically looks for *product characteristics* as a primary source of complexity, but also for the *circumstances* within which this product is developed.

Product characteristics are the hardware and software components, their respective fit, form and function as elements, sub-systems and systems, across interfaces, to form the product as a whole.
The circumstances are usually the conditions under which the project as such is carried out including all (relevant) internal and external influences (e.g. disturbances). What is meant are primarily the people themselves, the organisation, partners and suppliers, the "stakeholders" in general as well as company rules, directives and principles, to name just a few. But it can also be market dynamics, competitive pressure or rules and regulations of authorities that have direct impact on the emerging product.

5.2.6 Phase II: Method processing - Step 3: CXI definition and Object and Meta level analysis

In this step the very Complexity Indicators (CXI) are formulated, and it is checked whether they indicate complexity for the object level or for the meta level. The aim is to find out the *relevant* indicators, those that represent the *determining factors* contributing to complexity. The distinction between object and meta level not only helps in finding the right "mix" of indicators. It is vital for initiating the *right* corrective measures, as consequences from changes on the object level or from the meta level go in fundamentally different directions.

Object and meta level CXIs may be recruited from both areas of variety comparisons: the decision situation and management. But there *may not be* a match in numbers from either side, such as five CXIs from the decision situation balancing five from management. This would spoil the investigation, as it will not be clear how many measures on one side will be matched by how many measures on the other side. For instance, it may well be that one factor of the decision situation side will have to be controlled by a full suite of measures on the management side.

[32] 2c may also be a likely entrance level for experienced practitioners. They often intuitively know what the complexity influence areas are. Such selections are essentially based on *schemes* (as introduced further above) in the investigator's minds. Crosschecks with 2a and 2b will round up the task and ensure that no relevant consideration is left aside.

If there is a vast supply chain, this definitely adds to variety on the decision situation side and can be taken as object level complexity indicator.
It determines, or one could also say *constraints* the whole development effort. Control measures on the management side are likely to involve measures on the object level, such as keeping a high head count to actually manage suppliers. But it also means taking actions on the meta level: E.g. clearly specifying quality rules, norms and standards, processes and responsibilities. In this respect it is less important to argue to where e.g. "rules of operations" may be attributed: To the meta level of the decision situation within the context of finding out the playing rules of business, or to see it as a variety increasing meta level factor on the management side. What is important though, is that the factor isn't forgotten at all. Assignment to whatever side may come later, in the wake of both exercising through the method and associated with it, better insight into the complex problem.

Another example: If data quality is regarded to be a complexity driver, two alternatives shall highlight the challenge finding the relevant CXI:
One can take the number of 3D CAD designers as an indicator (object level). Each of them is obliged with respecting the latest data quality requirements (when creating the 3D models). On the other hand one could define the degree of implementation of data quality rules (meta level) in the CAD or PDM system itself as an indicator.
Some designers will obey the rules, anytime, but some won't (e.g. due to lack in trainings, but also by loopholes that had not been considered). So, it is more difficult to find out what the actual status is, especially if hundreds of people are involved, and not a half dozen whose performance is well known. The indicator is potentially variety increasing (on the decision situation side) as there is a lack of "playing rules" and effective control measures.

Taking the second approach, one can be certain that everyone using the CAD/PDM system obeys data quality rules. There is no way out, no matter if ten people design or five hundred. Everybody is impacted by the rules that are implemented in the software tools. This not only gives a better indication on the status of data quality. It reveals where to put on the lever if quality output has to be increased project-wide. Here, the indicator has variety decreasing character (also on the decision situation side).
The second approach would be the better choice, not because of its variety decreasing character, but because of higher confidence that the complexity driver is measured correctly.

Another point is to distinguish factors that actually and obviously contribute to complexity, even if humans do not particularly perceive that complexity. One issue could be the *site* question. Even if perfectly integrated (from a communications and EDI point of view) a new development site *does* represent another (remote) element in the play, which at first glance does increase variety and also intransparency. One simply can't pass by and inform about the actual situation, one needs to make a business trip. Modern communicational equipment like videoconferencing only conditionally bridges that gap.

Language is an example of a so-called soft-factor. Even if someone regards himself and his/her direct counterparts perfectly fit in English that may not be assumed for everybody else. It's a matter of fact that clear expressions and fine nuances are best delivered in one's own mother tongue. In a foreign language it is always more difficult to express oneself. Thus it can't be ensured that messages get along and are received as intended so that exactly those (re)actions are triggered one had in mind.

Language is a steady source of misinterpretations thereby adding potentially to wrong hypothesis. On many multinational projects however, English will be spoken on a daily basis, as kind of lingua franca. Education and long-lasting training may, therefore, rule out the language question as a candidate for a CXI. In this respect one can argue that errors and misinterpretations occur in mother tongue *and* foreign language. Potential wrong hypothesis may sometimes be matched by a greater willingness to understand one another and to make oneself better understood when using a foreign language.

Step 3 also addresses any issues on novelty, control, maturity, dynamics and flexibility. In addition, any kinds of deviations from smooth and problem free executions of development efforts are sought. Step 3 is essentially a 'question-answer game' to reveal the relevant complexity indicators. The following questions give some guidance on identifying CXIs:

- Where are *interfaces* (technical, organisational; are they given or deliberately set)?
- Are there any *disturbances* (in the process, workflow, information flow)?
- What is *new* (e.g. recently introduced)?
- Are there *changes over time*? (e.g. in terms of goals or missions, requirements- or technology "creep"; this addresses similar aspects to the "what is new" question)
- Do we *control/master* it, also if conditions considerably change?
- Is it *mature* (e.g. readiness levels)?
- Are there *hidden potentials*?
- Is it a *source of conflict, uncertainty, and ambiguity*?
- Are *previous developments considered*, and to what *extend*?
- Does it *increase or decrease the number of elements and relations*?
- Are there *differences, similarities or overlap* among elements and relations?
- Do we have *sufficiently accurate data* for the indicator?
- Supposedly everything went *smoothly*, would the issue really be worth a CXI?

In practice, and to exclude personal preferences and intellectual or experience shortcomings, it is recommended to exercise through the crucial steps 3 to 4 within a team.

The outputs of step 3 are clearly and carefully defined complexity indicators.

Not all possible CXIs that are thought out are applicable for the actual problem. But if the situation changes, or if a different problem is to be analysed these CXIs could be worth being considered once again. The indicators can be used later on or stimulate thought in finding the correct ones for the new problem. More important, the pool of "CXIs not taken" provides evidence on what is actually *not* considered, and why.

5.2.7 Step 4: Defining Complexity Indicator Subdivisions

"Subdivisions" are plausible different *states* the system – represented by the CXI - can assume. They are, in fact, the culmination of all complexity reduction efforts aimed at revealing the relevant issues of the problem.

They serve to express the individual conditions that were or are present for the different projects. Example: a new cabin layout for an airliner may be either

(1) only a slight variation of an existing one,
(2) a major derivation, or even
(3) a tradition-breaking new design.

Each of these three subdivisions implies a different level of variety and has different implications for schedules and costs.
Basically, this step comprises two actions:

(1) to define a *discrete*, not too large *number* (up to a maximum of 10) of *subdivisions* the system is likely to assume with great probability.

(2) to *sort these subdivisions* according to their contribution to complexity and *assign numerical values* between 0 and 1; no or very inferior complexity would get a "0", the highest complexity subdivision would get a "1". The states in-between get proportionate values, e.g. broken down equidistantly (in a first approach).

The following table shows some examples:

Table 5.2 Examples of CXI subdivisions

N°	CXI Name	CXI Definition	Subdivisions	Value(s)	Remark
1	CXI A	Definition for "A"	Subdiv. 1	0.33	Here: subdivision 1 is not "0" as it actually contributes to complexity
			Subdiv. 2	0.66	
			Subdiv. 3	1	
2	CXI B	Definition for "B"	"yes"	0	Only two system states chosen; the one with complexity contribution gets "1"
			"no"	1	
3	CXI C	Definition for "C"	Subdiv. 1	0	Here: 0 = no complexity or neglect able; 1 = highest complexity
			Subdiv. 2	0.25	
			Subdiv. 3	0.5	
			Subdiv. 4	0.75	
			Subdiv. 5	1	
4	CXI D	Definition for "D"	Given Ratio, e.g. 0.82	0.82	Calculated ratio corresponds to complexity, the higher the ratio the higher the complexity

Assigning values to subdivisions may not always be straightforward: one guiding question is whether the division increases or reduces variety. Furthermore, for calculated values, the respective absolute contribution to complexity has to be assessed first, hence their *sensitivity*. Some care has to be taken with relative values, as they may not always show the "true" contribution to complexity the same way as absolute numbers do. Mathematically calculated values can therefore be mapped by a discrete pattern or "mesh". The more scattered the distribution of values, the finer the "mesh" shall be. The aim is to place values in correct categories, which accurately reflect the respective contribution to complexity. For instance, absolute values can be plotted as bars and then seen through a mesh of e.g. 10 levels. Each level then corresponds to a 0.1 complexity value. If a bar is about double in length to another bar, then the complexity value will also need to be double. This ensures that differences in the programs are accurately accounted for, and over- or underassessment errors are reduced.

Subdivisions may be described simply by "yes" or "no", which is whether or not a state is/was present, as expressed in the definition (e.g. CXI "B" in the table above). They can also represent maturity stages the systems runs through. Which configuration is actually chosen depends on how long the discrete states lasted, and which had the greatest impact on results (e.g. time-cost-quality targets). A new software tool set that had all of its planned functionalities available (long) *after* the lead systems had been build would probably not be considered as fully operational for the assessment (even though it might be running perfectly well in the end). Assessments may also be the sum of mean values over distinct phases. On one hand economic considerations will determine if such an effort is worth doing. On the other hand it must be judged very carefully that statistical techniques do not cover up important complexity aspects.

There is no upper limit for the number of CXIs. It is logic that the bigger the project the more parameters might need to be taken into account. But more than about 40 are likely to consume too many resources for evaluation, will be difficult to keep the overview and may sidetrack from filtering out those which are relevant. Also, there is increased risk of mixing different levels of detail. The method and its subsequent application were based on the premise that around 20 CXIs should be sufficient and manageable.

5.2.8 Step 5: Evaluation, Plot and Success Criteria

This step includes the calculation of each CXI in its individual subdivision telling the relative impact within the overall system. Therefore, for each project, all values are summed up to derive a global CXI value. That value is put in diagrams and plotted against time and budget, respectively. The diagram below resembles in principle the results of Bearden (1999) and shall be taken as example (each box, crossed box or cross represents one project):

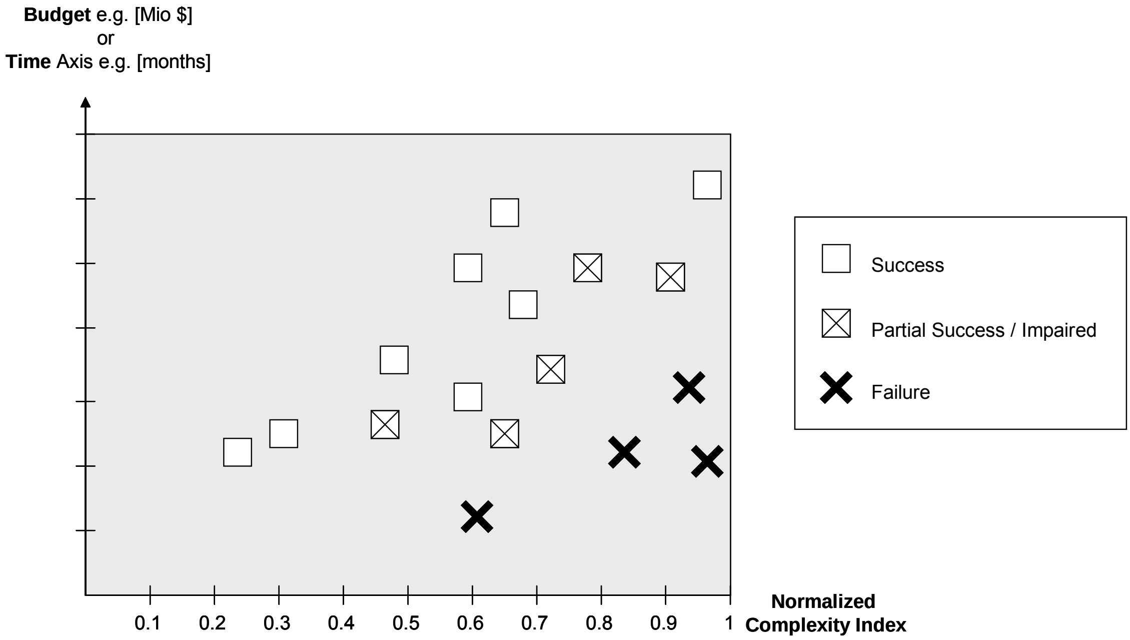

Fig. 5.6 Fictitious example of time/cost–complexity diagram for 17 projects

Before planning for action we need to correctly interpret the results. For that it is crucial to assign certain *success categories* because they give a meaning to results.

Judging success is not straightforward[33]. It strongly depends on criteria against which the results are measured. For commercial assessments, one way is strictly decoupling factors from one another: success in terms of *schedule goals* reached, in terms of *cost goals*, in terms of *quality goals* or of *performance goals*. A widespread approach for single events, as common for spaceflight and science missions, is assessing *mission success* – hence the product doing the job as expected (product is technically/scientifically/economically successful for its customers). But a thorough analysis also needs to shed light on *project success*, which is mainly the degree of meeting time/cost/quality targets. Together, a global assessment on *program* (= mission and project) *success* is possible.

[33] The Hubble Space Telescope turned out to be a tremendous scientific success, though its mission was impaired due to a technical problem in the beginning. It required an extra and very costly and risky maintenance service mission by the Space Shuttle to fully benefit from it. But at last its scientific success can be regarded also as a technical success – though unfortunately not from the onset.

Another way of differentiation is simply to regard whether the project/program was *technically* and/or *financially* successful (the latter assessment might be done after some time). If a single statement is sought, assessments need to be expressed in a single term, for commercial projects most probably a financial one. For instance, schedule overrun can be expressed in financial terms: Revenues and profit lost, penalties, recovery measures…

A proposal for some discrete success categories is shown below – taken both a technical *as well as* a financial centric approach:

Table 5.3 Proposal for project success categories

N°	Success Category	Definition
1	Very successful	Exceeding expectations in one or more crucial areas: e.g. longevity, performance, staying considerably below budget and becoming operational sooner than planned…
2	Successful	Product working as anticipated, within normal parameters; time/cost/quality targets are met within accepted tolerances…
3	Impaired/partially successful	Product works only to a degree as anticipated, some mission goals can't be reached; or considerable budget and schedule overruns occurred…
4	Failed	Product failed to perform in key areas of its mission, e.g. due to technical malfunctioning or budget/schedule constraints were surpassed and product is no economic/market success…
5	Disastrous/catastrophic	Product completely failed to perform its mission, substantial technical hurdles couldn't be overcome, was destroyed, did harm to people and/or brought with it substantial financial losses, or even drove the company to the brink of exhaustion/bankruptcy…

Success categories can of course be refined and distributed over more or fewer levels. Coupling financial and technical/scientific aspects in declaring success might be worth doing. But to better separate causes and effects of either side, it is recommended to decouple them. For a holistic assessment however, it will be necessary in one way or the other to combine both views.

Not regarded here are some "soft" categories even more difficult to measure such as *customer satisfaction* or *international collaboration*. Declaring success will even more be based on reasonable, critical and honest judgement rather than expressing financial terms. Customer satisfaction *may* result in more orders for the product, but this might also not be the case. A final product may – from a pure objective point of view - be declared financially impaired and probably be introduced or be fully operational too late. Nevertheless it may be regarded as a striking success for international collaboration, as the International Space Station example shows.

The approach for this study is to relate complexity to time, costs and quality. These relations shall now be examined a bit more in detail. The items are not any different to common breakdowns and listings; it's the point of view that makes the difference:

- *Complexity and costs*. The costs of complexity can be broken down into three areas (compare Schuh, 2005):

    - *Non-recurring costs (NRC)*: These are basically one-time expenditures for design and development. It is the cost for setting the right development context with (new) tool environments and processes (including methods and documentation), checking pre-series specimen and the costs of elaborating the general way of working (laying down the "playing rules" with partners and suppliers; establishing communication and reporting lines…).

    - *Recurring costs (RC)*: These are costs that occur on a regular basis, especially quality assurance activities, product data maintenance (incl. documentation and administration), variant specific validations or personnel trainings.

    - *Opportunity costs*: These are costs that have to be accounted for if resources dedicated to coping with complexity aren't used properly or efficiently. It would include "cannibalization" effects on other projects in case of e.g. a "brain drain" from one project to another, hampering the formers' progress.

- *Complexity and time*. Time or schedule means the project duration, and the time to sort out developmental issues, in particular difficult problems. It encompasses learning effects and the time it takes for reducing ambiguity and indeterminism, which essentially equals to a reduction in variety. A schedule too over-ambitious to sort out critical issues (through more trade-offs, tests, prototypes, evaluations…) would indicate a complexity trap: more time would be needed to find the answers to difficult questions but that time isn't available. In such cases problems will arise that in the end will consume more time and money for resolution.

- *Complexity and quality*: High quality and maturity requirements of modern technical systems (by law, safety regulations, reliability targets…) demand high determinism of the product itself and its operational behaviour. This in turn implies sophisticated measures from the very beginning of development to ensure meeting the high-level goals. Superior products will be the result of stringent quality requirements and constraints on one side and an adequate development (and management) context on the other side.

5.2.9 Step 6: Unravelling the nature of CXIs

Till here, the method revealed the key factors contributing to complexity, expressed as complexity indicators. Comparing them does already enable to conclude what to do. Therefore, this step is not mandatory.
On the other hand, it is still not sufficiently known what the very nature of CXI is, how they interact, actually their role in the play. To find out more about that two methods or tools are proposed here. One is the *cross-impact matrix*, to expel impacts and intensities of CXIs to find out whether they are active, passive or critical. The other is the *connectivity analysis*, which actually is a linked network of feedback loops.

Exercising them through can be very time-consuming, so one has to consider whether the results sought are worth the effort. The in-depth assessment will be worth doing if one is longing to control the direction of a project, maybe correcting its path and to reveal new alternatives for action. These two methods are an aide to show what the *key drivers* (or the levers) are, that need to be activated appropriately.

The tools might not be very useful for deriving further clues on *past* projects. It would be rather an academic exercise, for finding out what could have been done better. The biggest pitfall is the missing ability to change the course of the project.
Nevertheless, in elaborating this CXI method the two tools were exercised through manually for one past and one contemporary project. It helped proving the feasibility of using them within the context of this CXI method and for analysing changes from one project to the other.
Beforehand, one major result is that especially when dealing with more CXIs (in the range of 20 to 40) it may be advantageous to draw support from some features of commercially available software tools[34].

(1) The Cross Impact Analysis

With the cross impact analysis CXIs are compared pair-wise in a matrix. The major question asked is

- What and how intense is the impact of system state subdivision “abc” of CXI “A” on the complexity of subdivision “xyz” of CXI “B”?

Intensities are taken discretely and may range from “neutral” or “no interaction” to “strong”.
Please note that only the very configurations of the CXIs are assessed, and not all possible configurations set up in step 4 against all others. The reason is, as mentioned above, that complexity takes effect always in a distinctive manner, based on certain conditions, namely what is here called “subdivisions”. Therefore a matrix has to be elaborated for each project that shall be analysed.

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[34] One is the “*Sensivitiätsmodel Prof. Vester* ^TM^” (Vester, 2002). Within that software suite there are tools aiding the establishment of cross-impact matrix and the connectivity analysis. Other commercial tools are “*Heraklit* ^TM^” (Lindig, 2004) and “*GAMMA* ^TM^” (Hub, 2004). Both software suites follow similar objectives as the “Sensitivitätsmodel” and are effectively derived from that method. Another complexity management software solution is “*LOOMEO*^TM^” of Teseon corporation (www.teseson.com), a spin-off of the Technical University of Munich. The advantages of all of them are especially the interactive build up of the connectivity analysis and their flexibility to changes and adaptations, while keeping the overview.

The figure below shows the set-up and intensity calculations:

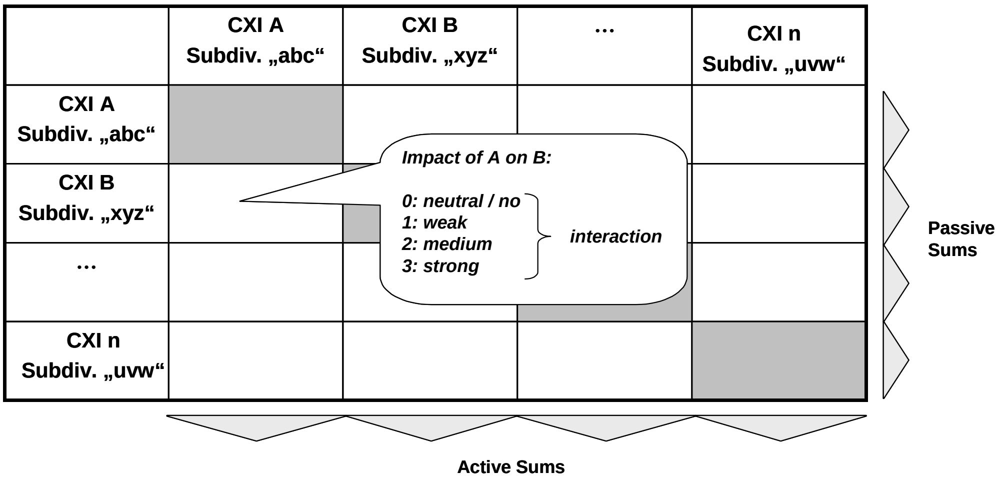

Fig. 5.7 Cross-Impact Matrix

The row sums indicate how “passive” an indicator is, the column sums characterize its “activity”. “Active” actually means that the CXI is actively interacting with others, triggering events, probably forcing the system into a certain direction (if this direction is favourable then emphasis on the CXI may be increased). Rather “passive” CXIs are on the “receiving” end of interactions. They do not interact as vividly as others; they swallow up developments and may inhibit the course of action. The quotient Active/Passive reveals the relative character of the CXI. The positions can then be shown in a diagram revealing their specific *tendencies*. That’s the prerequisite for understanding the roles of CXI and general system behaviour and is a basis for launching the right actions.

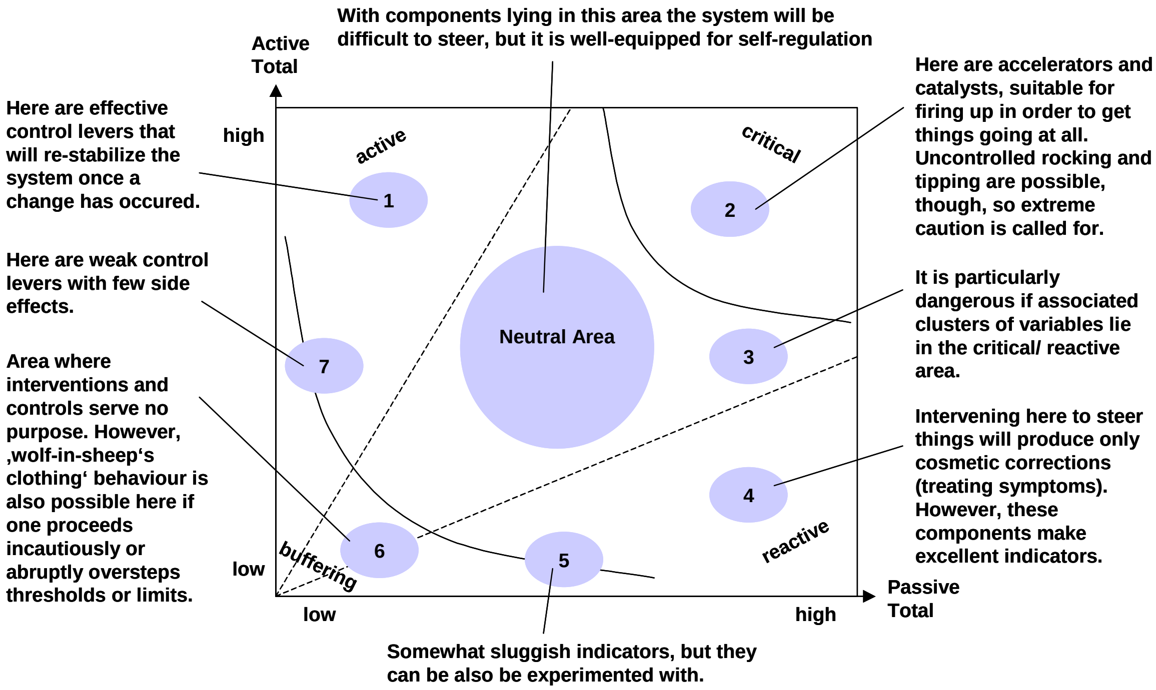

Fig. 5.8 Areas indicating the different roles of CXIs (taken from Vester, 2002, 2007)

The figure below shows the result of such a cross-impact analysis. It is broken down in four quarters. Vester's diagram above shows a bit more sophistication. Nevertheless, the four important areas are portrayed. That way they are also presented in Strohmayer (2001), Lindig (2004) and Hub (2004).

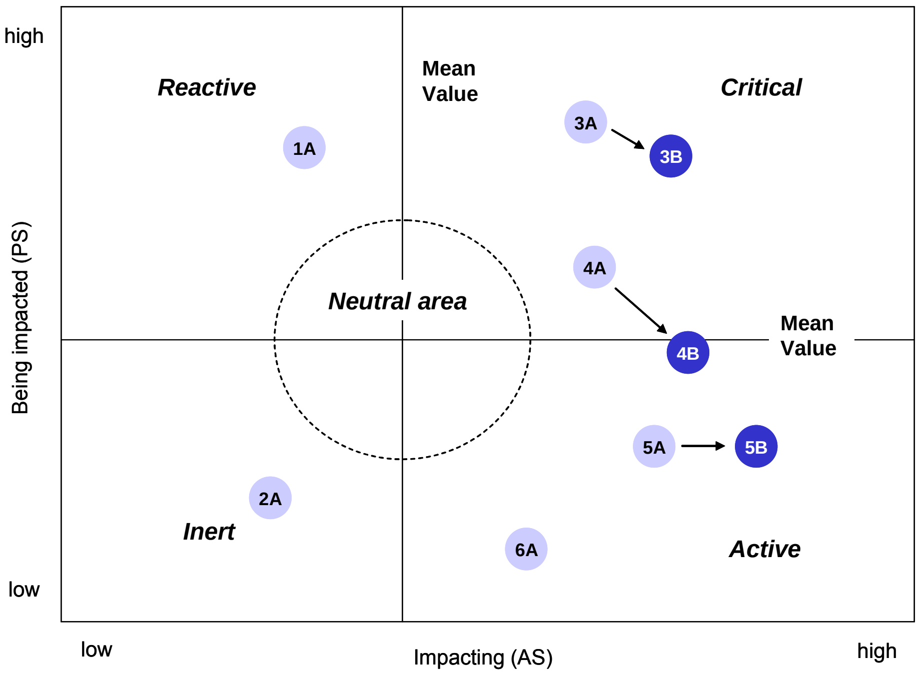

Fig. 5.9 Example of CXI assessment results: changes of three CXIs are shown from a second investigation (assessments A and B)

(2) Connectivity Analysis

This tool aims to give answers on the complex *pattern* of the specific *interplay of CXIs*. Revealing the dynamics of relations enables a better orientation where to change and on the likely consequences of actions.
Therefore some of the following characteristics may be expelled, broken down in discrete qualitative measurement units:

- *Connectivity:* positive / negative feedback loops
- *Impact:* increasing / decreasing / non at all
- *Intensity (of interaction):* strong / medium / weak / non at all
- *Timely horizon*[35] short / mid / long term impacts
- *Location of action:* impact felt or taken place locally / globally

[35] In dynamic systems the timely horizon will need to be coupled with appearance behaviour of impacts. These can be
- *discrete* single or multiple events (the latter with either regular or stochastic appearances)
- *continuous* impact events (all with or without time delay)
    - linear/progressive/degressive increasing to full intensity
    - linear/progressive/degressive decreasing to zero intensity (fading away)
    - constant after appearance
    - piecewise constant after appearance
    - following a mathematical or approximated function , piecewise or not

Not all characteristics might be revealed at once. The important thing is to draw control or feedback circles, and judging whether they are of positive or negative nature. Positive means a direct correlation between input and result: e.g. the more/less of X, the more/less of Y.
A feedback loop is negative if the correlation goes: the more of X, the less of Y and vice versa. Positive loops are important for triggering processes or keeping them running. They have the tendency to amplify. Without correctives the system could be destroyed. Negative loops on the other hand are of dampening, stabilizing character. They are important to smooth out actions and not letting processes be swung out of order.

That is why one can first of all concentrate on feedback loops. Later, impact, intensity (e.g. thicker or thinner arrows) and timely characters may be revealed (e.g. by applying "Δt" for short term and "ΔT" for long term impacts). As Vester (2002) stated, not all factors – here CXIs - that are taken for the cross-impact matrix will need to be handled. As the question is different with this analysis, so can be the approach (thereby using fewer CXIs).

The connectivity diagram is drawn through identifying the *central cycle* (or cycles) first. This depends on the perspective that shall be focused on and on what the objectives and key factors are. This cycle is self-amplifying and actually the "motor" for the situation as a whole. Other factors are placed around the cycle(s) and a network of interactions (feedback loops) is drawn between them.

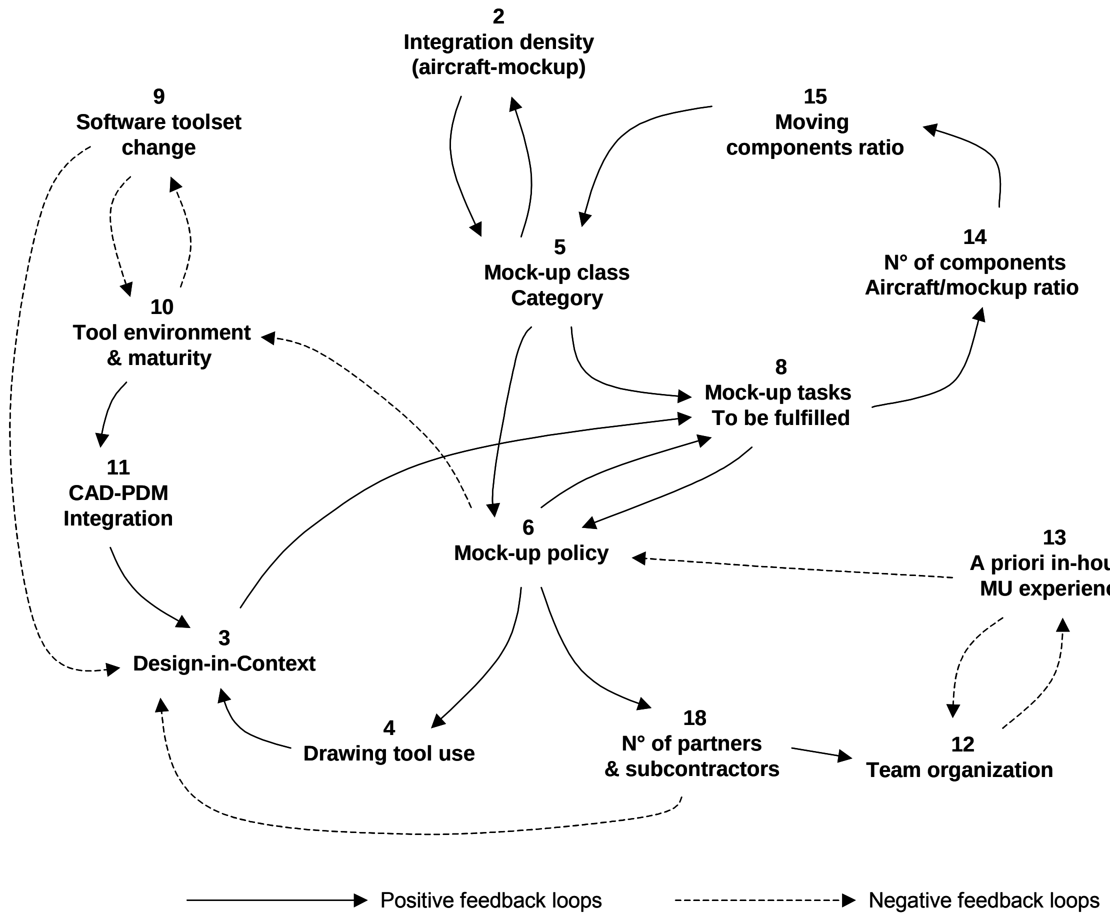

Fig. 5.10 Example of a connectivity analysis; one central cycle for instance goes from CXIs 8 via 14, 15 and 5 back to 8. (here simplified without intensities and timely horizons)

The final step is to extract all positive and negative feedback loops. That reveals which CXI is part of how many loops. Furthermore it shows via how many steps impacts pass, and of what nature they are. It can expel those, which determine the direction of the system and its evolvement. This is shown in the table below:

Table 5.4 List of positive and negative feedback loops (taken the example of figure 5.10)

Negative feedback cycles	Loop number	Positive feedback cycles
6-18-12-13-6	1	2-5-2
6-18-3-8-6	2	6-8-6
6-18-3-8-14-15-5-6	3	9-10-9
6-10-11-3-8-6	4	12-13-12
9-3-8-6-10-9	5	3-8-6-4-3
9-3-8-14-15-5-6-10-9	6	8-14-15-5-8
	7	6-8-14-15-5-6
	8	6-4-3-8-14-15-5-6

Long impact chains, that are feedback loops with many intermediate steps, tend to take effect with delay. They can be dangerous if noticed too late. Short chains on the other hand will usually show a rather rapid reaction.

The above example shows that e.g. CXI N°3 - ‘Design-in-context’ appears in 5 of 6 negative feedback loops hence plays an important role in stabilizing the system.

On the other hand, CXI N°2 - ‘Integration density’ is in a self-reinforcing positive and short loop with N°5- ‘Mock-up class’. Such a situation has a potential tendency to amplify if not matched by dampening loops in which either factor is involved (here N°5). But in this case there exists a “physical” end to potential amplifications by the fact that there is no higher mock-up class than class III, and the space volume available also considerably constraints the number of components that can go into.

The advantage of this analysis is to show the dynamical structures within which CXIs are embedded. It enables better anticipation of consequences of corrective and control measures: Which “levers” to pull, where and about when to see (initial) results and determining those factors that can act as indicators for the correctness of measures.

There are several ways to ensure that the connectivity diagram shows the correct relations: the most obvious is to elaborate it as a team effort. Then it’s appropriate to exercise through some questions from different entry points: each chain of impacts must be consistent by itself. Another possibility is to alter intensities and asking ‘what if’ – questions like “what happens if the intensity of the impact on this CXI is (strongly/moderately) increased/decreased?” Both impact relations and feedback loops shall then still be consistent.

5.2.10 Phase III: Way forward - Step 7: Interpretations and plans for action

Drawing on the above example there are several ways to deal with results. Being among past successful projects is fine but a closer look on complexity drivers might still be worth doing. “Sleeping” or inherent problems and impacts of unexpected events can thus be eased. As typical for complex systems and situations usually an array of measures in the right intensities and right timely sequences has the best prospects for *lasting* success. The whole method here is intended to support making the right decisions.
Should the evaluation reveal a more critical position of the project, usually some risk reduction initiatives need to be triggered. This is shown below.

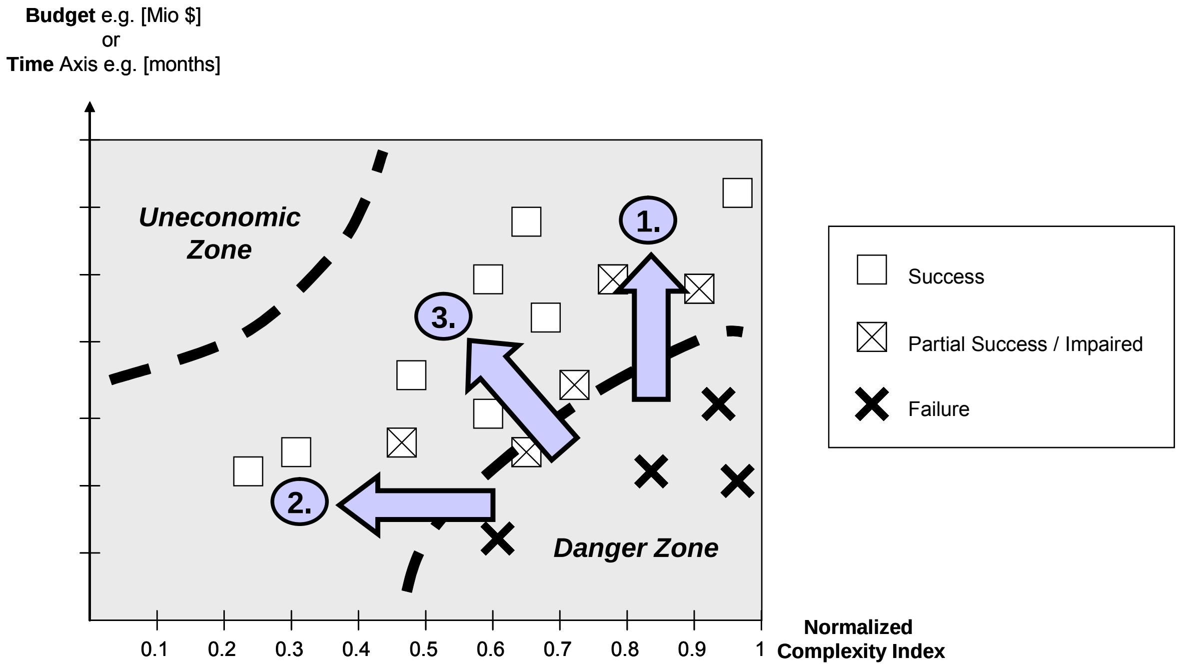

Fig. 5.11 Three primary directions out of the danger zone

To move out of the “danger zone” in principle one has to avoid the right bottom corner area. This is where high complexity meets low budget and stringent schedule constraints. Three strategies are possible:

1. Keep the (high) complexity level and devote more time and money to the project to sort out unknowns and to thoroughly design, trade-off, test and evaluate.

2. Drastically reduce the complexity level while keeping the ambitious budget and schedule targets. This can imply making (mission) performance cuts.

3. This is actually a combination of 1 and 2 and aims at careful trade-offs between mission and product parameters, time and cost constraints and the underlying complexities. Nota bene: initiating the right measures on the “complexity front” may avoid cutting any mission or product features!

The other zone to keep out is called here the “uneconomic zone”. Thinking it to the end it would mean too high an investment for too low an outcome. Projects in that area are likely be criticised as pure job-creating measures. For them the same success categories apply, with the focus being more on financial aspects.

The threshold line to the two keep-out zones may be defined only through reasonable judgement and the evidence of several failed and impaired projects. But one cannot rule out that there are actually projects that will be successful at high variety levels in spite of strong cost and schedule pressure. Therefore the lines are not intended to be dogmatic. From a qualitative point of view, and hopefully supported by statistical evidence, the prospects for successful project completion are considerably lower than outside those areas.

Which strategy to pursue will be up to the evaluators: One can change the schedule and or the budget. This can be one consequence but is unlikely to happen at the beginning. It is more likely that a closer look will be taken on the complexity situation itself.

In general, getting complexity under control will require adjustment- or regulation actions. Some key drivers, either already being known or derived through step 6, will need to be altered to steer the project in the favourable direction. Actions can take place both on the object and the meta level. They can be of variety increasing or decreasing nature, depending on which side they are activated. The following list shall give an indication what that may mean:

- *Acting on the object level*: one can increase or reduce the number of elements and their relations, e.g. by limiting the number of partners and suppliers and work with a few major suppliers instead, or by increasing the number of employees to cope with particular difficult issues; reducing part count and technical interfaces, streamlining lines of communication; part and technique standardization and modularization;

- *Acting on the meta level*: introducing rules, regulations, guidelines and standards and their enforcement; triggering self-regulation, establishing clear roles and responsibilities within the organization, working with higher educated and more experienced people;

- *Changing variety of decision situation*: finding out the playing rules; getting to know better the requirements and constraints as well as the consequences of actions in a near and far perimeter;

- *Changing variety of management*: granting more freedom to explore new ways, executing processes in a proactive manner, co-location of key personnel for short communication ways, training personnel, enabling and empowering them for the tasks ahead;

A strategy then is a fine-tuned mix of all approaches. In this respect, the recommendation of Malik (2002) is appropriate, namely on an approach with the best prospects for success when dealing with highly complex systems: Solving problems a decentralized way on the object level, while the whole process is steered and controlled by a central meta-system. This ensures a unified direction whereby exhausting adaptability and flexibility to full extend.

5.2.11 Scope, reference frame and limitations of the method

The scope of each model application is determined by the numbers of projects to be investigated and compared, by the availability of research data, the timely focus and the intended use of results. The level of detail sets the reference frame both for indicators as well as complexity categories. Doing an 'integrated' approach does not mean covering a topic exhaustively from each and every viewpoint. The method *isn't primarily intended* to solve *any* first hand problems (curing symptoms), but it does provide – probably unanticipated and unexpected - insights into complex situations and problems. For better understanding of impacts parameters can and should be varied. But evidence on – especially non-linear - consequences of some very small changes is not within its scope. This field is deliberately left to more sophisticated (and hereby computer supported) simulation models.

The *cross-impact analysis* is admittedly somewhat ambiguous: On one hand it has the advantage to give clues where measures will have the greatest leverage, and where one should be careful not triggering any unintended chain reactions. On the other hand pair-wise comparisons may not really expel the *linked nature* among variables and might leave out side effects. Finally seeing numbers again may lull somebody into a false sense of security. This is because indicators can be coloured subjectively and through multiple counting – which cannot be excluded – and thereby distort results (compare Gomez and Probst, 1999). The more CXIs one has to deal with the sooner it can become confusing without dedicated software tool support. The iterations one has to perform to converge to a "stable" or robust analysis may as well become more work-intense if numerous indicators have to be re-arranged and feedback loops need to be adjusted.

The *connectivity diagram* might also reveal only a slice of the truth if *crucial* timely dependencies, in particular appearance behaviours of impacts are not sufficiently known. Therefore, *timely delays* with which actions showed effects are only assessable with relative accuracy: long feedback loops tend to take longer to effect than shorter ones. But this doesn't degrade the effectiveness of the method, its inherent approximate nature.

A general difficulty is to reveal *systemic effects.* This is, for instance, the increasing of impacts because combinations of effects are stronger than single events (so-called "compounding"). The method considers the accumulation of effects only conditionally. Also difficult is recognizing *implicit* problems. Such "latent" issues can become dangerous as they are at first not observed or perceived as such. Only when someone tries to solve different problems may these appear and correlate with solutions in a negative way. It is difficult to figure out adequate CXIs for that kind of issue.

Further it is theoretically possible to choose a “wrong” CXI or not to define complexity categories correctly. One may choose too few or too many categories or neglect distant effects. But the very sense of the iterative approach is to *avoid being trapped* by these issues. If the evaluation is part of a team effort then its fruitfully different and conflicting views help sorting out such kind of difficulties. The model also does not provide answers about the adequate levels of complexity that might be necessary for projects. The only available rule is the law of requisite variety, which has to be fulfilled for having a project (or system, or a decision situation in general) adequately under control.

Human behaviour is particularly difficult to cover. Attitudes and feelings like trust, respect, disappointment and especially their daily variations among participants may need to find their way into the evaluation – if relevant - via different ways. They can either be accounted for directly as a general “mood” factor, or indirectly via results (increase or drop in number of defects, innovations and improvement proposals, off-times e.g. due to illness) but also via stimuli like the company operating at the verge of bankruptcy or with the project on the brink of termination. All these factors can be taken into consideration - and used with care - as they can show symptoms of human behaviour.

Hierarchically composed parameters (such as the well-known Return-of-Investment indicator – ROI) are not within the scope of the method presented here. They will neither be supported nor dismissed as usable in this context. The guiding rule is to be able to easily correlate implications to its originating factors. Thus, care needs to be taken not to loose touch of complexity by creating compositions of too many elements and by compressing too much.

Finally, any prognosis needs to be handled carefully not to return to linear extrapolations so common with traditional methods. Having actually exercised through the method one should be enabled to avoid that kind of trap. Better knowledge about the system state does allow and actually favours pro-active interventions to induce the creation of favourite conditions.

Chapter 6 Case Study: the Complexity Indicator Method in application to Engineering Mock-up and Digital Mock-up campaigns

6.1 Objectives and focus of the Case Study

This case study is an application of the Complexity Indicator Method described in the previous chapter. The objective is to find out more on the relation between the complexity of mock-up campaigns and the time, cost and quality impacts. Another objective is to validate the method itself. The quality impact in particular is assessed through an additional "spotlight" investigation. A second spotlight sheds light on the nature of Complexity Indicators for an EMU and a DMU campaign. It shows what has changed by going from hardware and 2D to the digital world and 3D.

Six large transport Aircraft development projects form the basis of the case study. The investigational subjects are their Hardware- and Digital Mock-up campaigns for Wing Integration. This activity comprises the installation/assembly of all moveable components plus all systems (electrics, hydraulics, bleed air, flight controls…) on the wing's leading and trailing edges. Two of the Aircraft programs were supported by Hardware Mock-ups, four were/are based on Digital Mock-ups. For consistent naming reasons only "Engineering Mock-up - EMU" shall further on be used for the Hardware Mock-ups, because that was also their official name.

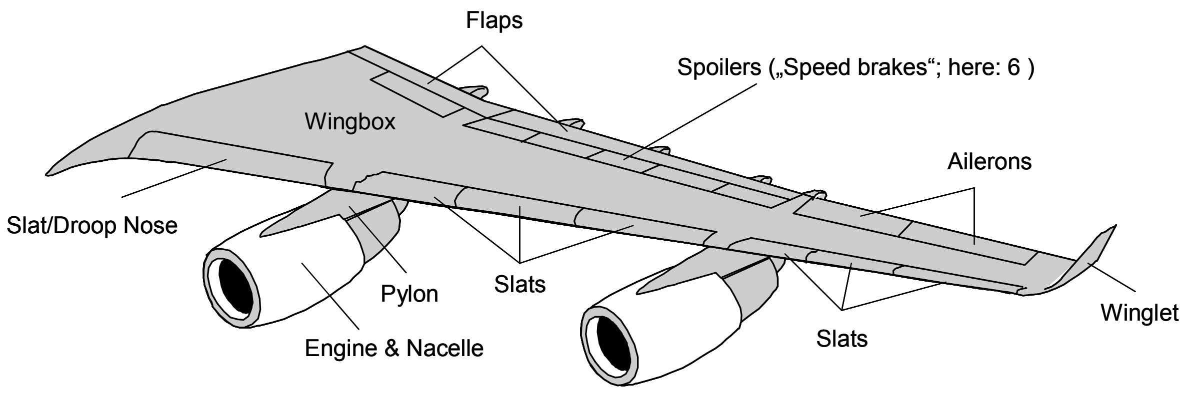

Fig. 6.1 Typical left hand wing for a four engine large transport aircraft with major components

There are a number of reasons for choosing that particular subject: First, the programs can be compared, as objectives, processes and tasks are the same or at least similar. That is also true for design and integration requirements and constraints. Four Wing Integration efforts took/take place at one site, namely in Bremen, Germany. The other two take place partly in the United Kingdom, in France and in Spain.

Second, most development work was/is being done on one site. Often the same people were working on them. That eased the access to crucial data and reliable information. Specialists and their expertise especially on past Engineering Mock-up campaigns were therefore an important factor in judging results being correct or not and for the contribution to the method's validation.
Third, it was crucial to always being able to crosscheck the method with real business circumstances. This is particularly important when applying a new method to an area that is not sufficiently documented. It would draw the risk of not placing it in the right overall context and of not being able to interpret the results correctly. The authors' own experience with the four DMU campaigns as well as important input and feedback from various people from the EMU campaigns will hopefully have by-passed these risks.

6.2 Introduction to Engineering Mock-up and Digital Mock-up Campaigns

6.2.1 Similarities and Differences of the Mock-up Approaches

Both approaches had/have in principal the same objectives: to anticipate installation problems before they occur in the assembly line. Modern Aircraft wings are densely packed with numerous pipes, cables, structural elements, deployable or not within relatively small space. The geometrical forms can be quite sophisticated, nevertheless everything has to fit together perfectly. As assembly workers are not granted unlimited time to install the parts, at least all major problems should be sorted out before the to-be-equipped wing enters the assembly line.

The two top goals with the Engineering Mock-ups were addressing schedule and budget risks:

- *Lead time reduction.* That meant keeping the overall development schedule by equipping the first pair of wings within 3.5 - 4 months. Without an EMU, planners estimated the first pair to require double the time.

- *Reduction of recurring costs.* With all major and most minor problems being sorted out during the EMU campaign it was hoped that recurring costs for the following wings would be lower, the learning curve steeper and that the wings would be subject to fewer installation problem related variations.

EMU and DMU top requirements for a Wing Integration EMU campaign are shown in the following table; from a technical point of view, most mock-up tasks were in fact the same for both types:

Table 6.1 MU requirements for Wing integration

Requirements	Applicability
• Checking geometrical fit of structure and system installation including clearances (installation of pipes, cables, flight control systems…)	EMU, DMU
• Geometrical definition of built-parts (tubes, fittings, connections)	EMU, DMU
• Definition of Interfaces of buy-parts (e.g. equipments such as actuators)	EMU, DMU
• Checking iterative changes of geometry	EMU, DMU
• Fast clarification of quality non-conformities (manufacturing errors)	EMU
• Acceptance of master specimen	EMU
• Performing live functional tests (e.g. demonstrations to authorities)	EMU
• Demonstration of accessibility, installation and de-installation of parts/equipments, creating and validating maintainability concepts	EMU, DMU
• Configuration Control: to track conditions during pre-installation in mock-up and on original wings; checking modifications, e.g. with series modifications	EMU, DMU
• Checking communality with other similar wing (e.g. two-engine and four-engine aircraft having basically the same wings)	EMU, DMU

The EMU was executed as a separate sub-project lead by manufacturing departments. It was hence decoupled from the critical path. In contrast, the DMU is integrated in design activities, continuously refined and iteratively matured, actually being one of the major deliverables of Engineering. The requirements whether or not (full-scale) EMUs should be created for certain areas (fulfilling dedicated mock-up category standards) were usually formulated in official project documents such as work-sharing reports. The mock-ups were therefore unique parts of the work-breakdown structure. Today, 3D CAD design is both common practice and actually in the *centre* of Engineering activities, without requiring special attention in the work-breakdown structure. Differences can be found in the extent to which 3D CAD design is done: areas fully or partially detailed, the degree of (re)usability for other disciplines (e.g. Technical Publication) or the DMU being kept up-to-date for any configurations along series production. EMUs today play an inferior role, but nevertheless are an option should the need arise to check highly risky areas.

Table 6.2 Major advantages and drawbacks of the two mock-up types

	Advantages	Disadvantages
EMU	• Hands-on learning effect • Better assessment of difficult geometrical situations taking material properties into account (e.g. curvature of tubes, spring-back effects…)	• Time, money, people and space consuming (material, tooling, labour…) • Difficult to keep up-to-date • Takes longer to check multiple solutions and configurations • Usually stuck to the site where it is build
DMU	• Anticipation of problems already during design • Easy keeping up-to-date • Fast and inexpensive checks of a multitude of options, solutions and configurations • Fast tracking of progress through exchanging/sharing data electronically	• No hands-on learning effect (Virtual Reality solutions with tactile capabilities are still insufficient substitutes) • Sophisticated processes, Hardware & Software tools and capable IS/IT environment required

6.2.2 The Engineering Mock-up campaigns in retrospect

Two large EMU campaigns were executed at plant Bremen, Germany. In the investigation they are denoted “A” and “B”. The first one was done around 1980, the second almost exactly ten years later. For both it was beneficial that smaller scale Hardware Mock-ups had been built before and for the latter, there were some done in-between. The EMU of program A focused primarily on the installation of pipes, cables and equipment for the systems and on checking clearances. Even then there was already the strong requirement to have important surfaces, system lines and interfaces made from metal in order to have tolerances equivalent to original items. As later in program B some equipments were simulated as dummies, for schedule and budget reasons. Configuration control was deemed important for both campaigns aiming for the same installation conditions in the mock-up and the first flying wings. At important areas the EMU had the characteristics of a *gauge*, and was assembled using then state-of-the-art measuring systems (e.g. theodolits).

For compatibility with the real wing important interfaces were adjusted with so-called “*master tooling gauges*”. These jigs had exact dimensions and were provided by the British wing partners. They were flown to Bremen in pieces, each about three meters long. After the EMU was adjusted (e.g. hinge lines, interface points), the master tooling gauges were flown back to the United Kingdom.

The success of EMU campaign A was remembered when launching program B. That EMU of both left- and right hand wing leading and trailing edges was even more advanced. It resembled category II/III mock-ups (the former was largely rather category I/II) and was used also for the evaluation of maintenance procedures. Furthermore, it was later modified to accommodate systems unique to the twin-engine configuration (the original EMU was for the four-engine variant of program B).

In ideal case, problems showing up in the EMU should be known about three to four months in advance. This would give Engineering and Manufacturing enough lead-time to react. For equipping the wing that time span was deemed sufficient to either change the part(s) or the assembly, to order new material and to introduce the change in the normal design and production flow (e.g. updating drawings, checking interfaces, adapting NC programming…). In reality that proved difficult as systems definitions were late and changes were submitted the last moment. That resulted in shifting the EMU effort to the right and made reacting on problems often a race against time. Installations were then checked on the EMU just before being done on the real wing, which already was in the assembly line.

Figure 6.2 compares planned and real progress of EMU campaigns. Although starting early enough, a full EMU was available only around start of equipping of real wings. Mock-up activities were therefore pro-tracked into the equipping phase of the real wings. Reactivity on problems was reduced.

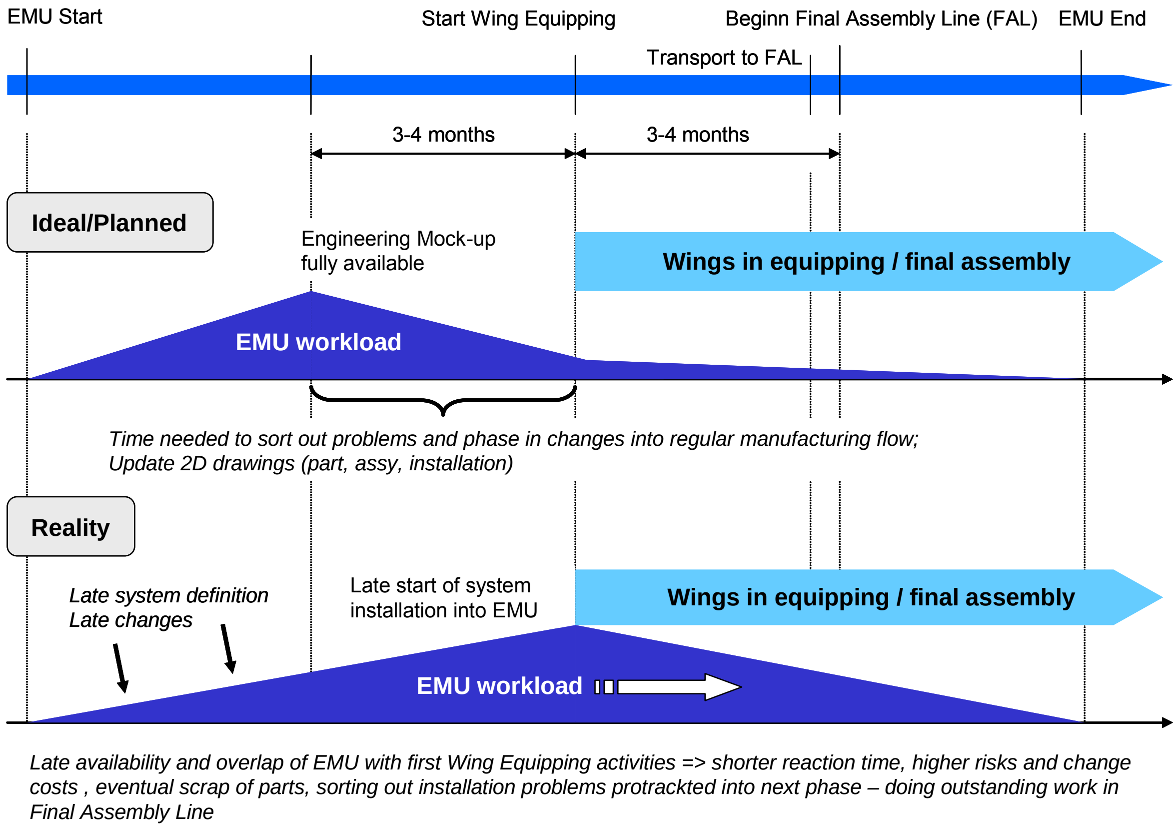

Fig. 6.2 Planned and real progress in Engineering Mock-up campaigns

The principal flow of information and documentation for the EMU campaign is illustrated in the figure below.

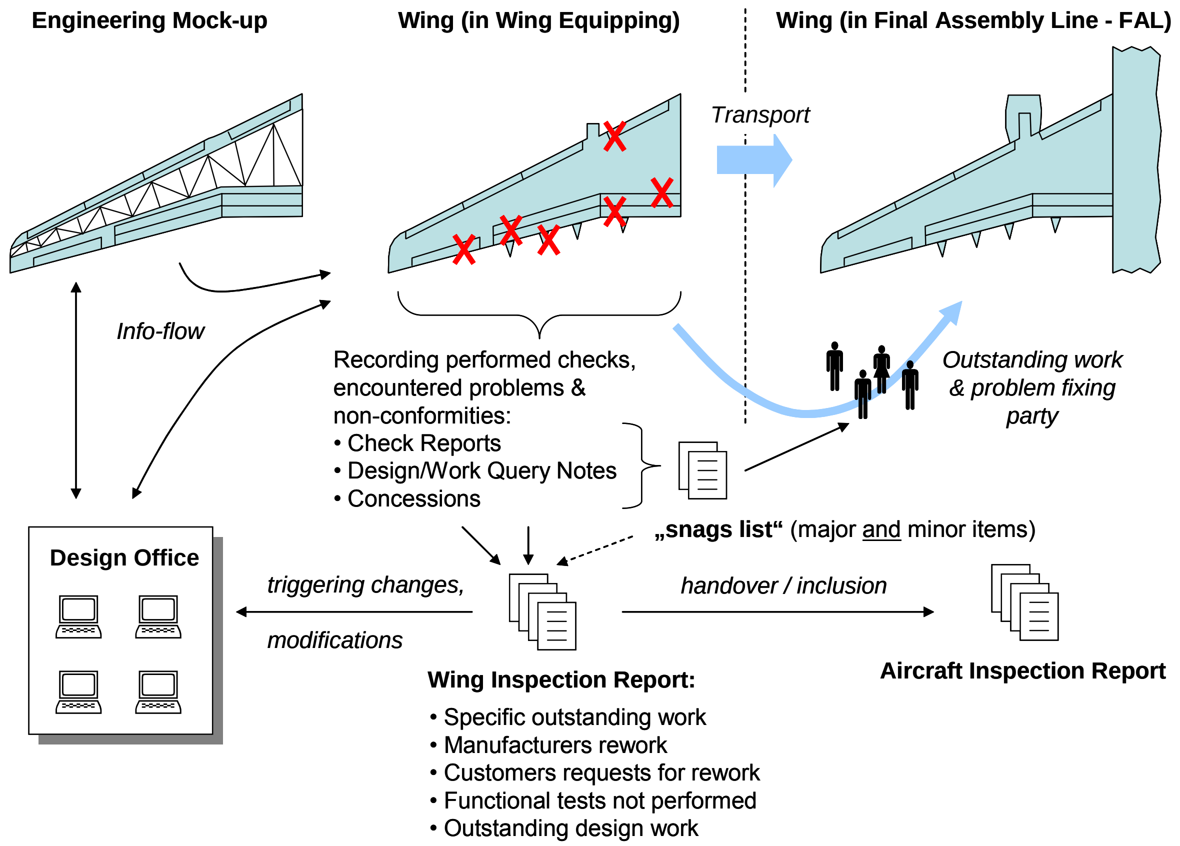

Fig. 6.3 Engineering Mock-up – information flow supporting the wing and Aircraft assembly process

Most assembly/integration issues could be sorted out in the EMU, before the first pair of wings came into wing equipping. Nevertheless, all problems, major and minor ones were recorded in a so-called "snags[36] list", some of them finding their way into the official Wing Inspection Report. That was prepared by Quality Assurance and handed over to colleagues in the Final Assembly Line. Anything that could not be solved during the wing equipping time slot was "outstanding work". All issues had then to be solved in the Final Assembly Line while the complete Aircraft was being assembled and integrated. For the sake of keeping the overall schedule (a very dominant requirement) not finishing the work as originally planed created substantial additional work and a number of problems: travel costs and lengthy stays abroad of key manufacturing personnel and extensive logistics (from necessary tooling to actual components, everything had to be re-routed to the FAL).

In addition, people that would have been needed at home were now cramping the final assembly space, waiting for slots to access the Aircraft, working extra shifts and during weekends. In spite of all these follow-on measures, the EMUs were attributed as one key factor to overall keeping the development schedule.

[36] A snag is "a hidden or unexpected difficulty" (Longman Compact School Dictionary of English)

6.2.3 The Digital Mock-up Campaigns

Program C was the first big aircraft project that had used the DMU for designing major components (wings (partially), pylons, centre fuselage). It started about eight years after B. Aircraft C was actually a derivative design of B, so the decision was taken to go for a Digital Mock-up as a complete substitute for an EMU. That was done for three reasons: First, the 3D CAD and DMU simulation technology was deemed mature enough to cope with the expected large amount of data and with stringent aerospace requirements[37]. Second, it was expected that expenditures for the DMU would be about half of the budget needed for a hardware mock-up solution. And third, being a derivative design, C installation procedures were expected to be largely the same as for B. In addition, wing integration crews had already gained a lot of experience with program B wings, so that any unforeseen issues were expected to be handled on time.

Pursuing the Digital Mock-up[38] initially had several objectives:

- First, the DMU should be used as a *cost reduction* measure. As said above, savings were estimated at about 50% compared to Engineering Mock-ups.

- The second aim was *lead-time reduction* and *keeping the development schedule* (equal to the objective of the EMU).

- By going 3D, the aim was also to achieve *higher quality* of the product itself, with much fewer installation problems, considerably reduced outstanding work and therefore higher maturity when introduced into service.

These points are still valid today. But there is another issue that soon drew the attention of the Design and Management community:

- A very dominant aim became the ability to *master the complexity* of concurrent development: a huge – often globally dispersed - team with an extensive supply chain was working on heavily customized Aircraft. One had to cope with late (and often customer induced) design changes as well as with the challenge of evaluating multiple configurations of an entire aircraft family in parallel. The DMU became *the tool* that enabled to do exactly that.

[37] For program B 3D CAD was already available and therefore in discussion, but the option was abandoned due to performance shortfalls. In the meantime till the start of program C several pilot projects on particular areas explored pros and cons of 3D design (some quoted in Herrmann, 1992). It was used only selectively during development, such as surface design or for geometrically critical areas like the cockpit.

[38] Not only aircraft C itself was modelled (partially) in 3D, some of its jigs and tools were designed with 3D CAD as well. Under the realm of the Manufacturing organization the approach was similar to that of Engineering: it was done only where deemed critical. For instance, the 3D models of the wing's new transportation jig were requested from the supplier. Stowing the wing mounted on the jig into the fuselage of special transportation aircraft "Beluga" could then be verified with the DMU. Due to the new wing's increased size safety clearances to the outer fuselage skin fell short. The result of the DMU study was that several components of the already equipped wing had to be demounted before fitting the wing into the Beluga.

As part of the Wing Integration Design-Build Team (DBT) of program C a dedicated DMU team was formed. Initially, it was the intention only to look for collisions over the motional envelope of wing movables. That belief was founded in the inherent assumption that designers would draft the design collision (or "clash") free in its static (= non-deployed) mode. It was actually not always the case; therefore the focus was shifted to checking non-deployed conditions first.

The three main causes for problems encountered during that first DMU campaign were the following:

1. the *3D model* (or assembly) was *not available*; therefore any interference detections with surrounding ("environment"-) geometry e.g. of interface partners could not be performed. Hence, problems could not be detected, or at least too late, when data eventually arrived.

2. the *3D model* (or assembly) was *not correctly positioned*; sometimes that error was corrected too late as production was already running. The model had then either to be redesigned and/or the part had to be reworked, with subsequent adjustment of production itself.

3. the *3D model* (or assembly) was *too old*; design was done "in-context", but that context was dated. Interface models had changed in the meantime. Because the latest status was not distributed (e.g. due to difficulties in data exchange) the design could be perfectly collision free and fully obeying all rules, and therefore be released for manufacturing. Nevertheless problems were then encountered in the assembly line.

Despite of these problems the DMU revealed considerably fewer issues as in former EMUs. Most were minor problems that could be repaired on site and within the available time frame during wing equipping.

The only major setback for the campaign was the decision not to continue with the DMU after the first few machines. By keeping track in 3D of all following modifications on subsequent aircraft could thus have emerged a Configured DMU. The Wing Integration DMU therefore ended after almost two years, after having completed its initial mission to secure wing integration of the first pairs of real wings. Only the most important changes for those aircraft taking part in the flight test campaign were actually held evident in the DMU. This was mainly due to budgetary reasons and design resources (internal and external ones) being shifted to other projects.
Nevertheless, this campaign showed the potential and the benefits of a DMU: in addition to static and kinematics collision checks studies were performed to verify maintainability, ensure installation procedures and use the DMU for particular risk studies (e.g. propeller detachments from the ram air turbine or engine rotor burst analysis). The DMU team also responded to particular requests from the development community, for instance verifying the positions and angles of view of new taxiing-aiding cameras. The team also pioneered the 3D wings from tip-to-tip: initially it was assumed that a port wing alone would be sufficient. The starboard side was largely seen a mere handed assembly. But as systems installations can vary considerably on the right hand side (e.g. hydraulic connections on different sides, tubes and cables having to take different paths, systems and equipments installed only on one wing…) a starboard wing was elaborated to check and verify installations there as well.

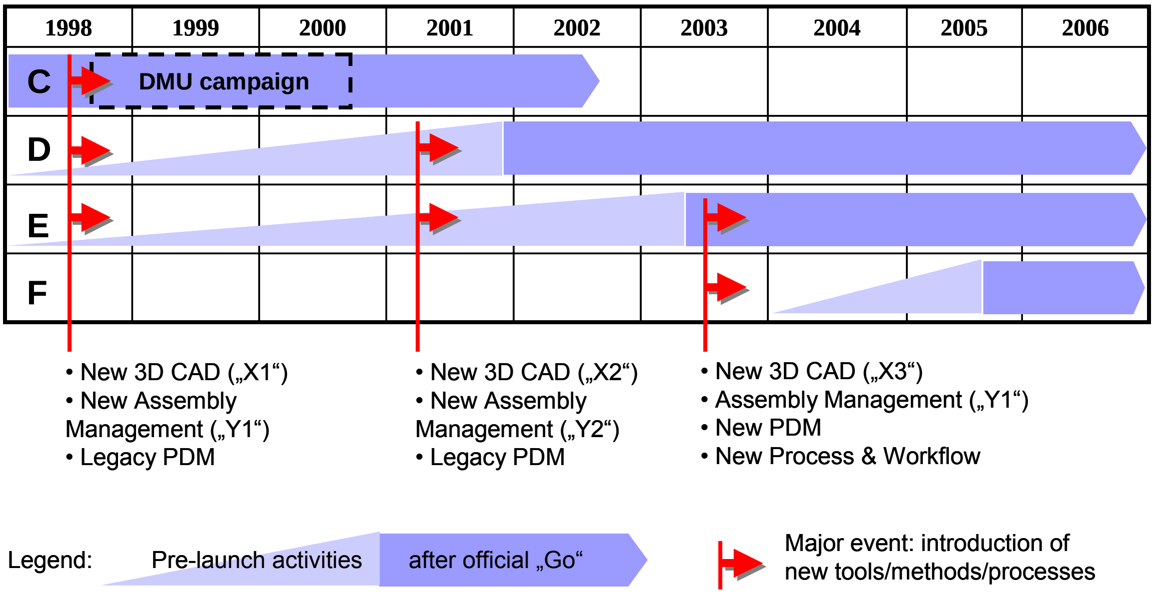

Fig. 6.4 The four DMU campaigns in comparison, all were subject to major changes in the tool environment (with accompanying adaptations of methods and processes)

Both the positive DMU experiences as well as the drawbacks in other areas that didn't make use of it were crucial in the decision to go for a full digital 3D aircraft[39] in *program D*. It rose to high gear about a year after C. Many experiences with software tools, methods and processes were then applied to D. They were extended, adjusted and fine-tuned. The greatest efforts were bundled on the three main problem areas, which were still the same in the new program. In spite of a change in the development tool set (new 3D CAD software and new assembly management tool for handling large product structures) plus the very heterogeneous tool and process environment throughout the program, impacts on wing movables and wing integration were relatively moderate. This was because extensive effort was laid in the first years to ensure a complete, up-to-date and consistent Digital Mock-up. Only after these issues sufficiently under control could the focus be shifted to fully exploiting the DMU with interference detections and related studies.

Program E was the next in the row to profit from combined experiences of C and D. It was already going on for several years on a low intensity basis. At the time of its launch, program D was in its high gear. It therefore suffered from a high percentage of personnel still bound to the other project. Then it also had to cope with another complete tool environment change (new common 3D CAD and PDM software for all partners). This was accompanied by the elaboration of new common methods and processes, offering the unique chance to take into account a lot of lessons learned from C and D.

The latest *program F* is currently the biggest beneficiary of everything done so far on the field of DMU. Using the same tools and processes environment as E, it adjusts, extends, fine-tunes and simplifies them accordingly. The aim is also for higher capability and robustness to allow its full exploitation and for even closer and earlier integration of the supply chain.

[39] For the first time also all production means (jigs, tools, factories, transportation equipment…) were fully modelled in 3D.

Even more, the DMU is standard procedure now; DMU awareness has increased through all ranks and disciplines. DMU knowledge is spread more widely than ever with more people trained and experienced through preceding programmes and extensive documentation available. Though far too early for an assessment, but given the circumstances program F does have the best prospects of getting the most out of the potential of CDMU.

A few conclusions can already be given at this point: from a strategic-operational point of view the close succession of four large aircraft development programs – all launched within roughly eight years with considerable overlap of their activities – was in favour of the development of sophisticated tools, methods and processes in support of Configured DMU operations. This was accompanied by refined organizational measures. It saw the introduction of new jobs (e.g. DMU Integrators) with new functions and roles on a vast field of new DMU applications. In those years the DMU rose from a mere substitute of Engineering Mock-ups right to the centre of design efforts. Handling the shear complexity of multiple configurations (the fuselage and cabin in particular are subject to high customization, much more than the wings, which are practically the same for all customers) is no longer possible with former methods and techniques in an increasingly tight time, budget and personnel frame.

The DMU information flow for wing integration in contrast to the one exemplified for EMU operations shall round up this sub-chapter. The clearest differences are the DMU as direct input to and cross-reference for manufacturing and its availability everywhere in the company. This greatly increases the consistency of information and enables faster and easier feedback on many assembly/integration related issues.

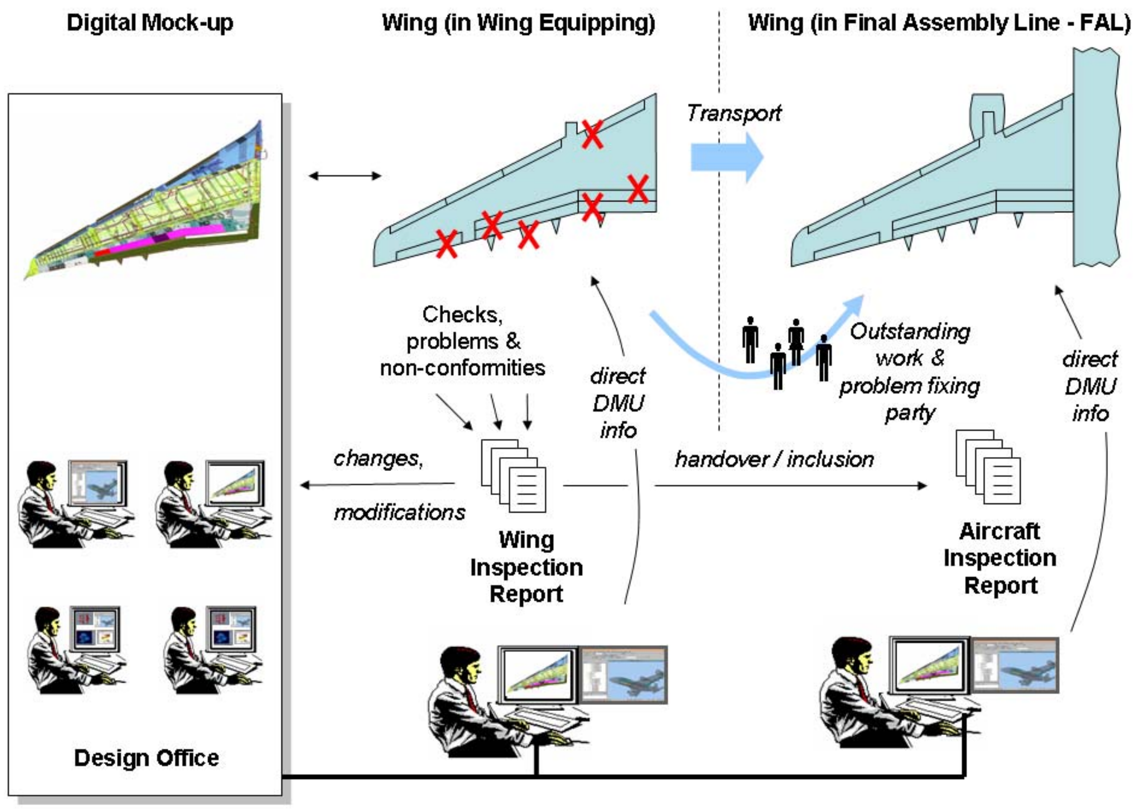

Fig 6.5 Digital Mock-up – information flow within the wing equipping and Aircraft final assembly process.

6.3 Application of the Complexity Indicator Method

6.3.1 Overview of the six Wing Integration Programs

A few figures and tables shall introduce the area of investigation.
Figure 6.5 shows the so-called fixed- and movable leading- and trailing edges of the wing. That is where most wing integration work takes place with installation of system routings and all other static and deployable components.

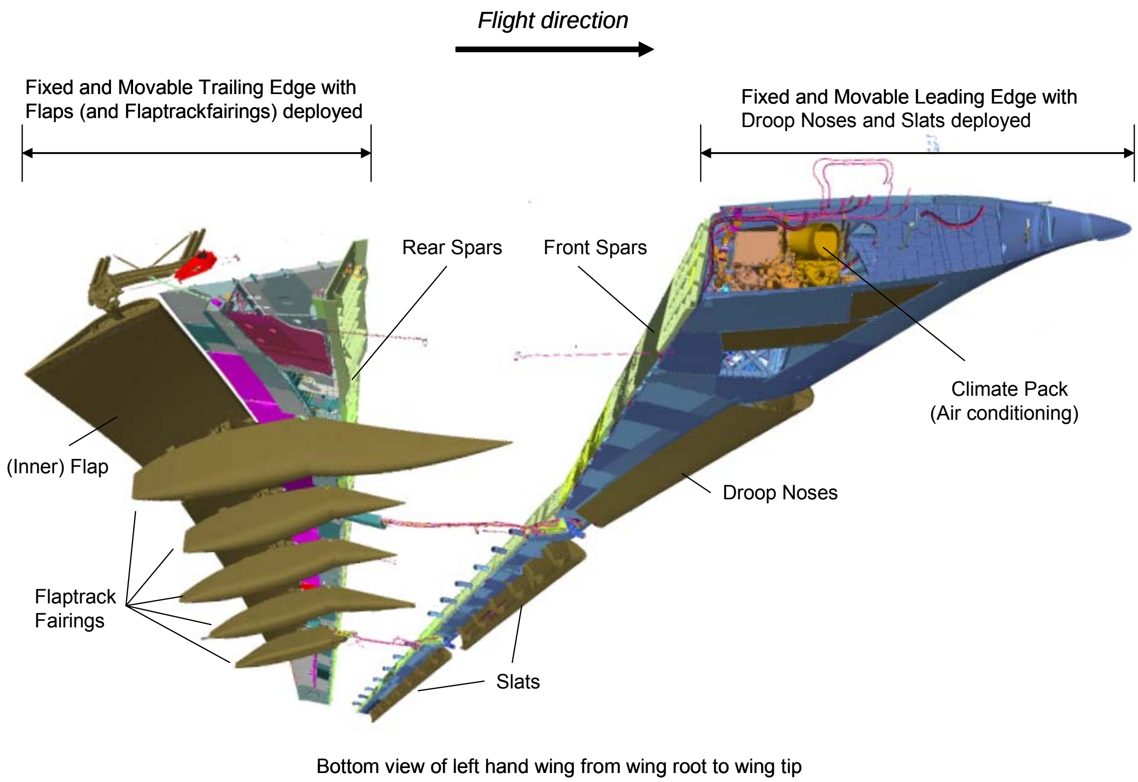

Fig. 6.6 Wing leading and trailing edge; not shown here is the wing-box itself, which occupies the space volume between front and rear spars.

Table 6.1 below lists key characteristics of the six programs for closer comparison. It presents technical figures and extensions of the design focus from one programme to the next.
A few remarks to *program F*: the whole programme had been *rolled back* (from concept phase to feasibility phase) to present customers with a completely new design. The figures in this study however represent the status *before* that happened. This was done to have available comparable data in sufficient detail, to be used for analysis with the same complexity indicators as the other five programs. The number of aircraft programs that could be taken for investigation was very low anyway so that investigating another program – even though being in a different phase and in spite of its rollback – presented an opportunity not to be missed.

Table 6.3   Technical data and mock-up related design activities and focuses

Program	**A**	**B (B1 + B2)**	**C**	**D**	**E**	**F**
Wing Area [m²]	219	362	437	846	222	363
Specialty of program	2 Engines Mechanical flight control	B1: 4 Engines B2: 2 Engines same wing; Fly-by-wire	Extended version of B1	Configuration similar to B1/C; Largest wings so far	Military transport A/C; No leading edge high-lift devices	Derivative of B2; Latest technolog. achievements of C, D, E taken
Wing Design	New	New	Derivative	New	New	Derivative
Wing movables (per half wing)	*LE:* 3 Slats 1 Krüger Flap ----- *TE:* 2 Flaps 7 Spoilers 1 Aileron	*LE:* 7 Slats ----- *TE:* 2 Flaps 6 Spoilers 2 Ailerons	*LE:* 7 Slats ----- *TE:* 2 Flaps 6 Spoilers 2 Ailerons	*LE:* 2 Droop Noses 6 Slats ----- *TE:* 3 Flaps 8 Spoilers 3 Ailerons	*LE:* None ----- *TE:* 2 Flaps 5 Spoilers 1 Aileron	*LE:* 1 Droop Nose 6 Slats ----- *TE:* 2 Flaps 6 Spoilers 2 Ailerons
Type of mock-up	EMU	EMU	DMU	DMU	DMU	DMU
Design Tool	Conventional 2D +2D CAD	2D CAD	2D CAD +3D CAD	3D CAD	3D CAD	3D CAD
(MU) Space allocation studies	No	No	Partly	Yes	Yes	Yes
FIT-FORM checks*	Yes	Yes	Yes	Yes	Yes	Yes
FUNCTION checks*	Partly	Partly	Yes	Yes	Yes	Yes
MU check part of release process	No	No	Yes, but decoupled from release for production	Yes, but decoupled from release for production*	Yes, integrated in release for production	Yes, integrated in release for production
Maintenance considerations assessed	No	At the end of EMU	Yes, first checks in DMU	Yes, fully integrated in design	Yes, fully integrated in design	Yes, fully integrated in design
Configuration Managem. reflected in MU**	First A/C	First A/C	For first few A/C	Yes, from development phase on	Yes, from concept phase on	Yes, from concept phase on
Kept up-to-date after EIS	No	No	Partly for first few A/C	Yes, fully	Yes, fully***	Yes, fully***

**: Mandatory release for production DMU checks introduced late in the development program; First A/C were already built or in assembly-integration process.*
***: the whole suite for developmental and series A/C; EMUs were actually build based on a distinct configuration to enable smooth integration of first flight wings.*
****: planned for this program*
Remark: Slats are all single slotted and vented devices; Flaps for A are one single slotted Fowler and one a double slotted with a vane; Flaps for B, C, D and F are single slotted Fowlers; For E they are Flaps with a fixed vane and a drooped hinge actuation;

Last but not least will table 6.3 provide an overview on how organizational issues evolved in the wake of the six campaigns.

Table 6.4   Organizational evolutions for the development program

Program	**A**	**B**	**C**	**D**	**E**	**F**
Overall type of design activities	Rather Sequential	Rather Sequential	Parallel	Parallel	Parallel	Parallel
“Concurrent Engineering”	No	No	Yes	Yes	Yes	Yes
Type of organization to do design	Functional	Functional	Integrated (Design Build Team - DBT)	Integrated Team	Integrated Team	Functional*
Organization for mock-up activities	Functional	Functional	Separate DMU team integrated in DBT	Part of Integrated Team, DMU key users	Part of Integrated Team	Separate DMU team*
Roles & Responsi-bilities (R&R) in workflow	Functional role	Functional role	First DMU R&R elaborated	Refinement of initial R&R	New overall Role Concept	Role Concept (from E)
Mock-up activities placed in	Manu-facturing	Manu-facturing	Engineering	Engineering	Engineering	Engineering
MU objectives and rules for supply chain	Clear	Clear	Partly clear, not part of standard contract	Partly clear; Insufficient coverage in contracts	Clear through intensive communic.	Clear, through communic. and contracts**

NOTE: No classification can be interpreted; Engineering Mock-ups proved vital for the success of A and B programs. Team structure and organization reflect historical developments.
These naturally evolve in the wake of new insights how to best do design and development or due to financial and organization-political considerations.
** That has changed for the new re-designed aircraft. But initially there was no co-located team for wing integration activities.*
*** Generic and specific DMU requirements are being set up for inclusion in standard contracts (e.g. CAD/PDM environment, integration level, quality requirements, procedural treatment of quality non conformities…)*

These figures and tables only tell a part of the circumstances for mock-up campaigns and are by no means exhaustive. Such an endeavour is beyond the scope of this study. It shall make the reader aware of the similarities and differences among those programs. They present the overall context under which they preceded and which is background and reference for the following methodological exercise.

6.3.2 The complexity indicator method “Large Transport Aircraft”

Step 1 – Problem Description

The six Wing Integration Mock-up campaigns are regarded as complex, because work had/has to fit into the wing as a whole, dealing with many technical and organisational interfaces, numerous partners and suppliers on different sites, located mainly across Europe. The DMU campaigns may be regarded as more complex than EMUs due to the relatively new matter of Digital Mock-up itself and the software tool environments with all its different statii of integration, of its maturity and the heterogeneous software architectures. Engineering Mock-up campaigns were, regarded in hindsight, on the threshold from complicated to complex.
On the other hand the mock-up campaigns were in general quite restricted to scheduled paths within aircraft programs, with most objectives clear, a given budget, personnel and time frame, without too many ambiguities. Changes over time (= dynamics; e.g. the “rules of mock-up operation”) were manageable. Therefore the “action-repertoire” was rather conventional and quite limited as far as project circumstances are concerned. Real “surprises” in terms of “no-go” items and program-threatening difficulties were not encountered (especially that was one reason why hardware mock-ups were built and DMUs were created, respectively). Nevertheless, attributing the campaigns as complex seems to be justified. Much more complex (“highly complex”) would be the development of an entire new aircraft, of course.

Step 2a – Selecting global influence areas

The following influence areas were considered: they actually come from the internal side of the aircraft project. External (or outside the project) influences play(ed) an inferior role. This is a crucial statement, as campaigns were/are executed entirely in context of the aircraft project. The major influence areas are therefore identified as:

- *product* (here: the wings leading and trailing edges)
- *process*
- *organization*
- *partnership and supply chain*
- *information, - planning and control systems*
- *people*
- *generic issues* (e.g. soft factors…)

Basic assumptions and what is out of scope

Mentioning basic assumptions would cover a broad range of topics. Therefore only a selection can be presented: All projects are assumed to have experienced execution frictions, but not above normal levels. Any tools and means (e.g. communication equipment) for successful execution were available and could be readily used. Motivation of the staff and dedication to the project's success was taken for granted as well. Factors that are usually out of control of the people involved, such as natural conditions (weather…) or political and economic developments for example did not have any traceable effect on the campaigns. Aerospace standards, norms and certifications (material, equipment, junction parts…) were out of question. All suppliers were qualified and have fulfilled the prime's (at least minimum) requirements (otherwise they would not have been chosen).
No classified materials and technologies were used, the secrecy level was not above the usual "company confidential" and there were no access restrictions to facilities.
The budget for the campaign was available (meaning was not reduced throughout or subject to serious fluctuations), and scheduling was done using established planning assumptions and techniques. The people involved were sufficiently experienced and trained to take part, and neither did basic requirements for the mock-up itself change throughout the campaign (no mock-up "requirements creep") nor were there technology changes in-between, that would had to be coped with. Not considered for this study were drawing release and single tool/method/process shortfalls.
All in all a quite 'normal' and rather smooth and unspectacular campaign environment. But other projects under different circumstances might need to take above factors into account for their assessment (see Appendix D for a list of further factors that could be useful as indicators).

Step 2b – Framing the choice from a timely perspective

All but the last campaign were assessed in the same phases:

- Programs A, B, C, D, E were assessed in the *transition and laminar* phases
- Program F was assessed while being in the *turbulent* phase

There are two reasons for the last point: First, F was launched while writing the study. Second, assessing another program was found appealing, as there are not too many of them in general, and revealing complexity levels in the early phases of a program drew the author's curiosity.

Figure 6.6 shows the time frames taken into account for the assessment plus where they are (as of 2007) from a progress point of view:

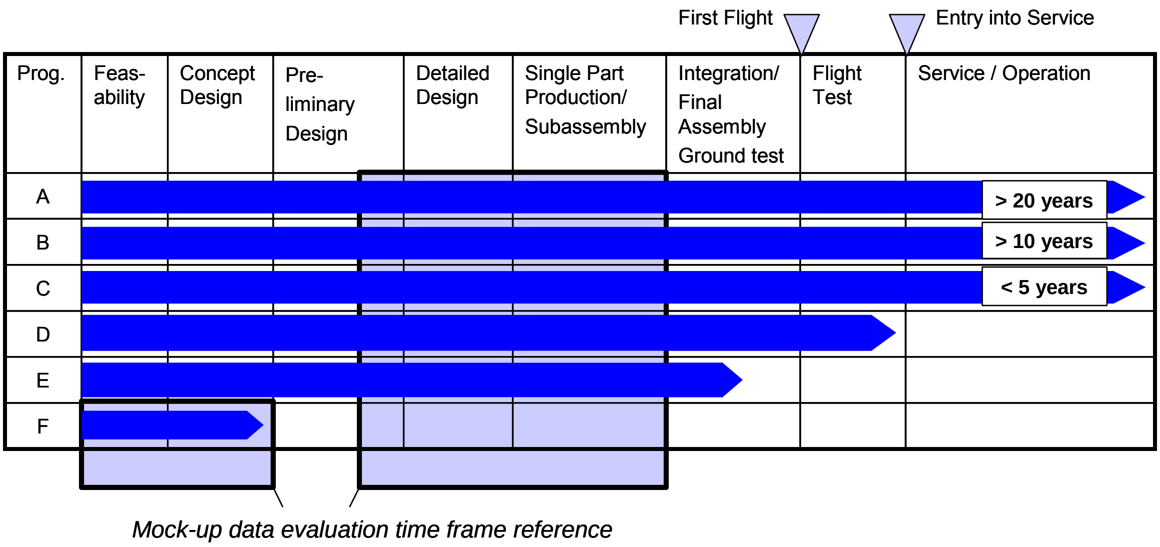

Fig. 6.7 Evaluation time frame for the six campaigns

Step 2c – Identifying specific complexity driver areas

The relevant specific driver areas were identified as the following:

- Product: *geometry, kinematics, technology, configuration, communality*
- Process: *objectives, tasks, procedures & guidelines, data and information availability*
- Organisation: *teaming issues, location of work*
- Partnership and supply chain: *partners and suppliers*
- Information systems, planning and control systems: *tool environment and maturity*
- People: *know-how, experience*
- Generic issues: *standards, quality, disturbances*

Step 3 – CXI definition and Meta and Object level analysis

This paragraph is dedicated primarily to a discussion of the eighteen complexity indicators that had been elaborated and to their respective object and meta levels. At the end some remarks will be given on those CXIs that had been considered but not chosen. They, together with other candidates for similar assessments, actually make up the pool of “CXIs not taken”.

Complexity in product development is primarily due to advanced product features and characteristics. That’s why the list starts in this area. The very calculations and their input data are laid open in Appendix E.

1. *Type of parts in mock-up (object level):* These are the different technological types of parts that are actually produced for the EMU or designed to be in the DMU. The classification scheme goes from simple to very complex. It is important to note that not each and every part had been counted. Nuts, bolts, rivets, shimming plates and other small items (e.g. brackets) were not considered as they would have spoiled the assessment over the six campaigns: E.g. components of differential build-up construction are likely to have more junction parts than integral build-up ones. Therefore, part count alone has not been judged to be a sufficient criterion for complexity assessment. For that reason, 'type of parts' as well as other CXIs are based on a "reference part count", and as such form part of the object level.

2. *Integration density (object level):* The more components are to be installed in a certain space volume, the more challenging and complex the integration task becomes. Therefore this indicator approximates the real integration density situation in the mock-up with the reference part count and a simplified wing volume calculation, based on wing size data, fuel volume and estimations on wing leading- and trailing edge ratios of the whole wing volume. Being 'mathematically' calculable, this indicator is an object level CXI.

3. *Design-in-Context (object level):* It denotes the degree to which one has all data and information available to do the design. The 'context' here means all relevant interface 3D geometry and metadata from partner (-sites) and suppliers. The design situation being visually assessable (e.g. on screen, or interrogating the EDM/PDM system), this factor qualifies for the object level.

4. *Drawing tool (object level):* This indicator considers the question of how to actually create the design or the drawing – e.g. without or with 3D CAD - accounting for more or less complexity. It takes into account human perception and correct or flawed realization of the overall geometrical situation. The plain and discrete assessment of which drawing tool was/is used makes it an object level indicator.

5. *Mock-up class (meta level):* The three classes of mock-ups as defined in specification MIL-M-8650C are the basis for this CXI. They tell the level of detail as well as scope required for representation of the geometrical situation in the mock-up. As these classifications have the character of requirements and overall concepts (defining what has to be done), make this a meta level indicator.

6. *Mock-up policy (meta level*): The mock-up policy describes the generic and operational rules to be followed for the mock-up campaign including quality assurance rules and roles and responsibilities, internally as well as across the supply chain. In fact, it details the overall strategy to be pursued. As it is has law or contract-like character, and as it is defining the "playing rules" qualifies it as a primary meta level indicator.

7. *Kinematics complexity (object level*): Having movable components on defined motion paths accounts for considerable design complexity. This indicator assesses how sophisticated the kinematics is. The range of this goes from "zero-kinematics" (= static components) to sophisticatedly coupled 3D rotations- and translations. Basis for the assessment are the kinematics behaviours of the components from the "reference part count" list.

8. *Mock-up tasks to be fulfilled (object level):* This covers the range of tasks and checks that have to be done in the wake of the mock-up campaign. It describes the “what” of mock-up activities to be done. This can be rough space allocation studies, detailed assembly-integration checks, maintainability validations or particular risk analysis. Each task can be separately identified and therefore be accounted as single items.

9. *Software toolset change (meta level):* Substantial changes of the CAD/PDM environment are primary contributors to complexity. This indicator accounts for such change events. Meant herein is, for instance, the introduction of new software tools and architectures with associated methods and procedures, but not software updates or “hot-fixes”. The question is not whether a better tool set is superseding a dated or insufficient one. The point here is that such changes usually affect a vaster number of developers often implying adaptations of company and personal rules and behaviour. This is accompanied by friction and uncertainty – at least for some time – until the new way of working has settled, technically as well as mentally. As such a change is a unique alteration of the “playing rules” makes it a meta level CXI.

10. *Tool environment and maturity (meta level):* This indicator addresses the actual tool set situation across the extended enterprise that prevailed for (most) of the time of the investigational time frame. The two major distinctions are the questions of a homogenous versus a heterogeneous tool environment situation and their maturities. This situation determines operational playing rules with respective efficiency gains or performance shortfalls. That characterization makes it a meta level indicator.

11. *CAD-PDM integration (meta level):* Another point of view on the software tool question, however more technical: this factors details how much (or how less) the CAD and PDM systems had been or are coupled. This level of integration clearly defines the degree of overview that is possible in a design situation. No integration will always need the designer him/herself to associate crucial information; full integration relieves people of some of these tasks allowing more intuitive exploration of the best design solution while relevant data are readily retrievable from either system. Even though “integration” may be identified as a distinguishable “item”, its character as inherent “rule-definer” for everyday working justifies it being regarded as meta level indicator.

12. *Team organization (meta level):* This factor accounts for the ratio of co-located vs. distributed working people as well as how they do it primarily: mainly in functional teams or as part of multidisciplinary design teams. It addresses behaviour in a broad sense and considers soft-factors in the working together of people (communication, information-flow…). That’s why it acts on the meta level. As noted above, having relevant data and information is crucial for coping with complexity, the team organization addressing that best will be assigned the least complex one (even though it may be hard work to establish such kind of working in practice).

13. *A priori in-house mock-up experience (meta level):* A crucial factor for success - and for coping with complexity – are the people with good knowledge and experience in their fields. This CXI considers how experienced people were (in terms of having been part of previous campaigns, having done similar projects…) when the campaign started. Very well trained and experienced people are likely to make a big difference compared to those working with a mock-up for the first time. The indicator addresses the soft-factors knowledge and experience, thus qualifies for the meta level.

14. *Number of components ratio (object level):* This is the number of components (parts, assemblies) in the wing compared to those being created for the mock-up as a whole. Also based on the "reference part count" it denotes the complexity of the campaign effort in terms of part/assembly creation: the more the mock-up resembles the real wing the higher the complexity, because more parts and their interactions have to be handled. While N°1 – "Type of parts in mock-up" focuses on the technological complexity of parts this indicators sheds light on the numerical extent to which the mock-up was actually done.

15. *Moving components ratio (object level):* Based on the components created for the mock-ups this factor sheds light on the difficulty to integrate fixed and movable components. The more movable components there are with respect to the overall (reference) part count the higher the complexity. Here, not the different types of defined motion paths are of interest, but the overall level of movable components that have to be integrated.

16. *Configuration similarity (object level):* This indicator describes whether or not teams had experience with wings with similar structure and systems arrangements before the respective campaign. If yes, that would imply a certain familiarity with the integration task, which in turn would contribute in reducing complexity. As the similarity is an obviously visible fact and can easily be distinguished it belongs to the object level category.

17. *Part communality (object level):* It indicates the degree to which single parts or even whole assemblies may be reused from a previous program. If that's the fact then it can considerably reduce the complexity of the design task. As with the previous CXI, this one is equally distinguishable and is therefore an object level indicator.

18. *Number of partners and subcontractors (object level):* This is the number of official partners and tier 1 and 2 subcontractors directly involved in the mock-up campaign. On one hand partnership is deliberately sought in order to spread the risk and the (financial) development burden. On the other hand, the management effort for synchronizing and controlling all partners and the supply chain and hence the need for agreeing on interfaces will considerably increase in order not to loose the overview. The notion here is that the complexity level is increased the more partners and subcontractors are involved, because there are more elements and relations in the play. Partners and subcontractors can be counted and so the CXI is therefore part of the object level.

The figure below actually serves as the bridge between step 2c and step 3: it exemplifies which complexity driver areas serve as input – single or in combination – to the respective 18 complexity indicators.

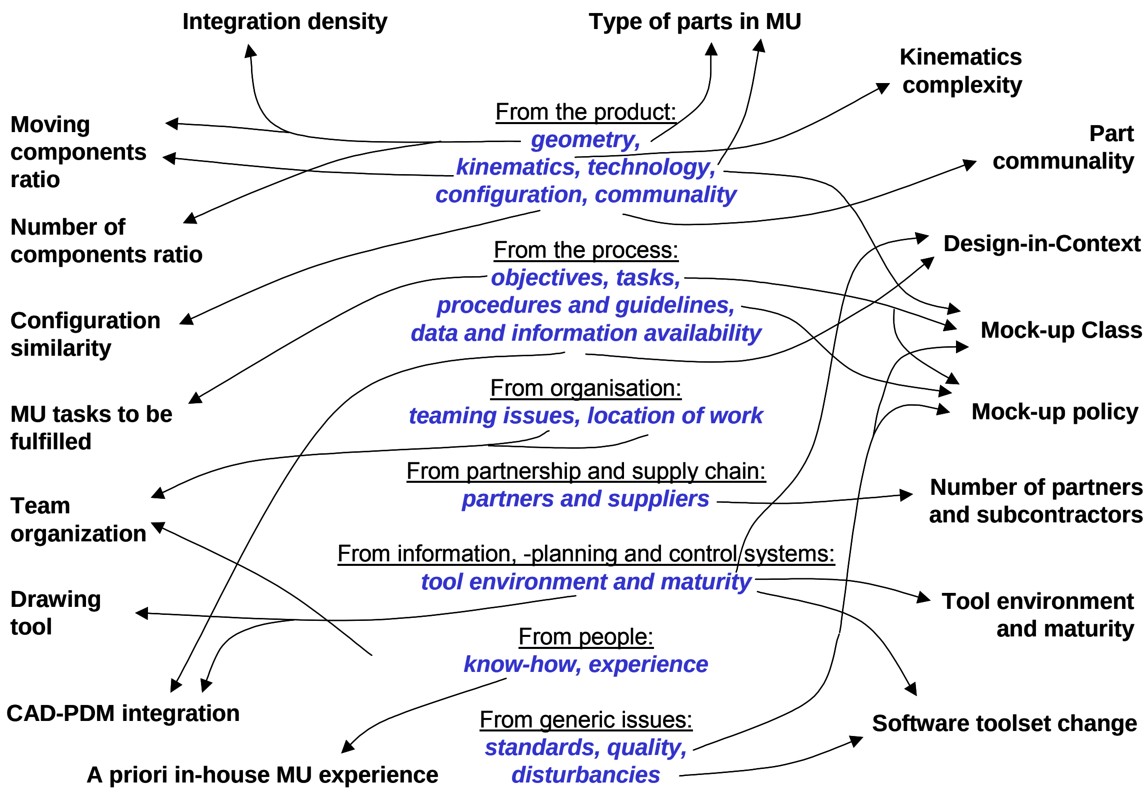

Fig. 6.8 Specific complexity fields and which serve as input to which indicators

On the way to deriving these CXIs several others were considered but eliminated step by step from the list. *"Culture"* and *"Language"* for instance: though primary candidates in a multinational project environment the author couldn't find any evidence that these were factors actually increasing ambiguity or indeterminism. Some cultural differences were present, of course, but none decisively influencing the run of the campaign. With English as lingua franca for German- and non-German speaking parties, actual contribution to complexity could be ruled out. *"Decision responsibility"*, that is if (most) decisions had to be passed via several hierarchical layers, could have been a factor as well. But the campaign responsible organization had been fully empowered to take those decisions necessary for accomplishment of objectives. This was done in close consultation with the lead team and overall program management, of course.

Similar considerations guided the question on *"Design flow smoothness"*. This indicates via how many "breaks" the design task goes, e.g. one partner doing conceptual design, a second preliminary and detailed design and a third one assembly-integration design. This would entail two substantial breaks, which are potential sources of uncertainty, ambiguity and for incompleteness of information and data. Even though such cases had been identified, they were the exception rather than the rule. It was induced through complicated work sharing, but was compensated by the team through intensive communication and "hand-over" agreements.

Therefore this had been neither a "road-blocker" nor a "show-stopper" and was not considered worth an assessment.

In addition to the four mentioned several other factors make up the pool of *"CXIs not taken"* and can be found in *Appendix D*. They may stimulate thought for future assessments.

Step 4 – Defining Complexity Indicator Subdivisions

The discrete subdivisions of the above-mentioned 18 CXIs and their contribution to complexity are presented in the following paragraphs:

1) Type of parts in mock-up	Values
• Simple	0.25
• Medium	0.5
• Complex	0.75
• Very complex	1

2) Integration density	Value
• Range between 0 and 1	calculated

3) Design-in-Context	Values
• Fully – near real time awareness of geometrical situation including all changes (in reality, daily awareness is usually sufficient)	0
• Partial I – regular updates (e.g. weekly)	0.33
• Partial II – irregular updates (e.g. on demand)	0.66
• No – no regular update, only interface points known, but not the entire relevant geometrical environment	1

4) Drawing tool	Values
• No CAD	1
• 2D CAD	0.5
• 3D CAD	0

5) Mock-up class	Values
• Class I	0
• Class II	0.5
• Class III	1

6) Mock-up policy	Values
• No coherent policy, ad hoc measures	1
• Policy in elaboration, effect based activities	0.5
• Policy defined and implemented	0

7) Kinematics complexity	Values
• No movement (static)	0
• 2D rotation or 2D translation	0.25
• 2D rotation and 2D translation	0.5
• 3D rotation or 3D translation	0.75
• 3D rotation and 3D translation	1

8) Mock-up tasks to be fulfilled	Values
• Rough fit & form and space allocation studies	0
• + detailed fit & form and space allocation studies	0.25
• + function and installation/assembly studies	0.5
• + maintainability studies	0.75
• + special verification tasks (particular risk analysis, human task modelling…)	1

9) Software toolset change	Values
• Yes	1
• No	0

10) Tool environment and maturity	Values
• Homogenous and established	0
• Homogenous and newly introduced	0.33
• Heterogeneous and established	0.66
• Heterogeneous and newly introduced	1

11) CAD-PDM integration	Values
• Full CAD-PDM integration (bi-directional associativity)	0.33
• Partial CAD-PDM integration (uni-directional associativity)	0.66
• No CAD-PDM integration	1

12) Team organization	Values
• Full co-location (of own personnel and of partners and suppliers), multidisciplinary way of working	0.33
• Partial co-location (e.g. temporary co-located availability of key personnel), at least temporary multidisciplinary work	0.66
• No co-location (of majority of own, of partner and supplier personnel), mainly functional way of working	1

13) A priori in-house mock-up experience	Values
• Experience from previous (similar) programmes	0.33
• Experience from different application available	0.66
• No experience available	1

14) Number of components ratio	Value
• Range between 0 and 1	calculated

15) Moving components ratio	Value
• Range between 0 and 1	calculated

16) Configuration similarity	Values
• Very high similarity (≈ 90%)	0
• High similarity (≈ 75%)	0.25
• Medium similarity (≈ 50%)	0.5
• Low similarity (< 25%)	0.75
• No similarity (0%)	1

17) Part communality	Values
• Very high communality (≈ 90%)	0
• High communality (≈ 75%)	0.25
• Medium communality (≈ 50%)	0.5
• Low communality (< 25%)	0.75
• No communality (0%)	1

18) Number of partners and subcontractors	Values
• > 10 partners/subcontractors	1
• > 5 partners/subcontractors	0.5
• < 5 partners/subcontractors	0.25

Sensitivity analysis for some CXIs

As mentioned in the method outline in chapter 5, it can be necessary to take a closer look on some calculated results. This is to correctly judge the individual campaigns' contribution to complexity. In this case, four CXIs are assessed: N°1 – 'Type of parts in mock-up', N°2 – 'Integration density', N°7 – 'Kinematics complexity' and N°15 – 'Moving components ratio'.

For the *calculations* please refer to *Appendix E*. The absolute values are plotted as bars for each of the six campaigns, and mapped with a "mesh" of configuration classes resulting in complexity values from 0 to 1. Priority was given to having adequate values for individual campaigns with respect to each other: e.g. if one bar is double in length to another then the complexity value also shall be double.

N°1 – Type of parts in mock-up

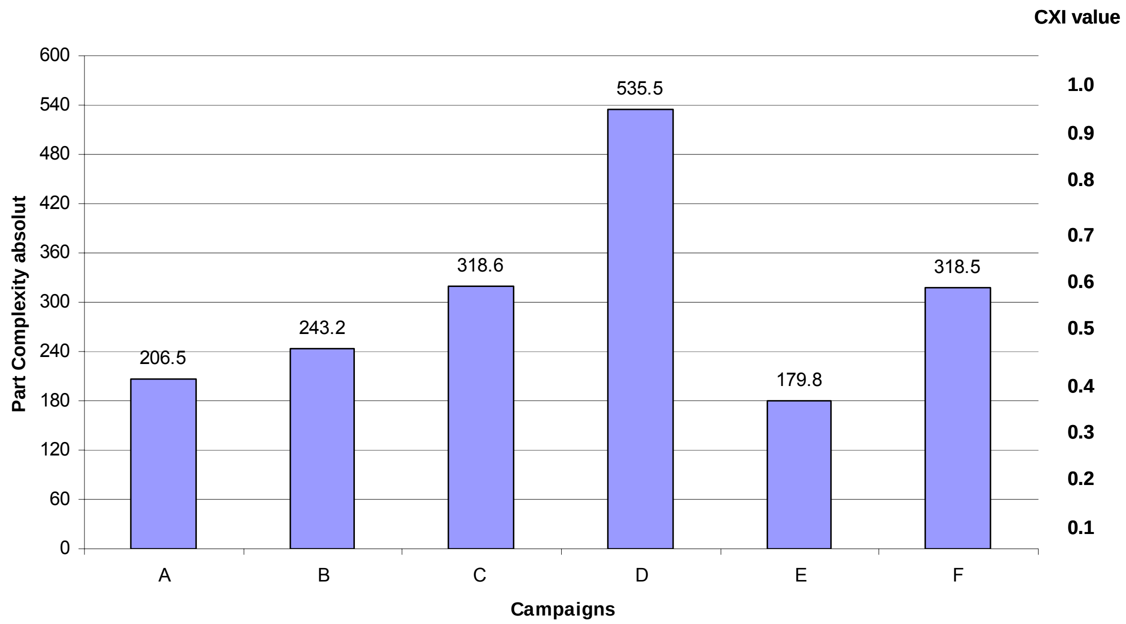

Fig. 6.9 CXI "Type of parts in mock-up" in absolute values

Here, program D has approximately three times overall part type complexity than program E. This is especially due to a higher reference part count of a much larger wing: more parts mean more elements and relations in the play resulting in a higher complexity value (0.9 for D vs. 0.3 for E). The very similar wing configurations of C and F accurately yield comparable values and have therefore the same CXI value of 0.6.

Going from EMU campaign A to EMU campaign B brought not only a higher part count with it but was also accompanied by a higher mock-up class. This in turn resulted in more sophisticated components in the mock-up. In that respect had campaign of program C been the natural evolution: same wing configuration as B, but done with 3D CAD, all relevant components available as 3D digital replica of real manufactured parts and representing the highest mock-up class category. Three points can explain the „jump" from C to D: first, a higher overall (reference) part count due to the shear size of D–wings. Second, more movable devices, and third, some unique innovations like Droop Noses on the leading edges that separate it from previous wing configurations.

N°2 – Integration density

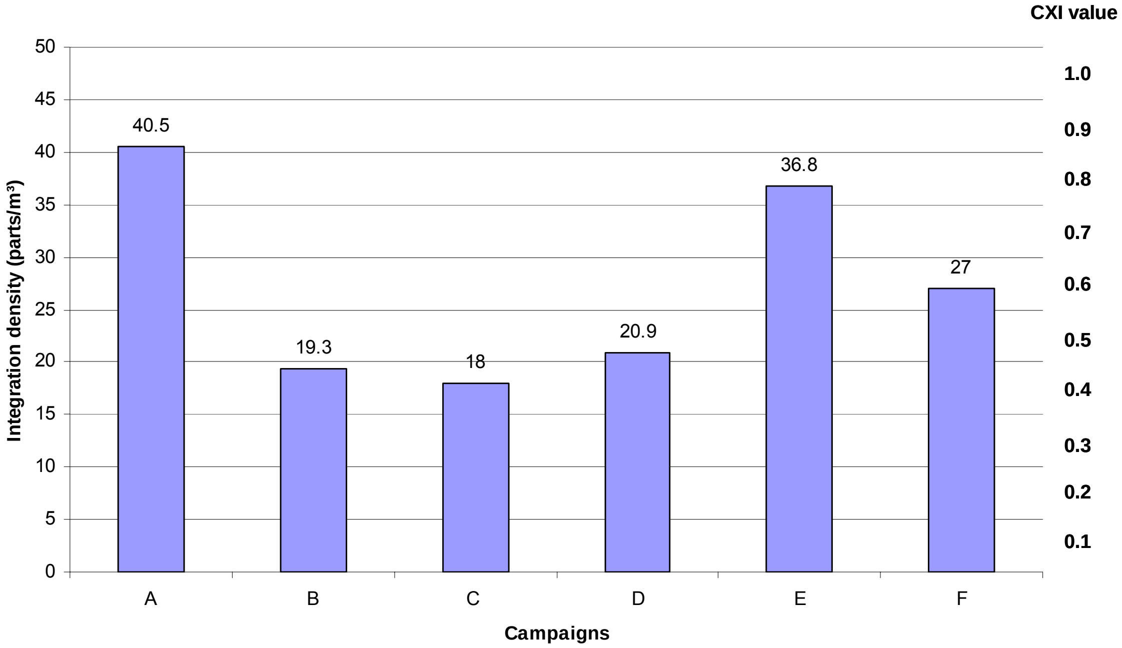

Fig. 6.10   CXI "Integration density" in absolute values

This figure reveals the highest integration density for EMU campaign A and DMU campaign E. A had many mechanical components in a comparably small wing. B had not only larger wings but benefited from the introduction of fly-by-wire technology, resulting in considerably fewer mechanical components needed to transfer control signals to end-users (e.g. actuators).

E wings were not only quite small, they also saw the introduction of some new technology with far reaching consequences: the wing box with its front and rear spars is made of CFRP. Leading edge and even more trailing edge space is relatively restricted, some military requirements have to be respected and segregation rules for system routings (electrics, hydraulics, flight control…) resulted in considerably higher density values than was the situation for civil aircraft wings.

For B, C and D integration space is not as big an issue as for A. The higher value for F is due to implications of new aircraft requirements demanding more systems (e.g. inert gas) to be integrated and additional routings such as for electrics.

N°7 – Kinematics complexity

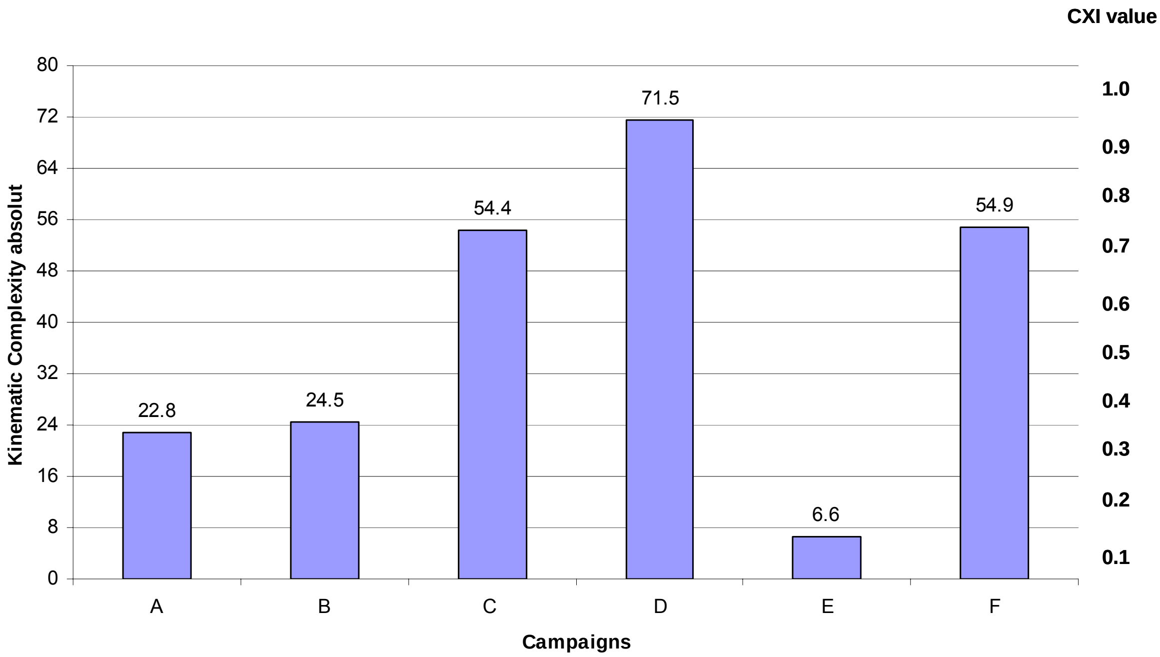

Fig. 6.11   CXI "Kinematics complexity" in absolute values

Here, D shows the highest values both in respect to moving components as well as with respect to the sophistication of motion paths they follow. The very low value of E is the result of comparably less sophisticated kinematics of its components, few movable components on the wing's trailing edge and especially a missing movable leading edge. In part this is due to the military requirement for "ruggedness" and simplicity when thinking of having to do maintenance in austere locations.

EMU campaigns A and B also show considerably lower values compared to the kinematics in DMU campaigns C and F which are of similar wing movables configuration. The reason is that not everything that can move had actually been verified in the EMU, therefore resulting in less complexity.

N°15 – Moving components ratio

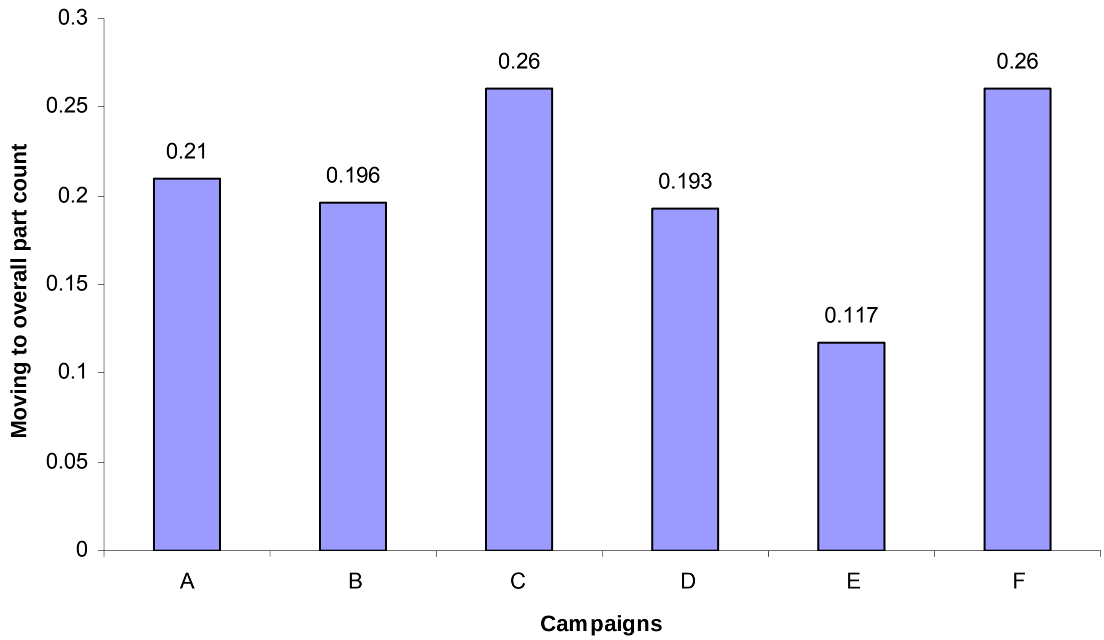

Fig. 6.12 CXI "Moving components ratio" in absolute values

These results show the highest complexity with campaigns C and F, each having the highest portion of moving components of the entire (reference) part count. D, while having the largest wing and the highest absolute number of moving components also needs a considerable number of static parts to support them, hence the lower value.

As said before, A hadn't seen the fly-by-wire revolution yet, thereby containing more mechanical elements e.g. in the form of linkages to steer the movable surfaces, yielding a slightly higher value than B.

The low value of E is based on the fact that, first of all, it doesn't have a movable leading edge and second, fewer movables and a comparably simpler kinematics design yielding the lowest complexity value of all campaigns.

In this case, no configuration "mesh" had been mapped over. The calculated ratios are found to sufficiently show an adequate contribution to complexity. The more moving parts per overall part count, the more complex the design. Thinking it to the extreme, a complexity value of 1 or close to 1 would – theoretically - mean the entire leading and trailing edges as moving components only with some fixtures on the wing box. Contrary, a complexity value of 0 would mean a wing with no movables at all, an entirely "static" wing.

Step 5 – Evaluation, success criteria and results

The four indicators just discussed in more detail plus the remaining fourteen are now compiled together to show the individual results per CXI for each of the six mock-up campaigns and to derive an overall index. The values read as follows:

Table 6.5 CXI results table

N°	Complexity Indicator / Program	A	B	C	D	E	F
1	Type of parts in mock-up	0.4	0.5	0.6	0.9	0.3	0.6
2	Integration density	0.9	0.4	0.4	0.5	0.8	0.6
3	Design-in-context	0.66	0.66	0.66	0.33	0.33	0
4	Drawing tool	1	0.5	0	0	0	0
5	Mock-up class	0.25	0.75	0.75	1	1	1
6	Mock-up policy	0	0	1	1	0.5	0
7	Kinematics complexity	0.3	0.4	0.7	0.9	0.1	0.7
8	Mock-up tasks to be fulfilled	0.5	0.75	1	1	1	1
9	Software toolset change	0	0	0	1	1	0
10	Tool environment and maturity	0	0	0	1	0	0
11	CAD-PDM integration	1	1	0.33	0.33	0.33	0.33
12	Team organization	1	1	0.66	0.66	0.66	1
13	A priori in-house mock-up experience	0.66	0.33	1	0.33	0.33	0.33
14	Number of components ratio	0.693	0.704	1	1	1	1
15	Moving components ratio	0.21	0.196	0.26	0.192	0.117	0.26
16	Configuration similarity	0	0.75	0	0.25	0.75	0
17	Part communality	0.25	1	0.75	1	1	0.75
18	Number of partners and subcontractors	0.5	0.5	0.5	1	1	1
	Sum	8.323	9.44	9.61	12.722	10.047	8.9
	Overall index (Sum/18)	**0.46**	**0.52**	**0.53**	**0.71**	**0.59**	**0.49**

Nota bene: each value is deliberately taken *without* a weighting factor. The intention was to show an overall index out of 18 values, each chosen from within same range of 0 to 1. Thus they are in fact equally weighted. This is only the first step in the assessment. *In what way and how much* individual factors actually contribute to complexity is to be revealed in more detail in the next steps. Without knowing the character and interplay of CXIs, applying weighting factors would most likely be biased by personal preferences. Nonetheless, they actually *could* turn out as correct judgements. That is why they shall not be deemed as illegitimate at all. But in this state of the investigation, it would be mere guessing and not scientifically justifiable proceeding.

Success criteria

As discussed in chapter 5, there can be different approaches to *success criteria*. In fact, none of the mock-up campaigns failed and all of them reached one of their primary goals – keeping the development schedule. Hence, the success classification has been based on cost and quality performances. Other assessments may be calculated with only one reference basis, e.g. costs. Therefore schedule overruns and quality and performance shortfalls will need to be expressed in financial terms. This study's classification, however, is deliberately kept simple; in part due to the difficulty getting reliable cost information, in part because the case study is augmented further below by a "spot-light" assessment of one EMU campaign compared to a DMU campaign.

Table 6.6 Mock-up campaign success criteria

N°	Success Category	Definition
1	Very successful	Budget was kept; much fewer quality deficiencies uncovered than expected, only a few minor issues encountered
2	Successful	Budget was kept; all major and most minor issues solved
3	Impaired, partially successful	Budget wasn't kept; most major and minor issues solved

Note: a schedule success assessment was done nevertheless down below, given the distinction of a campaign having simply met the schedule target (= successful) or even having finished (the vast majority of mock-up related-) work before that date (= very successful).

The overall time – complexity picture

The overall indicator values are now plotted against the time it took for the campaign (see also Appendix E, Table E8):

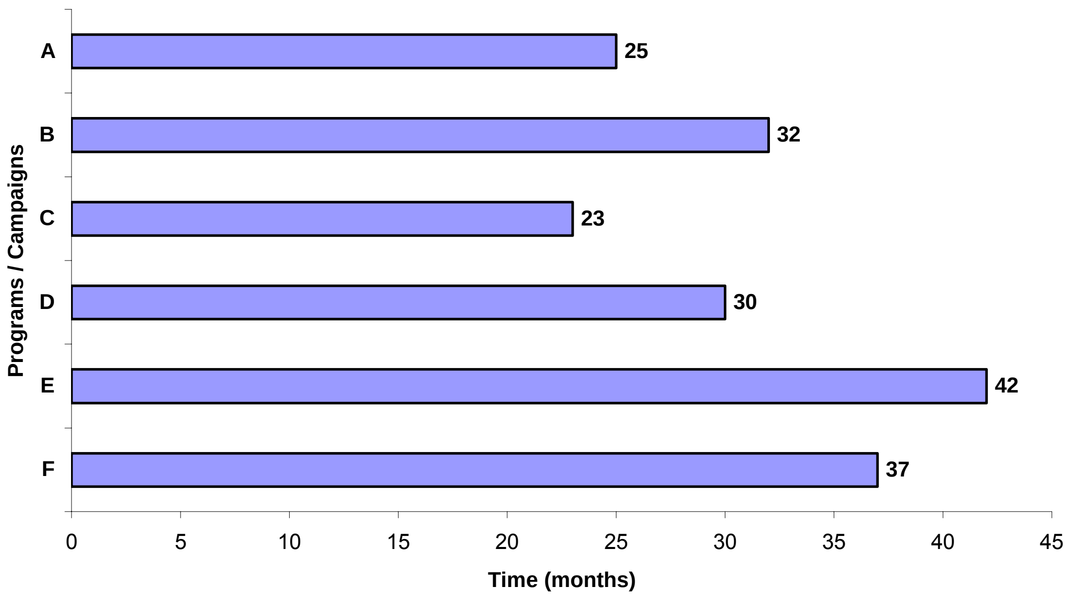

Fig. 6.13 Evaluation time frame and mock-up campaign duration

For A, B and C that was straightforward as start and end dates could be easily attributed. For the other campaigns the following assumption was taken: program launch till begin of final assembly, taken from official schedule planning. This is admittedly a compromise. As mentioned before, D, E and F where using DMUs even before official project "Go". But ramp-up of development activities and therefore broad DMU work usually commenced after launch. Furthermore, at the time of writing this study, both E and F wings have not yet entered final assembly. Thus, comparisons should be taken with care: on one hand because of the different assessment phase and on the other hand due to the prognosis character of extrapolating events far into the future.

The results show that campaigns are not too scattered across the spectrum, none is placed even near the bottom right or top left corners. This supports the argument that schedule planning had been right in principle. In spite of differences in complexity all are actually placed it in the “success corridor” (bottom left to top right).

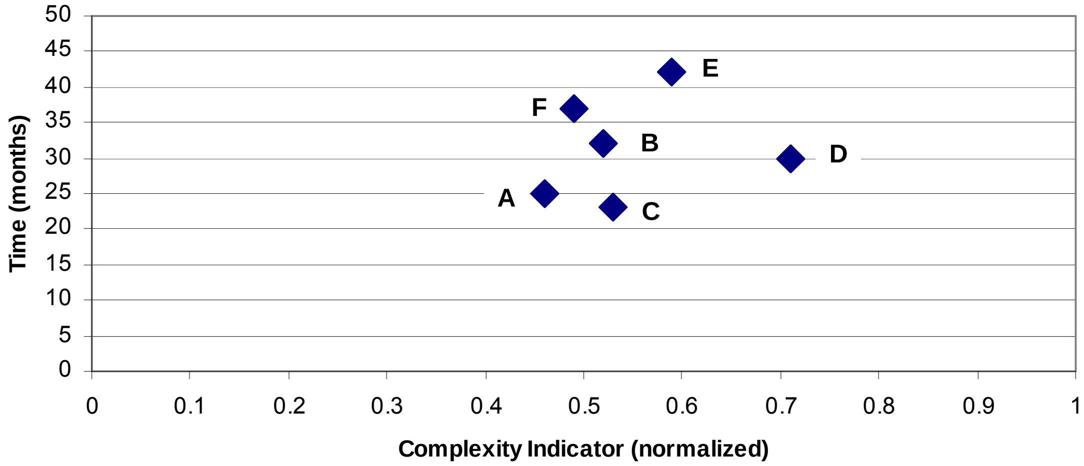

Fig. 6.14   The campaigns plotted against time

On the axis of ordinates 50 months were chosen to show the timely reference with approximately the mean development time from project launch until beginning of flight tests of large transport aircraft.

The overall cost – complexity picture

The second plot is CXIs against (non-recurring) costs. All values where adjusted to economic conditions (EC) of 2005.

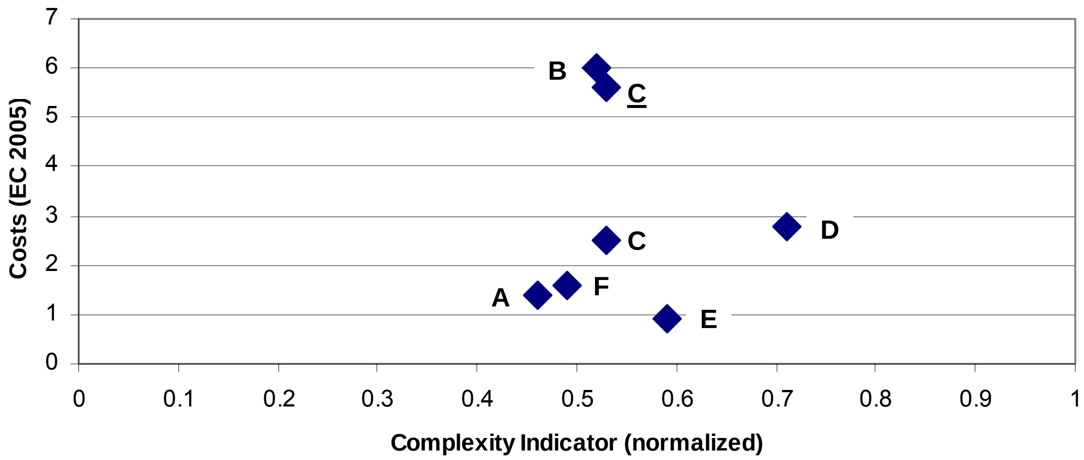

Fig. 6.15   The campaigns plotted against costs

Evidence could be found on expenditures for B and C. But due to a lack of sufficient data for the other programs costs were calculated taking B as basis for A, with “correction” factors ‘size’ (part count) and ‘mock-up category’ to account for differences. D, E and F were extrapolated from C. Also with them correction factors where used: Size of the mock-up (part count) and the time it took.

C is the overall expenditure of DMU campaign C including extra 2D drawing creation, because the 3D CAD tool functionality to derivate drawings was then not satisfactorily available. This accounted for more than a doubling of originally planned costs.

Both diagrams reveal that (1) all campaigns had/have an overall complexity level relatively high, but not too high in the overall picture, and (2) that they scramble in a quite narrow band of less the 0.3 counters (0.46 to 0.71). None of them is either in or near the right bottom corner marked as “danger zone” or the “uneconomic zone” in the top left corner.

A detailed interpretation of time and costs results is to be found further below.

Plotting all programs with reference to program B, as shown in fig. 6.16 below, reveals the relative character with respect to costs. This gives evidence on the fact that in the end almost the same amount of money was spent in the wake of the first Digital Mock-up campaign (C). But it also clearly shows that had the tool functionality been available in time had campaign C really cost less than half of a physical mock-up solution, as originally planned.

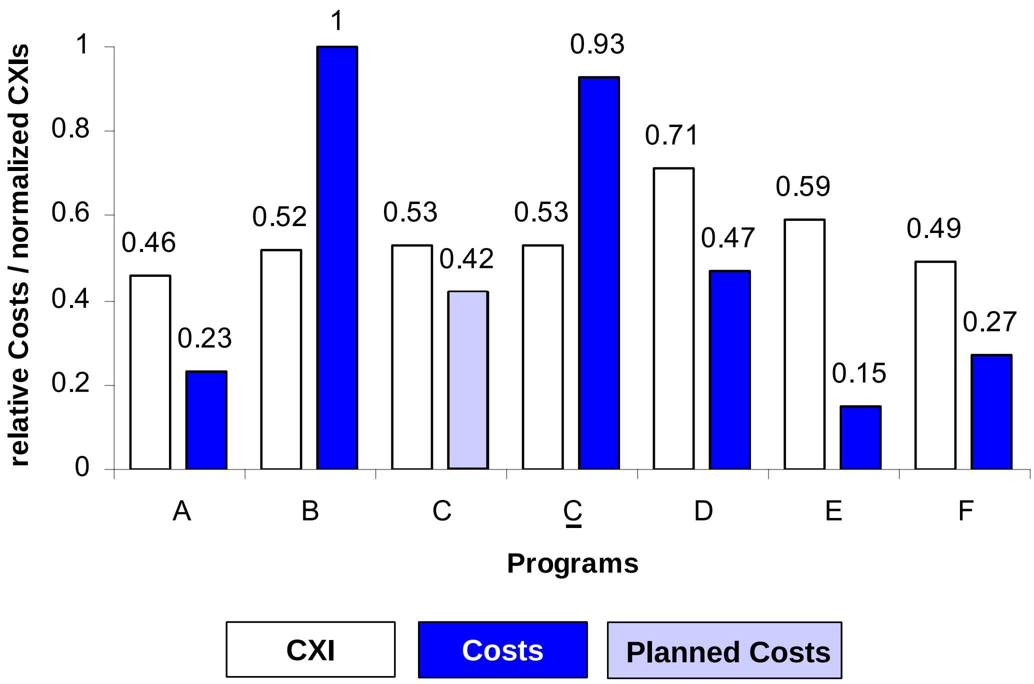

Fig. 6.16 Program cost distribution relative to Engineering Mock-up campaign B

The mean CXI value is 0.55; With the exception of D neither program is extremely above of below. The DMU campaign D has the highest complexity level, nevertheless its cost is less than half of EMU campaign B.

Campaigns E and F show the best prospects of contributing value to their programs: E because a slightly higher complexity index is matched by a longer time to develop, and F because a complexity level lower than mean is paired with the second longest development time span. In addition, it is the latest program and some other positive factors are likely to take effect, too. Among them there is a faster learning curve and a more skilled and experienced workforce, together with an overall higher awareness on CDMU issues.

As a reminder, program F in this study is still based on the originally planned design, *before* it was rolled back and a completely new aircraft emerged. Comparing B and C with F (which is the successor of the two former aircraft types) is therefore somewhat biased (also because of the assessment time frame – transition/laminar vs. turbulent). But with caution may one see the prospects for even lower costs for newer programs while possibly lowering the overall complexity level step by step. This can be attributed to steeper learning curves, better technology and better organization of the CDMU within the overall development context.

Steps 6 and 7 – Cross Impact Analysis, Connectivity Analysis, interpreting results and planning for action

Step 6 is interesting for uncovering more of the nature of complexity indicators. If one is not confident with results gained so far this analysis helps triggering the right actions based on knowledge of the interrelations of indicators.

The primary intention is to reveal the “levers”, or the “key indicators” that have to be pulled to steer the project into the right direction. Within the scope of this study the cross-impact matrix was exercised with Programs B and D. Firstly, to prove its applicability for the method, and secondly, to find out what changed from the EMU to the DMU campaign. The cross-impact matrices for both can be found in Appendix F. Here, only the results are shown.
Based on the matrices’ results the impact-structure cycles had been established with a reduced number of CXIs.

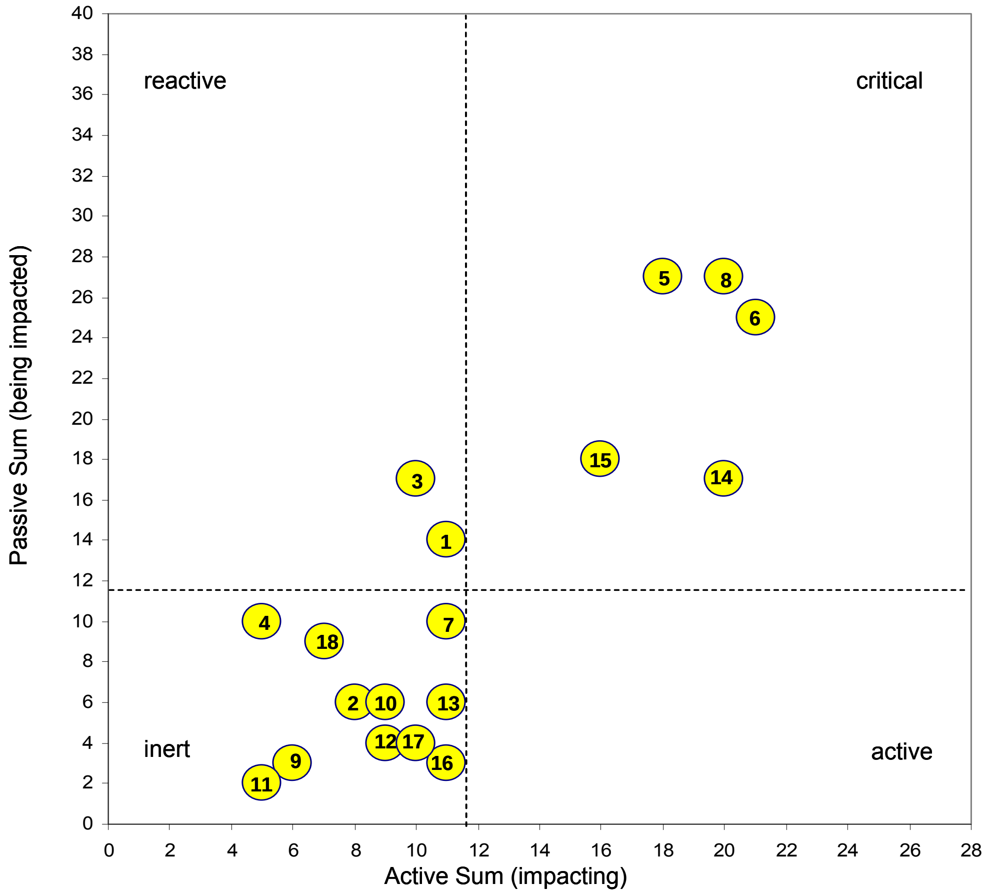

Fig. 6.17   Result of cross-impact analysis for EMU campaign B

The diagram shows that most indicators are neither very active nor very passive. Only five CXIs exemplify more activity and passivity than the others and are therefore in the critical area. They may trigger the campaign into the desired direction: ‘Mock-up class’ (N°5), ‘Mock-up policy’ (N°6), and ‘Mock-up tasks to be fulfilled’ (N°8) clearly frame the campaign, as one would expect, together with ‘Number of components ratio’ (N°14) and ‘Moving components ratio’ (N°15).

‘Design-in-context’ (N°3) revealed itself as rather passive. This factor may be used as indication for the campaign being on track or not, but would not be a good lever for triggering events.
As during B there hadn’t been a toolset change and CAD-PDM integration was out of question, the analysis correctly reveals CXIs N°9 and N°11 as playing very inferior roles during the campaign.

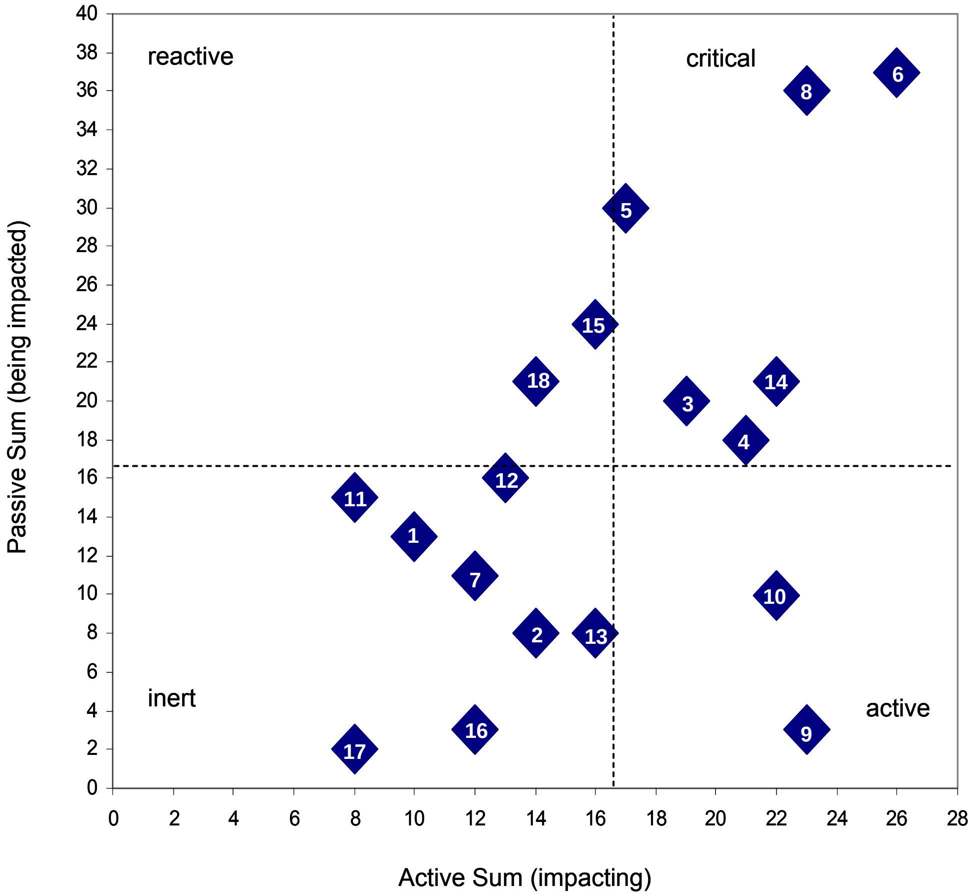

Fig. 6.18 Result of cross-impact analysis for DMU campaign D

The CXI distribution for D looks more scattered: Two CXIs, ‘Software toolset change’ (N°9) and ‘Tool environment and maturity’ (N°10) now populate the active field. These two issues actually have been of great importance to the DMU campaign. Both are meta level indicators and as such eligible for laying down the playing rules for the whole team. These would be two primary candidates for action, for steering the campaign into the desired direction thereby avoiding major obstacles. ‘Design-in-context’ (N°3) also has moved more to the right with a much higher active sum than in B. Though being in the “critical” field, however on its lower end, this indicator would be another first choice as key lever. This is logical as the up-to-date availability of DMU data is crucial for every developer in a concurrent design environment. The situation is similar with CXI N°4, ‘Drawing tool’. In campaign D it is 3D CAD that makes the difference. Getting it right (full 3D design, all required tool functionalities available, robust working, handling of large data sets…) will reap big benefits for the project.

The question now is 'how did the situation change from the Engineering Mock-up to the Digital Mock-up'? Mapping the two results can show this. Those indicators that have changed the most are connected via arrows.

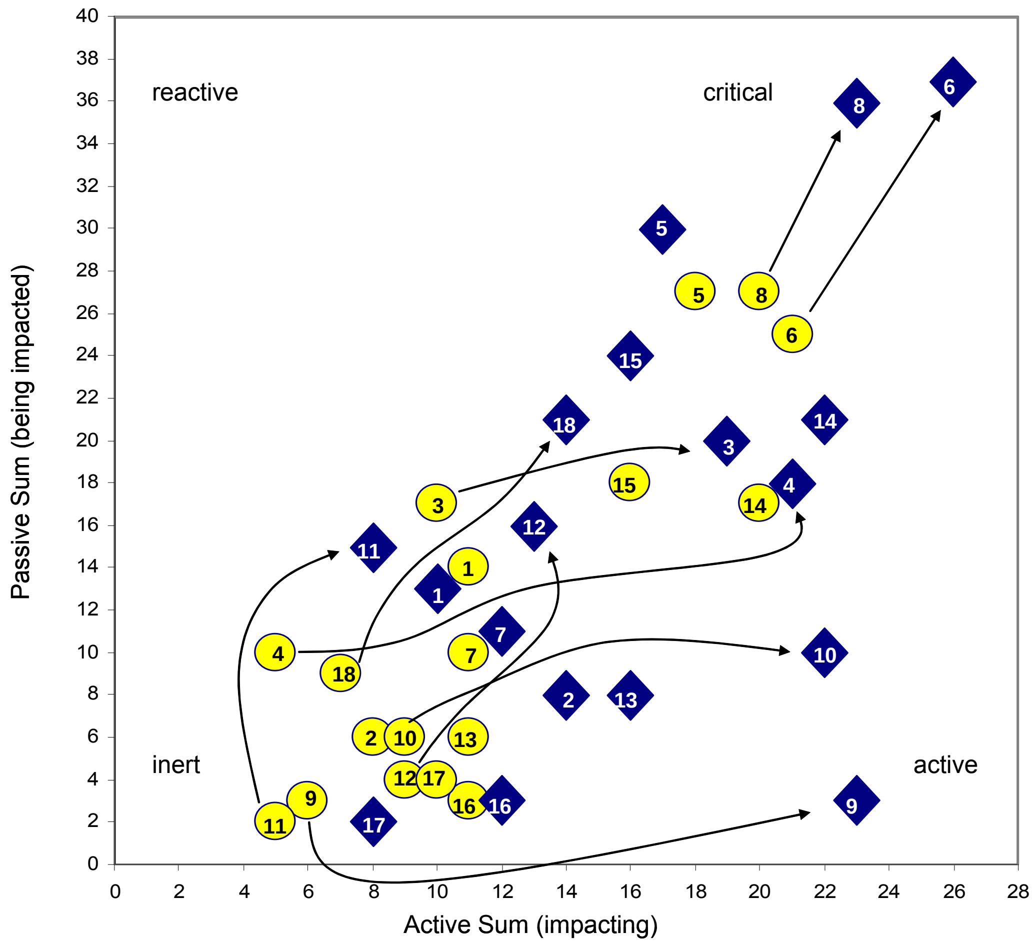

Fig. 6.19 Mapping of B and D – changes from EMU to DMU

A first observation reveals that parameter changes can be broken down into three groups:

(1) those with *big changes* (CXIs 3, 4, 6, 8, 9, 10, 11, 12 and 18)
(2) those with *small or medium changes* (CXIs 2, 5, 13, 14, 15), and
(3) factors with *no considerable change* (CXIs 1, 7, 16, 17)

Here it can be seen, that not only N°3 - 'Design-in-context', N°9 – 'Software toolset change' and N°10 - 'Tool environment and maturity' have become more active, but also 'CAD-PDM integration' (N°11) has a much less inert role in the DMU campaign. N°18, 'Number of partners and subcontractors" is playing a considerably more active and passive, hence more critical role. It is easily imaginable that having many of these players can render the campaign quite difficult to control; on the other hand will suppliers contribute considerably to overall success if lead and involved appropriately. In fact, "critical" indicators resemble a two-edged sword: if triggered and controlled wisely, there will be considerable benefit for the whole undertaking, but if neglected or steered wrongly, problems are likely to be seen soon and on many places.

The two factors, which got another astonishing boost versus the top corner in the “critical”-field, are N°8 – ‘Mock-up tasks to be fulfilled’ and N°6 – ‘Mock-up policy’. Especially the latter will take a leading role for project success or failure. It is part of the meta level, and the one CXI being impacted and impacting oneself the most. Thus it’s obviously a crucial parameter to what degree a policy for executing the mock-up campaign is defined and implemented. It can be *the* major leverage for success, as here the rules, the requirements and constraints are brought together, under which the campaign is to be executed. The less a policy is defined, the more room is being given for unintended and unwanted developments and quality and performance shortcomings.

The more clearly pronounced and the better understood and supported the campaign strategy is, the more will all efforts be directed towards achieving common and challenging goals: Delivering a superior product – first in digital format and then in hardware – under constant schedule, cost and quality pressures. The policy actually is also one of the major tools in mastering complexity, because it gives direction to all people involved, independent of location, the development status and a whole lot of other circumstances.

The cross-impact matrix has identified some candidates for actually controlling and steering the projects in a desired direction. The second tool – the connectivity analysis – is to give clues how the parameters (in general) are interconnected and in which feedback loops they are embedded.

The first question to be answered is which CXIs shall be assessed. Usually, the more factors are involved the more interrelations may increase exponentially. It may make the feedback loop set up and analysis a very time consuming task. This will only be handled appropriately by using dedicated software tools. But as the question focuses (1) on what the *relevant* factors are, and (2) to enable a rather fast analysis, a CXI filtering based on critical judgement is justified.

Looking at the results in figure 6.18, four CXIs can be identified which neither manifest much change from B to D nor may they be attributed being very active or passive. These four are N°1 – ‘Type of parts in mock-up’, N°7 – ‘Kinematics complexity’, N°16 – ‘Configuration similarity’ and N°17 – ‘Part communality’. All of them are placed in the inert field of the diagram and obviously do not really qualify as candidates for interventions and for controlling (compare the definitions given in figure 5.7). Their obvious inertness is the reason why they are ruled out for further analysis of the dynamical structure of CXIs. This reduces the number of CXIs to only fourteen. Figure 6.14 shows the feedback cycles:

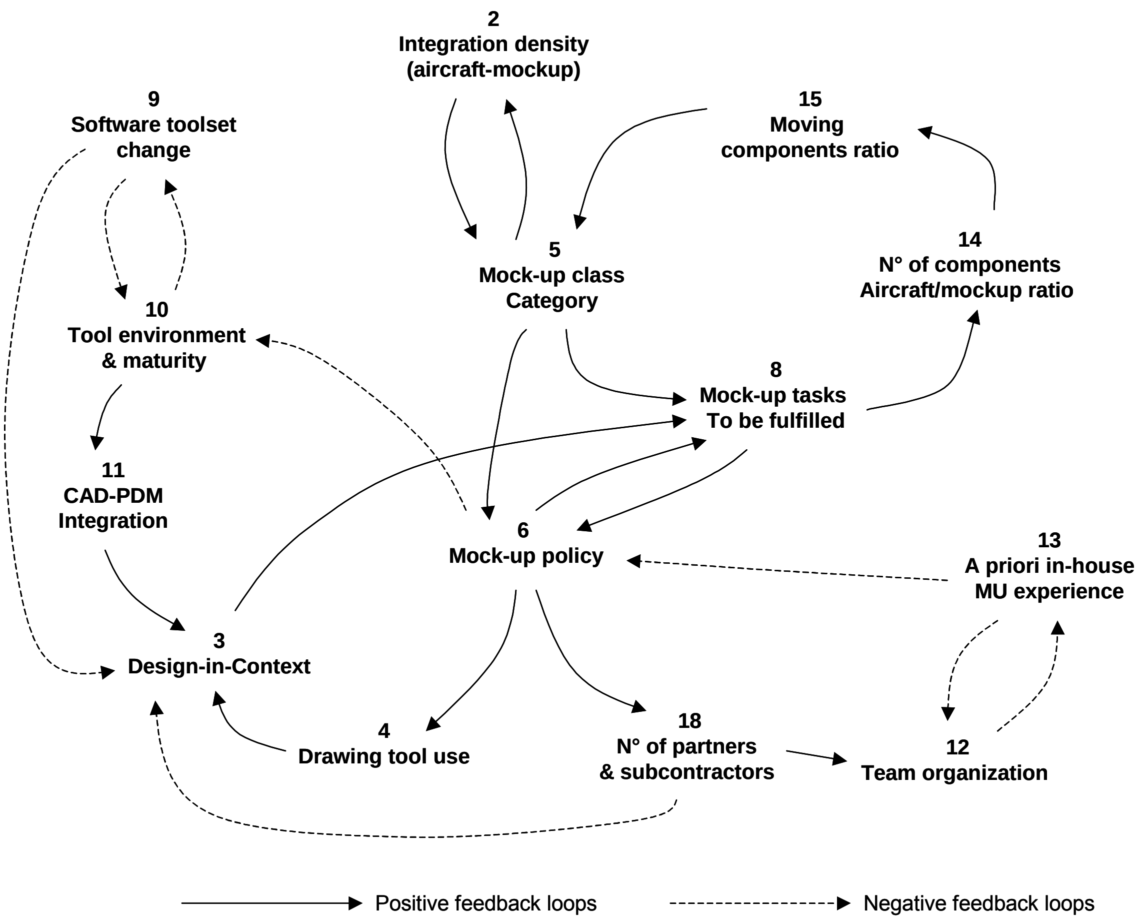

Fig. 6.20 Feedback cycles for fourteen CXIs

Analysing the amount and types of feedback loops, the result is the following:

Table 6.7 Result the assessment of feedback cycles

Negative feedback cycles	Loop number	Positive feedback cycles
6-18-12-13-6	1	2-5-2
6-18-3-8-6	2	6-8-6
6-18-3-8-14-15-5-6	3	9-10-9
6-10-11-3-8-6	4	12-13-12
9-3-8-6-10-9	5	3-8-6-4-3
9-3-8-14-15-5-6-10-9	6	8-14-15-5-8
	7	6-8-14-15-5-6
	8	6-4-3-8-14-15-5-6

As already mentioned in chapter 5, CXI N°3 – ‘Design-in-context’ is one important factor: Especially in campaign D where it has an increased active role it becomes a vital “dampening element” in the system, with 5 involvements out of 6 negative feedback cycles. But probably the major factor being crystallized out of the analysis is CXI N°6 – ‘Mock-up policy’. It is part of all negative and half on the positive cycles. Taking out this factor (which admittedly is a theoretical question as there is always a kind of “policy”, even if composed of uncoordinated ad hoc measures) would leave the system with four positive hence self-reinforcing loops. This could potentially destabilize the system and render it uncontrollable. It is not surprising that ‘Mock-up policy’ is a meta level indicator. It virtually penetrates the whole system and therefore makes it a key factor for establishing the “rules of the game”. It is a part of the guiding “central meta system” which results in local adjustments on the object level.

Plan for action

A good strategy always entails contemporary consideration of a number of key issues: It means working on the right fields while triggering the appropriate actions in parallel and in reasonable intensity. The mock-up campaign assessment has revealed some of the key parameters that shall be considered for getting complexity of the system under control.

Based on the findings above there can be drawn a plan how to become better; the plan is hypothetical as for both campaigns it is already too late to take effect. Thus, the recommendations here merely serve the question what *would* have been the best strategy.

- *Implement a clear and consistent mock-up policy right from the start of the campaign*; this obviously is a key leverage for overall project success. No matter how few or how many people work in the project, on dispersed places or on one site, whether they make mistakes or fall short in performance: the policy provides guidance and reference for work and for improvements.

- *Clearly specify what class of mock-up shall be created and what tasks have to be done with it;* this allows appropriate budget, schedule and personnel planning. It is even more important for partners and subcontractors, in order to enable those tasks being taken into account in the bidding process.

- *Consider design-in-context a key issue to be solved, especially in a concurrent environment;* complexity can be brought considerably under control by provision of relevant data and information, where and when they are needed, virtually in a “plug-and-play” style. This could entail that data exchange and data sharing efforts are appropriately considered in planning and executing the campaign.

- *Software toolset changes as early as possible or none at all, and pushing for a homogenous and mature tool environment;* the ideal solution would be a reliable and proven toolset. When there really is to be such a fundamental change (which is usually based on a business case) then it should be introduced as early as possible having only a few people affected, hence minimizing broad efficiency shortfalls.

In addition to all these points, one central figure in mastering complexity is always a trained and experienced workforce itself.

6.3.3 Spotlight: Quality and cost assessment of EMU campaign B vs. DMU campaign D

The results so far have shed light mainly on the relation of time and costs for all programs. The third question of how well EMU and DMU campaigns performed primarily with respect to quality (but also costs) shall be highlighted in this particular investigation. This shall be answered focusing on differences in the quality and cost performance of B and D. The former campaign was chosen because it can be regarded as then having been at a top of the practice creating hardware mock-ups. The latter was selected because it likewise represented a (temporary) height in DMU developments. Both drew benefits from preceding campaigns.
The Engineering Mock-up represented about 70% of components being built into the real wing. The team then had carefully identified which areas were deemed eligible for being pre-checked in a mock-up. Such a hardware mock-up will seldom contain each and every part that will be build into the first prototype for pure budget, schedule and overall necessity reasons. Construction of areas already being regarded as confidently under control would have been a waste of time and money.
The DMU of program D was nearly a 100% replica of the flying aircraft. Only some "minor" items (bolts, nuts…) had (initially) not been modelled in 3D, only within some work packages. They were thought to pose no problems during assembly/integration. As it turned out later, it would have been beneficial having had them pre-checked in some areas.
The major quality differences can be seen by comparing the respective reference part counts and the "major items" that were encountered on the first real wings:

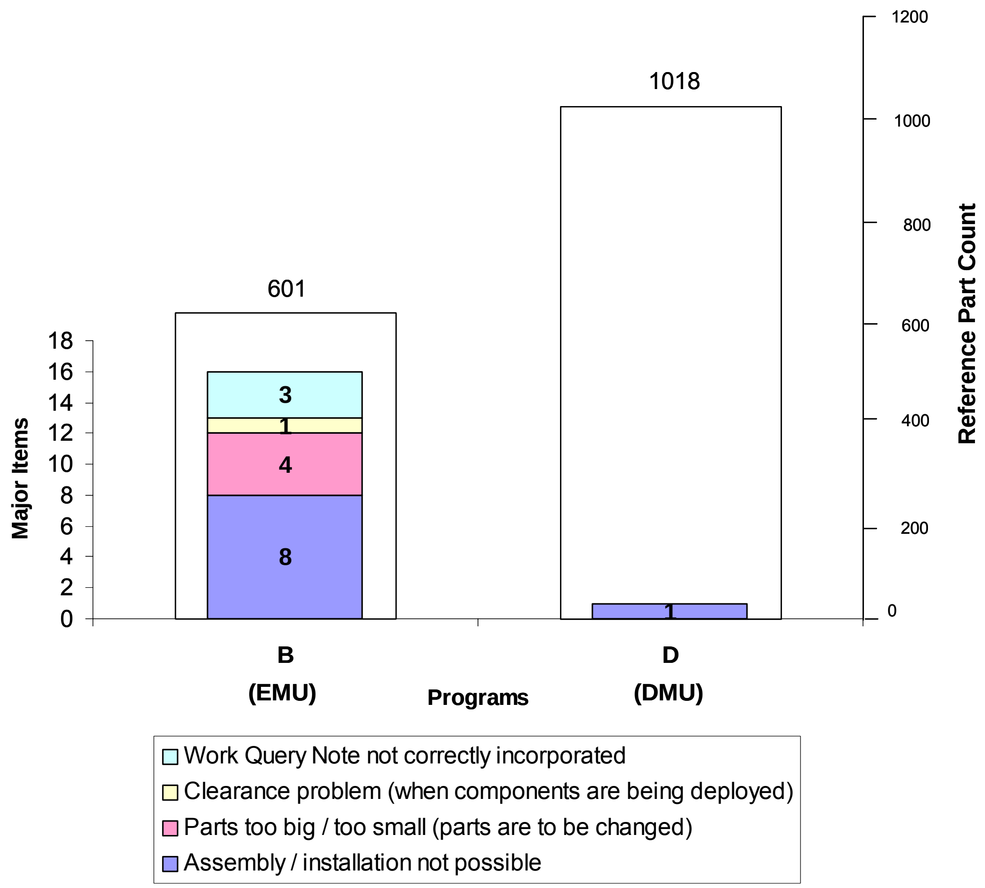

Fig. 6.21 Issues having caused troubles during wing equipping and final assembly in relation to the reference part count of the first left hand wing

The figure shows the four major classes of problems which assembly workers were faced with when integrating the first half-wing. Actually, left- and right hand wing problems were the almost the same. Background columns show the reference part count. Although D did have 40% more components than B had it only one “major item” to cope with. In comparison, program B wing was faced with 16 major issues. The majority of those problem areas were originally planned to be anticipated with the EMU. In hindsight, it is difficult to find out the *exact* cause why something didn’t work. The most common problem was that parts and equipments (sometimes geometrically correct dummies) had been provided to the EMU either too late or not at all. Thus, the first installation check had to be done on the real wing, eventually then causing troubles.

The single issue in D had its roots in one of three fundamental DMU problems already encountered during campaign C: Missing geometry. Some bolts of the movable leading edge (together with other standard parts) had not been modelled in 3D until it was too late. An interference analysis then uncovered a collision (“clash”) between a bolt (it actually was too long) and its adjacent part, the same week as the bolt (in fact the panel of which the bolt was part of) should be installed in the final assembly line. Fortunately, the issue was not flight critical. Nevertheless, it triggered the whole modification process with all its administration efforts, redesign work and production adaptations. All that could have been avoided had the bolt clash been found earlier, hence had the bolt been part of the DMU earlier.

Another D issue is interesting being mentioned: during ground tests assembly workers found that when deploying a slat it “crushed” into the fully opened engine cowling door (fortunately not damaging anything). This problem had actually been discovered over one and a half years earlier in a kinematics interference analysis with the DMU. The proposed remedy was either to open the engine cowling a few degrees less or not at all during slats tests. The advice had simply been overlooked in the heat of final assembly activities. That is why this case does not appear in the statistics above (as a clearance problem), as it actually was anticipated in the DMU and communicated downstream. It’s an example of a quite minor issue but demonstrates an important aspect, however: any investigational results are rendered useless if corrective actions are not remembered by the right people the right time, or if remedial activities are not becoming part of the overall work flow.

Besides major issues there had been a number of “minor issues” in wing equipping and final assembly, which cannot necessarily be attributed to EMU or DMU shortfalls[40]. Among them have been

- parts being damaged (e.g. during transport), being defect, had to be repaired or completely exchanged
- wrong parts delivered by suppliers
- some equipments were cleared for ground tests only; they had to be exchanged prior first flight
- missing features and small items (e.g. drilling holes, nuts, attachments for cables and hoses…)

[40] In that respect it is interesting which policy is followed: Documenting each and every (also minor and very minor) issue in Design- or Work Query Notes or bundling several of them in a “collection” Design/Work Query Note, or even a “collective” modification. Schedule pressure and high administration efforts are reasons for such bundling actions (especially commercial aerospace has one of the most stringent documentation requirements requested by authorities). Therefore, one can be misled by simply counting the number of documented “snags” without questioning their content. A closer look is required to actually find out realistic and defendable numbers.

- documentation problems (parts couldn't be categorized correctly, documents were missing or incomplete, parts were erroneously labelled…)
- parts had to be repositioned (e.g. for accommodating flight test installations…)
- missing check reports
- minor rigging/torque tasks (if it was not done sufficiently, or couldn't be done, e.g. due to rubber sealing…)
- assembly/integration errors (e.g. cables connected to wrong ports…)

The quality assessment shall now be complemented by an extract of the cost comparison of figure 6.16. Again, the costs of the two programs are presented with B as reference and respective complexity indicator values:

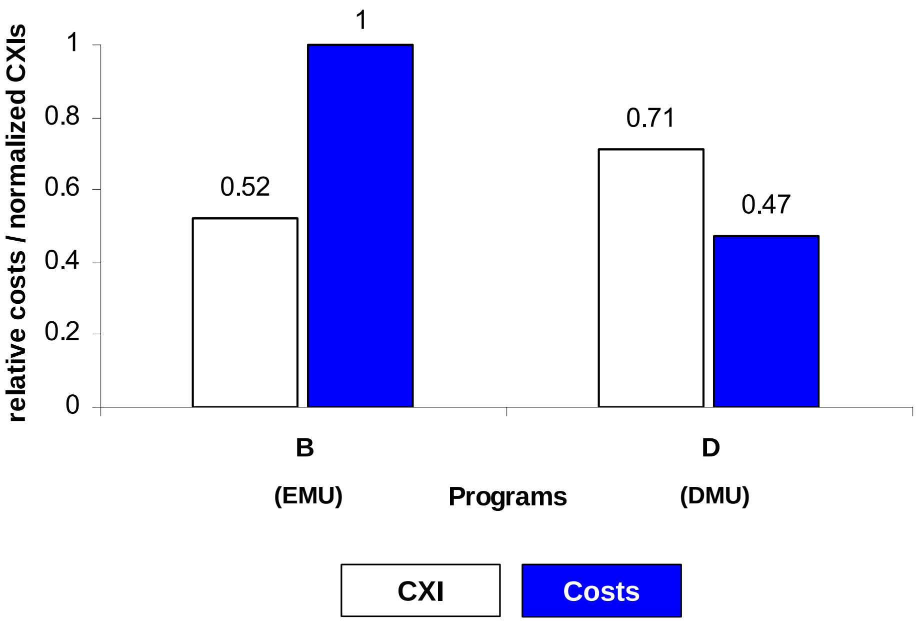

Fig. 6.22 Relative costs with B as reference and complexity values

This spotlight clearly shows that a DMU does have clear and quantifiable quality advantages over an EMU, given the same or similar objectives, requirements and circumstances. The simple reason is that 3D models are created faster and cheaper than real hardware. They can be checked earlier, in shorter periods, more often and in much higher quantities. Parts can be validated for perfect fit, form and function before the material is even touched.

Though the analysis isn't representative of the relation between EMU and DMU in general, this comparison enables to draw some conclusions:

- the Digital Mock-up the enabled the (non-recurring) *costs to be cut by more than half*,
- at a considerably *higher complexity level*,
- while integrating *40% more components*,
- with about *94% (=15/16) fewer major assembly/integration troubles*

The DMU can be both: an enabler for "right-first-time" top quality achievements with subsequent recurring costs benefits and a substantial development cost reduction factor.

6.4 Summary - Key Findings

The Complexity Indicators method has revealed the following details for time and costs for the six mock-up campaigns. At first, the *time* issue: As already mentioned, neither program comes near the so-called “danger zone” or the “uneconomic zone”. This is not astonishing either, as all campaigns were based on careful schedule planning. In addition, as far as success judgements are concerned, the only distinction can be made between “successful” and “very successful”. Nevertheless, a bar-chart representation of results reveals the time and complexity relation for the four projects. Here again, B shall be the reference:

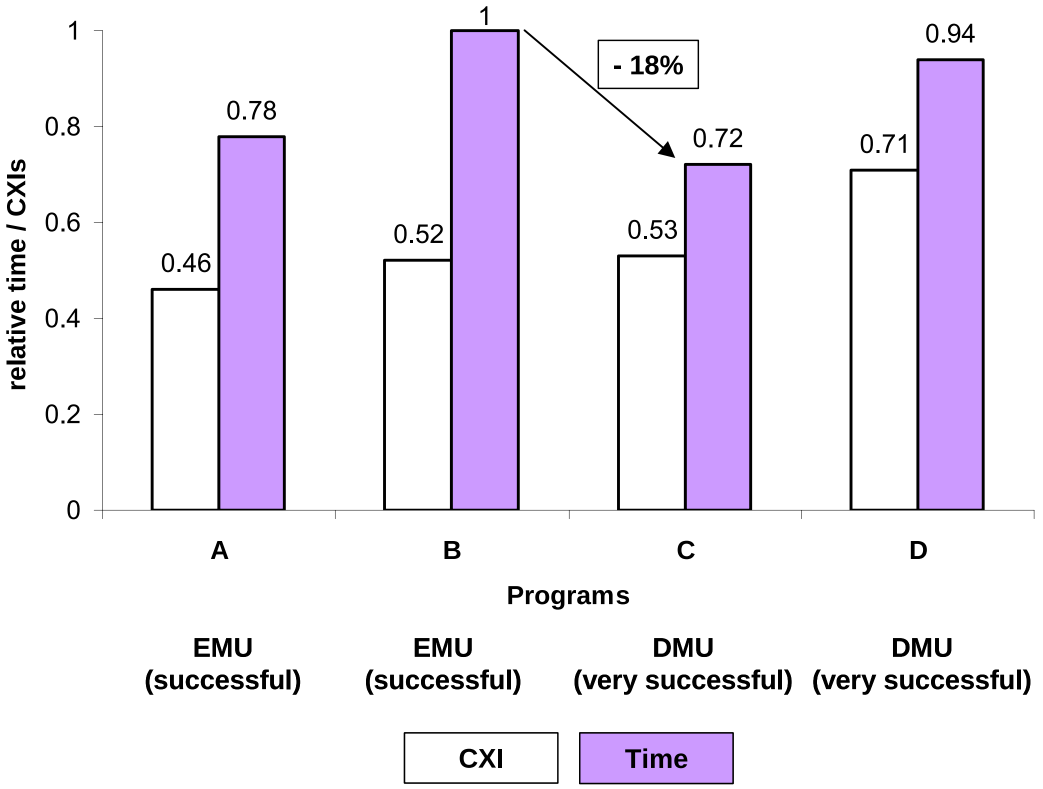

Fig. 6.23 The campaigns plotted against time in detail

As far as time is concerned, programs B and C best suite a comparison: First, both have the same complexity level. Then, the configuration of either wings were almost the same, with C merely an enlarged version of B. And both campaigns were executed with a timely limit, marking clear start and end points in time.
The results indicate a considerable time advantage for the DMU campaign, with C needing 18% less time. Assuming nearly similar times for manufacturing and assembly/integration activities, it means that the DMU could be started later in the development, having major objectives achieved even before the first real wings were fully equipped.

The key findings on the (non-recurring) costs issue show similar results but for program C: This one needs to be tagged “impaired” as cost goals were surpassed by almost 100%. Had the campaign had all required 3D CAD functionalities available on time – as the example with program D implies – would have also the cost goal been reached. But, those missing functionalities resulted in a costly 2D drawing creation, which was originally not planned.
Programs A and B are declared “successful” because they did not experience cost overruns. The considerable difference between A and B is explained partly due the higher complexity of the latter campaign, due to a higher mock-up category, increased wing size, due to more checks that had to be done with B but also due to ten years of inflation between them.
The clear “winner” of this assessment is program D, showing the best cost performance, paired with the highest complexity index of all mock-up campaigns (and that almost fifteen years after campaign B).

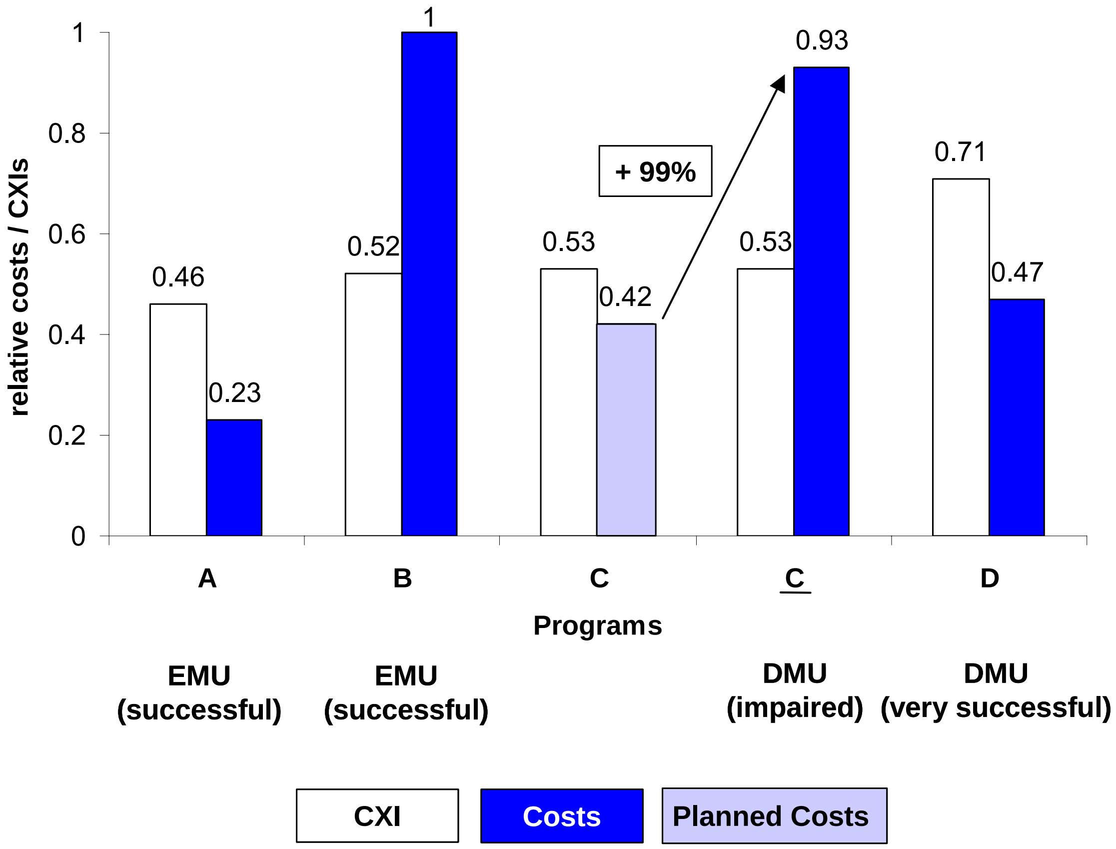

Fig. 6.24 The campaigns plotted against costs in detail

Even though only four campaigns could be judged on meeting success criteria, these two EMU and two DMU campaigns indicate the following:

- *on time:* Both EMU campaigns performed well with respect to schedule, but were actually protracted into the phase of real wing equipping. This was due to late systems definitions, late changes and the time delay caused through the construction of hardware models (the time delta "as-designed – as-build"). More important, and in spite of the EMU not being ready as initially planned it helped securing wing equipping lead times, accomplishing their primary objective.
  The DMUs exemplified their time advantage by not only meeting wing equipping lead times but also by incorporating late changes faster.

- *on costs:* The cost goals of EMU campaigns laid on recurring cost reduction. It was achieved, first by keeping wing equipping lead times, and second, by considerably reducing major integration troubles in the assembly lines.
  The DMU campaign fulfilled their promises with D not only to reduce recurring costs through fewer quality deficiencies and higher design maturity, but also reducing non-recurring costs by more than half.

- *on quality:* The spotlight example shows that quality deficiencies can be considerably reduced using the Digital Mock-up. But one may not be misled by assuming that high product quality comes automatically, or to say "for free", by going 3D. To ensure a defect-free product there must be a strong link between the digital representation and real hardware. The DMU must fulfil the strictest data and design quality criteria to be used as input for hardware creation. And there must be a link back so that changes made to the hardware (different build-in situation, fit and form of parts adjusted to integration constraints…) are reflected in the DMU as well. Otherwise the database will contain dated information, which in turn will be the source for future adjustments.
  To avoid such shortcomings it must be ruled for development processes that changes be introduced and checked in 3D first, whenever possible.

Chapter 7 Conclusions and Outlook

7.1 Conclusions on the complexity approach

In everyday business practice the application of complexity-based methods has just begun. This study offers a new approach, doing two things: first, it places a generic definition of complexity in the centre of considerations, and second, it assumes an integrated view taking also non-technical factors into account.
The intention of the method is to enable a rather quick assessment on complex products and projects from a new perspective. It then relates it to basic business terms. The result is an enhanced and extended view of the situation, which – hopefully – will help making the right business decisions. An even closer look can reveal where, when and how intense to trigger corrective actions. It is in strong contrast to making purely technological or financial centric evaluations. It is recommended working through the method with a team, as different views may sooner converge to robust definitions without crucial areas having been left aside.

The method deliberately "produces" approximations as results. It might be criticized that such an approach is no more than "approximated method-supported guessing". The counter-argument is the very definition of complexity as stated herein: there are not and there will never be mathematically *exact* values, as complexity in its holistic view won't be measurable in an ultimate sense. In addition, from a practical and pragmatic point of view, approximating the complexity phenomenon is the only reasonable proceeding, as one will never have all data and surely too few and often insufficient clues available (one can never have ultimate certainty!). It is of profound importance to never seeing results isolated from the investigational context.

Applying the method to six Engineering- and Digital Mock-up campaigns actually revealed more on their respective time, cost and quality impact. The method was validated hereby, producing results that fit into the overall picture and to different sources of evidence and personal experiences.
The results of the method are not an end by themselves. They usually serve as input for further and deeper analysis, and for action plans. This issue however, is beyond the scope of this study – it would be a good opportunity for further refinement of the method (in fact, historical comparisons could be used to determine whether the complexity level had been adequate; evaluations at discrete points during an ongoing project will thus need to be left to future assessments). Critical areas that had been identified may then be analysed more deeply, probably with support of sophisticated software tool solutions. They will be particularly helpful when doing cross-impact matrices and connectivity analysis. These two methods are time consuming, thus should only be done if one really intends to alter the evolution of projects.
The CXI method could be used also as company internal preparation for shaping a complexity management strategy. In addition to buying-in external consulting for building up what could be called a 'complexity management competence', teams could concentrate on holistic views on all complexities ahead and elaborate the best way through.

7.2 Conclusion for mock-ups

In conclusion, the Digital Mock-ups had/have better overall performance than their Hardware Mock-up predecessors. An EMU for the large wings of program D would not only have burst the budget. From a design point of view managing the shear size and complexity of D within the tight development schedule has made it virtually impossible not to use a DMU. The spotlight investigation further supports the view that DMU "produces" considerably fewer quality deficiencies in wing equipping and final assembly then before.

As far as development costs (non-recurring costs – NRC) are concerned did the investigation reveal advantages of DMUs over EMUs. DMUs therefore cost *one third to one half less* than EMUs. But the more important issue for an aircraft program is recurring costs (RC).
Still being highly labour-intense, development programs, particularly in aerospace, are subject to learning curves[41] (e.g. compare Liebau, 2002, and Roskam, 2002). The closer production resembles the calculated curve the fewer RCs are necessary to build subsequent aircraft.
From a cost perspective, it is of profound importance to have the quality of the design as close to definition as possible, so that the product will have high maturity right from the start. This in turn is a primary factor in attaining recurring cost goals, ensuring long-term company profitability. Both types of mock-ups, however DMUs in particular, are suited to provide a substantial contribution to achieving overall business goals: keeping the development budget, introducing a high quality product thereby ensuring the learning curve to be run through quickly, which in turn is key for targeting recurring costs. And by keeping the schedules, a fulfilled time-to-market is yielding long-term competitive advantages.

Not investigated however, but thinking it further reveals another crucial point for DMUs: they are even more important in cases of higher production rates. Usually the more machines per time-span (e.g. per month) are produced the later will modifications be able to be incorporated. Many parts require long lead times so that changes are not introduced from the immediately affected aircraft on to the next. Should parts need to be changed (triggered by an official modification) they have either to be reworked, or, in worst case, to be scrapped. A number of aircraft will stay equipped with the old parts, while, in the meantime, others are fitted with the new or reworked parts. Substitution or retrofitting is always a costly under-taking (flight and safety critical modifications are excluded as they get a priority track into the planes). The RC penalty is twofold: (1) a modification – which actually is an improvement of a situation – cannot be incorporated instantly, and (2) there are considerable administrative, financial and timely efforts necessary retrofitting the planes latter. The DMU renders this situation less critical in two ways: first, it supports a higher maturity of the design itself, making late modifications less and less necessary (or less impacting), and second, when a change does happen, it enables better anticipation what has to be done, which parts in which areas are affected and for figuring out the best replacement strategy.

In conclusion, the better the quality of the CDMU, the better will not only be the NRC but also the RC situation. Having to sort-out too many quality deficiencies and process flow problems will raise both NRCs and RCs, with negative impacts on company profitability. The DMU can ultimately be regarded a primary contribution to a manufacturer's goal of selling as many aeroplanes as possible at an affordable market price.

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[41] Learning curves are based on the assumption that subsequent aircraft require less working hours than previous ones. The curve describes a digressive slope of manufacturing effort (expressed as cost and time) at repetitive same and similar processes of a continuous production (Liebau, 2002).

7.3 Outlook

The Complexity Indicator method may be regarded as a first step, a prototype for complexity-based assessments of complex products and projects. It may be extended and refined for future applications. Its approximated nature has the advantage that results are obtained rather quickly and the holistic and open approach ensures the whole "complexity picture" to be taken into account. Figure 7.1 shows some evolution scenarios:

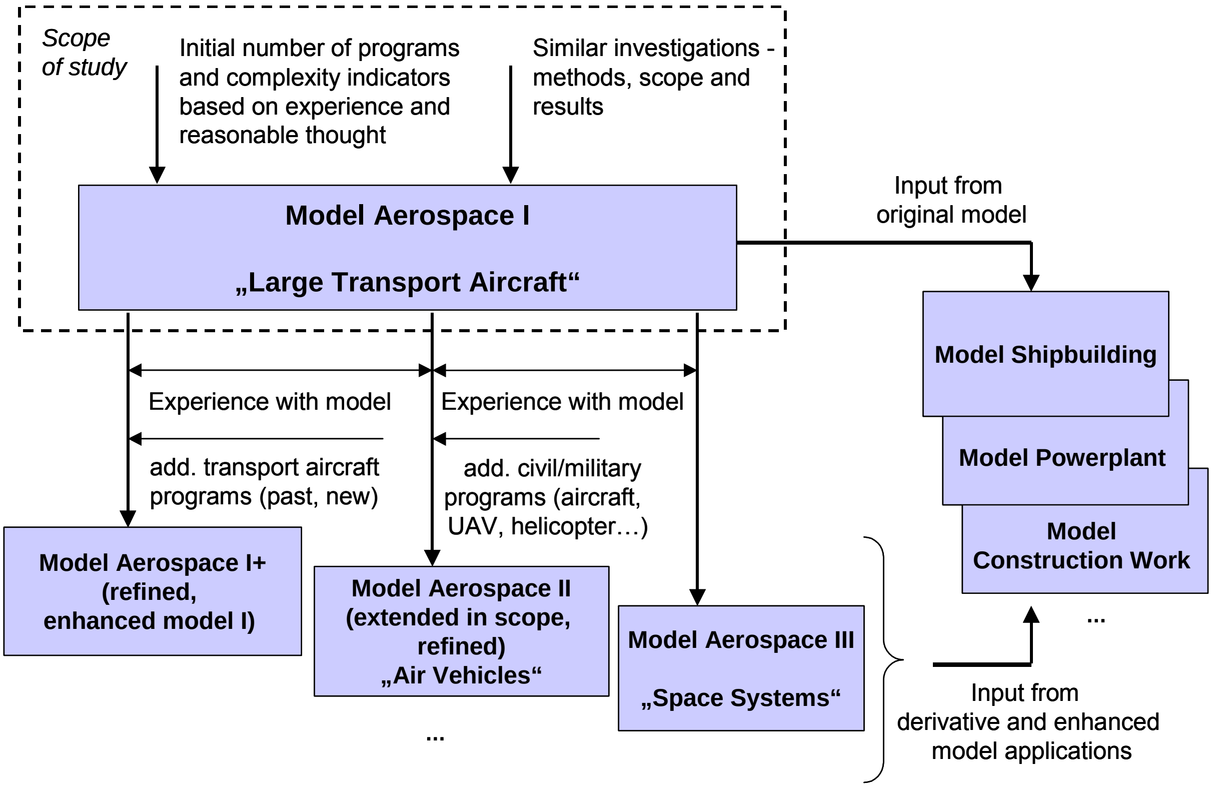

Fig. 7.1 Descendants of the Complexity Indicator method: evolution scenarios

Wing equipping EMUs and DMUs are actually only part of the picture of the development of an aircraft. To derive conclusions with validity on aircraft level one will be required to assess all areas where mock-ups are generated. The fuselage and the cabin for instance are subject to much higher customization than the wings. The variety induced by that will need to be taken into account.

Today, everybody talks about complexity and many try to cope with it systematically. Methodical approaches however, which are actually understood and applied by a larger group of practitioners, remain rare. This study tries to fill that gap – at least partially. It can be a starting point for both: for those interested in applying theoretical complexity concepts to real and practical problems, and for those to use it as a method with which actual business facts are gained and for better guiding the enterprise through today's highly dynamic business landscape.

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Appendix A Representations for 3D models to account for different design cases

Reasons for application	Application scenario	Separate 3D representation solutions	Remarks
Representation of real conditions during design, manufacturing, assembly and service	Position and orientation of geometry differs with built-in situations (e.g. due to technological properties) e.g.: flexible parts and assemblies like cables, bearings, isolation hoses, adjusted built-in position of hydraulic cylinders	Additional flexible model(s) for built-in positions: • "FLEX-part" • "FLEX-assembly"	No rework on parts/assemblies to be made to get it in the desired position; Enlargement of part naming to distinguish and reference between original and adjusted part, e.g. with suffix "FLEX"
	Parts/assemblies/components are pre-deformed, have a pre-shape	Additional model for deformed state	To be referenced separately in the product structure not to create geometry overlays; load/show on demand
	Sequences in manufacturing process necessitate the introduction of modifications on geometry in (pre-) assembled condition; e.g. positioning bolt or lugs that are subsequently removed (e.g. machined)	Creation of an "assembly-cut" model; this contains (a copy) of the original geometry with an additional subtraction model representing the machining process	Two cases to distinguish: 1. The later machining process can vary according to the area of the "cut" parts 2. The machining is independent of the installation area of the "cut" part and is always identical
Hardware and Software performance handling	Models requiring an extensive amount of bytes; exceeding capacity limits of the system; makes handling difficult due to reduced reply times and performance restrictions, e.g. complex castings	Model is split in several solids preferably at significant places without losing its logical unity; model to be represented as an assembly with n solids	Restriction of max. model size to e.g. 30 Mbytes, If all single solids are loaded together the whole part is shown correctly.
	Standard parts that are used in higher numbers in specific areas like bolts, nuts, rivets: e.g. rivet fields in aircraft skin and shell structures;	Due to higher numbers and relatively little information in respect to analysis of the structure standard parts are represented by one part	Amount to be grouped depends on trade-offs for comfortably changing and updating these parts; parts can be specifically suffixed
Simplification for the design work	Environment geometry is needed (e.g. for studies) without frequent changing; Drawing creation of large assemblies after parts have been released;	Creation of an auxiliary "environment-model": surrounding parts and/or assemblies copied in one model; Or: generation of a "merged models" e.g. at assembly level, in data reduced format (e.g. tessellation)	Limit of data volume as constraint; regular generation necessary even if only one "sub-part" is changed; zoning/boxing functionality as alternative
Differentiation of 3D models	3D geometry that originates from a different CAD system (and has been converted to company CAD format)	Converted model gets as suffix telling the origin, or part node in Product Structure gets different color	This is important to tell (especially in large product structures) whether a model comes from in-house or external environments

Appendix B Electronic Data Interchange (EDI)

In former days a lot of paperwork was exchanged between the customer, the contractor and the supplier. Step by step it was replaced by electronic linkages that nowadays often go via the Internet. Digital technology now enables close partnering between different organizations throughout project life. Suppliers can access a company's database (e.g. an Extranet) to get the latest information and updates. This can comprise documents (methods, schedules…) and configuration files for software packages. The content of an Extranet changes dynamically reflecting changes and innovations occurring in the wake of project progress. In general, five EDI integration levels can be differentiated.

Table B1 Levels of EDI integration (based on Weid (1994))

Integration level	Characteristic	
Classical data exchange	Communication channel is the mail service with physical transport: Paper, data storage mediums (CD-ROM, tapes), fax (special form: transport electronically)	
Door-to-Door EDI (EDI Level 0)	Data send electronically, but not incorporated in receiver information system; messages printed out, incorporation is extra step (data input done by special programs)	
Classical EDI (EDI Level 1)	Data transmitted electronically, incorporation in receiver database possible provided formats are correct (sometimes conversion to in-house formats necessary); file-based asynchronous transfer either online (e.g. FTP) or offline (e.g. per tape, CD-ROM)	Increasing degree of integration
Application-to-Application EDI (EDI Level 2)	Transmission electronically; no internal conversion processes necessary because sender and receiver use same EDI formats; Falls under "data *sharing*" by either having remote system access via online connection (e.g. PDM system client), or by online system data synchronization/replication	
Utilisation of common databases	Highest level of integration; no more communication in classical sense, as no more data are exchanged; no more partition in sender and receiver	

Large projects are characterized by dislocated engineering and manufacturing work, different processes and a heterogeneous tool environment. The prime contractor might have several (risk sharing) partners and numerous suppliers. To perform synchronized development work it is therefore very important staying constantly in tune with each other. This goes beyond the necessary build up and cherishment of communication links. Without an increased integration level of EDI, no effective Concurrent Engineering and Design-in-Context can be done.

Data and information interchange

The emergence of EDI varies with development phases. In the early phases rough estimations and other preliminary data are exchanged, usually not quite often. The quantity of data is rather low and so is the exchange frequency, and there are just a few participants. This changes radically once the project ramps-up and is in high gear. Data have to be provided by and to a many participants in large quantities often on a just-in-time basis to enable concurrent working. The determining factors are outlined in the figure below:

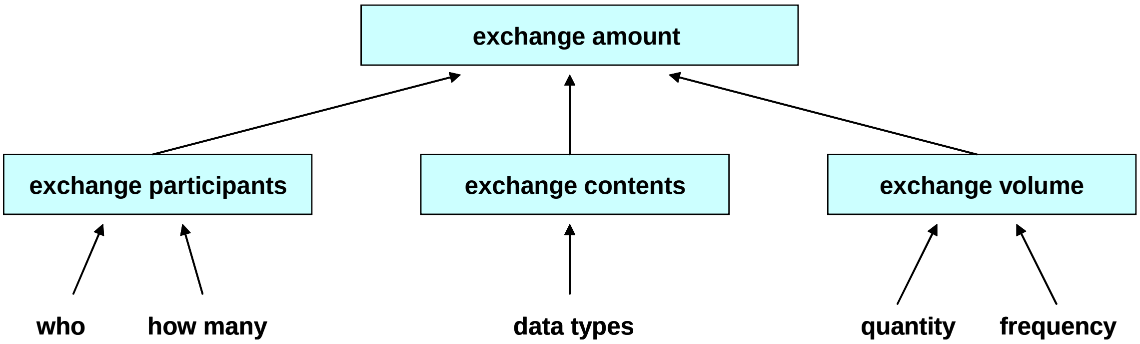

Fig. B1 Factors determining the emergence of data exchange (based on Weid (1994))

Large companies may be able to “dictate” the tool-set that shall be used (for a specific project). But the more partners and suppliers are involved (especially during ramp-up) the more difficult it is to have one set of commonly agreed tools. No company will just for the sake of one project completely change its toolset (and associated methods and procedures) but rather add the new ones to the inventory to satisfy exchange requirements.

Interactions of major players in EDI environments

Partnering companies agree on a set of issues that are valid throughout project life (maybe with time stamp). Many are organizational (e.g. work share) but all directly or indirectly affect the way of working for the teams. Suppliers usually have to comply (in one way or the other) with the environment defined by their customers (there are many exceptions today e.g. due to the overall heterogeneous tool environment and their status within the project).

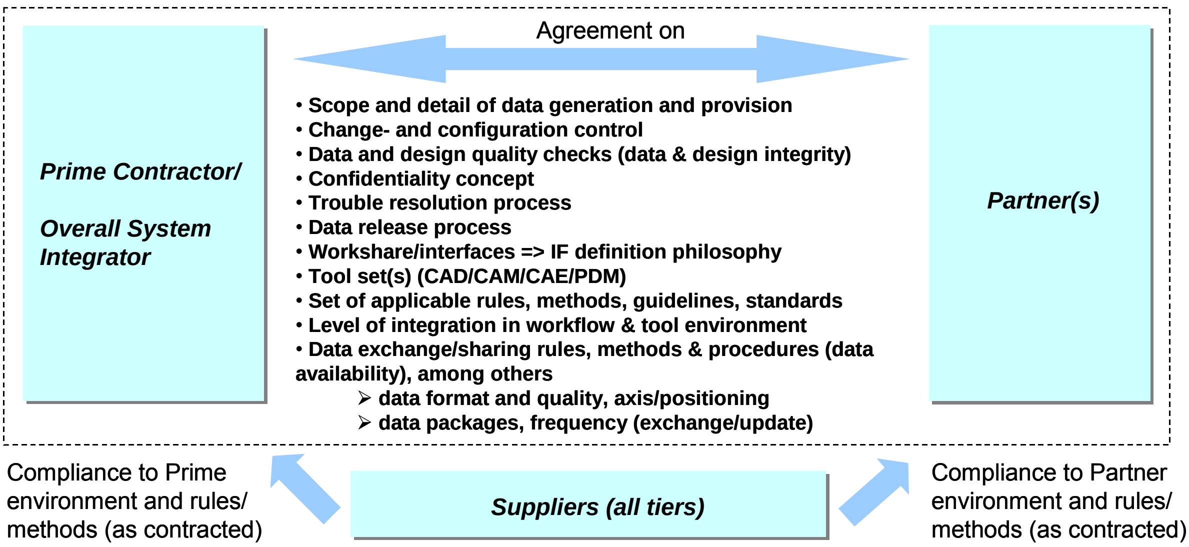

Fig. B2 The Prime-Partner-Supplier relationship in large development projects in principle

From a prime's DMU point of view it has to be clearly defined what a supplier has to deliver, in what format and quality, how (via which interfaces, using what technology), when, how often and who are the key contacts. Corresponding requirements, methods and definitions have to form part of any agreements (e.g. MoU –Memorandum of Understanding) and official contracts. Specific *security* demands of certain projects (e.g. military programs) might require additional restrictions. Manufacturers and integrators of sophisticated systems are the first to be held accountable against authorities. It is therefore in their interest to keep control over the design (at least to a certain level) before and after release to know exactly what is built in the systems[42].

Some *lessons learned* from recent years of DMU operations are becoming best practices to cope with increasing demands of exchanging and sharing information:

- Suppliers are chosen not only based on the cheapest offer but on the ability to deliver the DMU (and any other design data) within a concurrent environment. That could mean that not the cheapest but the *overall best offer* will win.

- Data Exchange/Data Sharing is recognized as a key enabler of concurrent engineering and therefore forms an integral part of contracts. In the wake of global agreements it is clearly specified what to provide/exchange, how, when and how often.

- All suppliers are informed as early as possible about any changes in the primes' tool environment (new CAD or PDM system, new releases, methods…). When a program gears up, so will the supply chain.

- People need to be trained to provide the data quality that is required. Design and data exchange people alike must be able to feed the information channel correctly, even under heavy workload. Only then can overall time delays and risks be reduced.

[42] The deliverables are therefore 3D models of detailed parts, sub-assemblies up to components with their product structure, and corresponding 2D drawings for manufacturing if required. Even if 3D models and 2D drawings need not be approved by the prime and not released via the prime's release system (PDM system) the DMU is required for interface design, analysis and documentation purposes.

Appendix C Electronic Data Management

The management of product data is done by Engineering Data Management or Product Data Management (EDM/PDM)[43] systems. Their job is to "*manage information of different kinds and from different origins in a lasting relationship dynamically over the whole life-cycle*". (Schöttner, 1999).

EDM/PDM systems differentiate between so-called *metadata* and *files*. Metadata are describing, classifying data and attribute information for the management and organization of files. They are managed in databases and represent information e.g. about the creator, creating date, release status and storage location. They reference those files that actually define the product such as 3D CAD models, technical drawings, bill-of-materials, text files etc.
The files on the other hand are stored in so-called "vaults", in a secured area of the system.
The format can either be proprietary of the generating system or neutral and standardized other formats (e.g. IGES, STEP, TIFF).

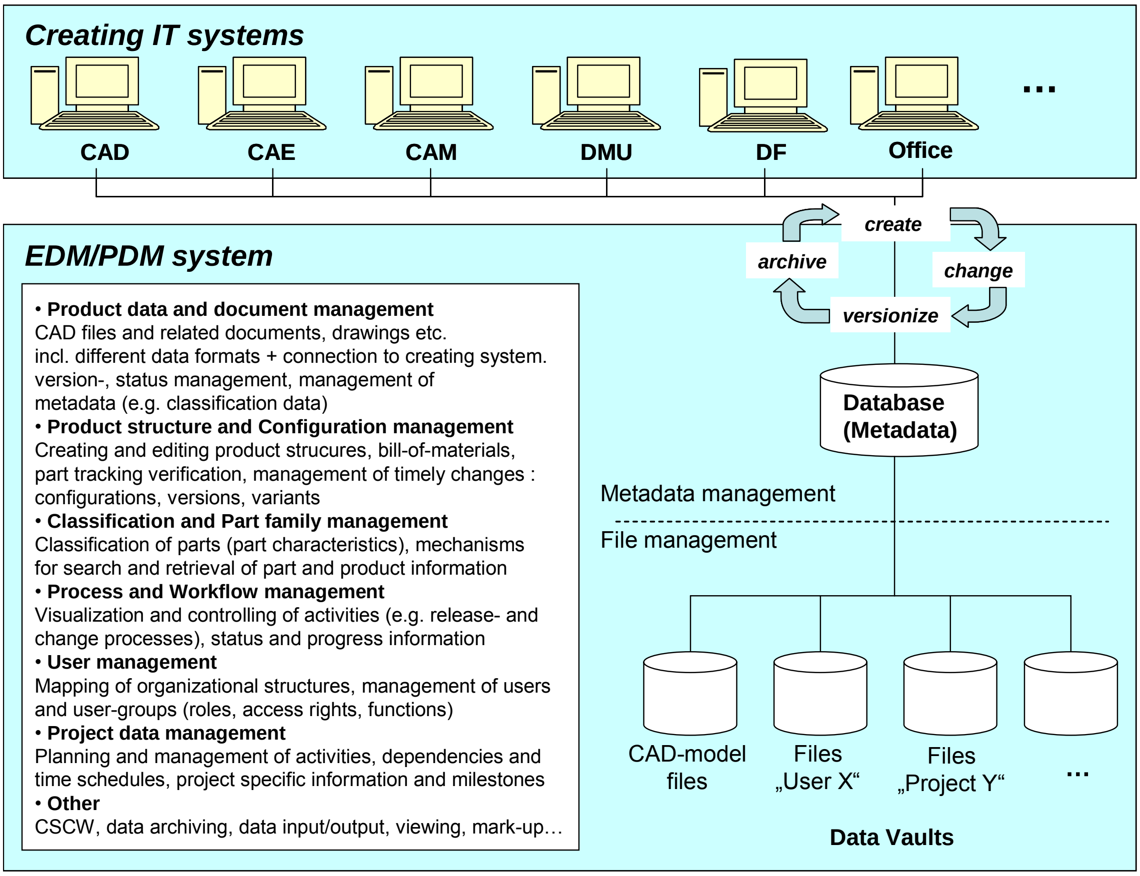

Fig. C1 File and metadata management within EDM/PDM systems with overview of the content of functional modules (based on VDI 2219 (1999))

[43] The difference between the two forms is that EDM focuses more on the management of "Engineering" data where as PDM system focus all development processes. The difference is diminishing more and more as system providers have extended either functionalities to both sides. Another term is TDM (Team Data Management). That is the management of data for a particular team. Though as an approach sometimes still used, TDM are gradually replaced by EDM/PDM systems having more applications and managing more teams.

EDM/PDM systems have particular importance for the Digital Mock-up. They allow the storage, retrieval and manipulation of multiple layers of information for everybody in the project[44]. Their functionalities enable data to be linked to product structures, which in turn represent a cornerstone of concurrent work by different people. Expert knowledge from a variety of fields is therefore available and accessible.

[44] EDM/PDM systems today support distributed or federated working. In that respect database systems can have different architectures. *Distributed* EDM/PDM systems have a hierarchical structure with a main server, sub servers and clients. An overarching database on the main server is to avoid logical ambiguities and has to ensure data integrity. *Federated* system architectures on the other hand have servers and databases with equal rights. They are a compound of individual installations that can be based on different EDM/PDM data models. (VDI 2219)

Appendix D "CXIs not taken" and further Complexity Indicators

This is a list of possible CXIs from different levels of detail that came up in the wake of searching for adequate indicators for that study. The reason why they were not taken was that the situation did not differ enough for certain subdivisions (and one condition was taken for granted for all projects), or the indicators were not relevant factors at all. But they can stimulate thought for future assessments. Subdivisions are therefore neither detailed any further nor are numerical complexity values assigned to them (only relative degrees are presented).

Table D1 Further Complexity Indicators

CXI Name	Definition	Proposal for Subdivisions	Relative contribution to Complexity
Decision responsibility	Responsibility to take decisions on design and progress with/without relying on higher authority (above the usual coordination level)	• Full decision authority • Partial decision authority • No decision authority	Low Medium High
Design flow smoothness	Breaks in the workflow per team, per system or per component; e.g. one team doing conceptual design, another preliminary design, a third doing detailed design and a fourth generating technical drawings	• Number of breaks	The more breaks the higher the complexity
A priori number of data available	Drawings/DMU data from Interface partners available at beginning	• Everything available, readily usable • Partially available and usable • Nothing available or usable	No / low Medium High
Culture	Different cultures that dominate business lives and social behaviour (business and social culture)	• Same culture • Different but known cultures • Different and new cultures	Low Medium High
Language	Languages that are spoken throughout the project environment	• Same language • Different languages but English as lingua franca • Different languages with dedicated interpreters necessary	No Low / Medium High
Development Philosophies	Following a single development process / plan / paradigm / philosophy or multiple ones. In the latter case the playing rules are considerably different and to synchronize development efforts and company specific processes can be very challenging	• one general philosophy with details the same for everyone in the game • one "umbrella" philosophy plus local variations • Different philosophies	Low Medium High
Application of Project Management	The intensity of application of PM principles and techniques within a project (incl. suppliers), e.g. establishment of an Integrated Master Plan, Resource Plan etc…	• Basic application • Advanced application	Medium Low
Application of Systems Engineering	The intensity of application of SE principles and techniques within a project	• No, insignificant • Basic • Advanced, extensive	High Medium Low

CXI Name	Definition	Proposal for Subdivisions	Relative contribution to Complexity
Application of Knowledge Management	The intensity and standardization of principles and techniques to capture, store and process any kind of knowledge and experience from within the project and from outside and making it available to everybody involved	• Basic, normally through personnel and company documentation procedures • Advanced, with dedicated processes, tools, and with adequate minded of personnel supporting the KM efforts	Medium Low
Materials & Processes	Standardizations in the way materials are processed, tested and procured. This comprises one or several measurement systems.	• Same • Different	Low High
Access to Research and Test & Evaluation facilities	Ability to do research work, tests and evaluations making use of the facilities themselves and their personnel.	• Priority access • Normal access (including waiting list) • Access restrictions (can be further detailed in minor/partial/local restrictions up to complete prohibition of access)	Low Medium High
Secrecy levels	If information is restricted to a few people then more effort is needed to maintain and supervise that secrecy and the higher will be the level of intransparency, incompleteness and wrong hypothesis. On the other hand not everyone on a project needs to know confidential or secret information to perform his/her work.	• No Secrecy / Confidential (e.g. company confidentiality) • Secret • Top Secrect	No / Low High Very High
Industrial Base	All companies with the required knowledge, experience and resources that significantly contribute to a project. In a prosperous environment at least dual-sourcing shall be maintained for a component as a minimum requirement.	• Vast, established • Reduced to a few players • Eroded – substantial services are no longer available	Low Medium High
Usage of classified hardware (e.g. materials) and/or software	As soon as classified material is used there will at least be higher levels of intransparency for a great many people on the project. But this can be deliberately sought to keep competitive advantages and to make espionage more difficult	• No • Yes (extent of usage can be further differentiated)	Non existent High
Result dependent on major external stimuli	This indicator shall take into account developments that have/had an impact on the project outcome. E.g. increased work with authorities, institutions, legal suites, compensational agreements, terrorist threats/attacks, environmental catastrophes, mergers/acquisitions…	• No dependence • Minor dependence • Major dependence	No Low High/ Very High
Market restrictions	Restrictions to enter a market or to seize a business opportunity (e.g. stronger state involvement, tougher regulations, higher taxes, customs and fares, adaptations product/service…) more than usual market differences	• No • Small • Strong	No Low High

CXI Name	Definition	Proposal for Subdivisions	Relative contribution to Complexity
Requirements Creep	That is change rate of requirements over time, notably *after* the project got its "GO". (often denoted as "dRequirements/dt"); e.g. if product has to perform more/different tasks than planned: new objectives or a new strategy force an air superiority fighter to become a fighter-bomber as well	• No • Insignificant • Significant • Substantial	No Low Medium High/ Very High
Technology Creep	That is the change rate of technologies over time, notably while the project is in full gear, and takes longer then anticipated ("dTechnology/dt"). E.g. better computer processors become available	• No • Insignificant • Significant • Substantial	No Low Medium High/ Very High
Substantial Re-organizations	Changes in the organisational structures affecting the effectiveness and efficiency of the team and contributing to dynamics, wrong hypothesis and incompleteness (not meant hereby are regular structural adoptions taking place again and again, usually with the aim to better face specific situations and thus increase effectiveness and efficiency)	• No • Significant re-structuring • Major restructuring (this also depends how its is introduced: gradually with intense personnel involvement or as "big band" virtually over night)	No Medium High
Resources Availability	That is the rate of available resources - mainly budget and people; e.g. project under funded, not adequately staffed, severe deviations in availability…	• Yes, adequate • Minor shortfalls • Substantial shortfalls	No Medium High/ Very High
IS/IT infrastructure	This refers to the capability to cope with the high demands of information compression, processing and distribution	• Ok, has enough reserves/can be extended as necessary • Working on limit • Inadequate for higher demand of project	Low Medium High
Number of sites involved	Amount of own, partner and supplier sites that are involved in the project; services, data or hardware can therefore be provided from more than one site (E.g if the design is done in one location and the manufacturing in another). More sites usually increase the complexity as there more elements in the play, higher challenge for communication network; A supplier being fully co-located will not be counted with his home-base(s).	• One site per partner/supplier • Two sites per partner/supplier • Multiple sites per partner/supplier	Low Medium High
Partner/supplier Creep	That's the rate of change for new partners/suppliers entering the game and others dropping out	• No • Minor/Insignificant • Significant	Low Medium High
Sites Creep	That's the change rate of sites involved- this is usually coupled with the parameter "partner/supplier creep"	• Less sites • No • Few more • Many more	Very Low Low Medium High

CXI Name	Definition	Proposal for Subdivisions	Relative contribution to Complexity
Level of Customization	That's the degree to which the products have to be customized for different customers: Three generic areas shall be taken as basis: 1) standard/regular items being on board in each product 2) catalogues options offered for pre-determined customization 3) customer specifc options/adaptations	• Only standard and catalogue options chosen • Minor customer specific options chosen • Major customer specific options/adaptations	Low Medium High
Number of organizational interfaces	Could be number of teams involved (on prime contractor side) Rational is that more organisational interfaces for the certain area (in the case study the Leading and Trailing Edges) will increase subjective and objective complexities as more players are involved	• More than usual • Normal • Less than usual	High Medium Low
Subcontracting Level	Make vs. Buy ratio (as this is somewhat ambiguous it is not taken as a complexity indicator for this study: Doing everything alone (=100% Make) may keep the overview and control, but the very reason for subcontracting usually is that the work cannot be done alone, due to lack of knowledge, resources or will. 100% Buy involves less overview, control, transparency (at least temporary) so complexity is increased here as well. Every company will have a unique subcontracting level around the optimum for its business processes to cope with. Here, in a generic approximation, a 50/50 ratio shall be taken as level of least complexity	• 100% Make • 75% Make • 50/50% Make/Buy • 75% Buy • 100% Buy	Very High High Medium High Very High

Appendix E   Calculations and Assumptions

- The *part geometric complexity* list is based on a similar categorization in Younossi et. al. (2001, pp. 70-72) as a step for deriving data for the estimation of military airframe costs. Some engineering and technical judgement is required to assign any given part to one of the four categories. The assignment was done for hardware components as well as for digital 3D models. For that it was assumed that part shape complexity can roughly be regarded as proportional to the effort designing it (in 3D).

Table E1   Part complexity categories

Complexity Category	Characteristics	Examples
Simple (s)	• monolithic • minimally contoured	Covers, doors, simple fittings, flat skins, panels, (sheet metal) brackets, tubes, boxes…
Medium (m)	• surfaces with moderate curvature and thickness • stiffeners and cut-outs • parts with moderate amount of unitization	Contoured skins, equipment trays, floor panels, bearings, shafts, fuel ducts, stiffened skins…
Complex (c)	• surfaces with complex curvatures • primary internal structures • extensive amount of unitization • complex mould parts	Beams, bulkheads, frames, ribs, inlet ducts, longerons, pylon fittings, spars, webs, 3D curved tubes/routings, actuators…
Very Complex (vc)	• extensive dimensional control & tolerance requirements (e.g. to keep aerodynamic shape) • multi-curvature shapes	Flaps, Slats, intake diverter lips, spindles…

Note: Not all characteristics of a category are necessary to assign a complexity category. Calculation of the CXI *"Type of parts in mock-up":* all relevant structural items and system installation elements of the six wings leading- and trailing edges were counted and categorized in one of the above mentioned four part geometric complexity groups. Respective part amounts were then multiplied with numerical category values (subdivision values). The sum of all was then divided by the total amount of parts, yielding values between 0 and 1:

E.g. for program A (mock-up): (58*0.25 + 107*0.5 + 183*0.75 + 2*1) = <u>206.5</u>

Table E2   Part complexity breakdown and results (from C onwards nearly 100% of parts were already put into the mock-up, therefore no separate calculation)

	A	B	C	D	E	F
total s-m-c-vc (real wing)	90s, 183m, 224c, 8vc	117s, 225m, 238c, 11vc	113s, 209m, 232c, 12vc	318s, 293m, 389c, 18vc	77s, 102m, 141c, 4vc	126s, 218m, 223c, 11vc
result	289.9	325.6	**318.6**	**535.5**	**179.8**	**318.5**
total s-m-c-vc in mockup	58s, 107m, 183c, 2vc	63s, 172m, 186c, 2vc				
result	**206.5**	**243.2**				

- *Kinematics complexity* refers to the type movement a component is subjected to over its motional envelope. In general, motions in a 2D plane are assigned lower complexity levels than motions in 3D space and coupled motions (rotation and translation).

Table E3 Kinematics complexity categories

Complexity Category	Characteristics	Examples
K1	No movement – static (zero complexity)	Fixed build-in parts
K2	2D rotation or 2D translation	Droop Nose rotating around a hinge line
K3	2D rotation and 2D translation	Fairing linkage
K4	3D rotation or 3D translation	Rearlink (connecting Flap and Flap track beam)
K5	3D rotation and 3D translation	Fowler Flap

Calculation of the CXI "*Kinematics complexity*": all structural and system elements were evaluated on their movement or non-movement. Equal to the above mentioned "Type of parts in Mock-up" respective parts were attributed kinematics complexity categories, which were then multiplied with these category values (subdivision values). The sum was then divided by the amount of moving parts (categories K2-K5), again yielding values between 0 and 1. To account for programs having movables only on trailing edges (here only program E) and therefore keeping the appropriateness with other wing configurations, a factor had to be introduced: "1" for movables on leading and trailing edges and "0.5" for movables only on trailing edge.

E.g. for program A (mock-up):

[275*0 + (56*0.25 + 19*0.5 + 0*0.75 + 0*1)] *1 (factor) = 22.8

Table E4 Kinematics complexity results

	A	B	C	D	E	F
total kinematics (real wing)	367k1, 84k2, 52k3, 0k4, 2k5	453k1, 87k2, 54k3, 4k4, 3k5	419k1, 86k2, 54k3, 4k4, 3k5	822k1, 117k2, 71k3, 5k4, 3k5	286k1, 27k2 7k3, 4k4, 0k5	425k1, 96k2, 50k3, 4k4, 3k5
result	44	54.6	**54.4**	**71.5**	**6.6**	**54.9**
total kinematics in mockup	275k1, 56k2, 19k3, 0k4, 0k5	340k1, 72k2, 11k3, 0k4, 0k5				
result	**22.8**	**24.5**				

- *Number of components ratio*: This CXI shows how much of the real wing had been modelled in the mock-up. Results show that both Engineering Mock-ups made up around 70% of the real wing. The DMU, on the other side, were 100% digital replicas of the wings. The calculation does not, however, take “small” items into account, such as bolts, rivets, very small brackets and fixtures or shimming plates. Only the most obvious integration relevant components were taken into account. So, for instance, an entire equipped Flap was counted a one part only, independent of the number of ribs, spars, skins, rivets and other items internally and externally of what is was build.

Table E5 Reference part count and component ratios

	A	B	C	D	E	F
total (real wing)	505	601	566	1018	324	578
total in mock-up	350	423	566	1018	324	578
ratio	**0.693**	**0.704**	**1**	**1**	**1**	**1**

- *Moving components ratio*: This CXI is calculated by dividing the fixed build in parts (static) from the moving parts in the mock-ups.

Table E6 Moving components ratios

	A	B	C	D	E	F
total moving parts	75	83	147	196	38	153
total MU parts	350	423	566	1018	324	578
ratio	**0.21**	**0.196**	**0.26**	**0.192**	**0.117**	**0.26**

- *Integration Density (Aircraft - mock-up):* The values of relative nature due to lack of crucial basic data on volumes of leading and trailing edges. Some assumptions are engineering judgement, data for the volume approximation are taken from respective Aircraft Maintenance Manuals (AMM) or technical specifications: total fuel capacity (1 litre = 1 dm^3) is divided by three (one for each outer wing, one for the centre wing tank and trim tanks). For a complete wing box volume 10% are added to account among others e.g. for ventilation tanks. Wing box volume is assumed to be 70% of the entire half wing (80% for wings without a movable leading edge, here only program E). Last but not least leading and trailing edge volumes are assumed to consume about 30% of the wing’s volume. The amount of mock-up parts is then divided by the remaining volume to derive parts per cubic metre.
  E.g. for program B:

$$139.56 / 3 = 46.52;\ 46.52 + 10\% = 51.172;\ 51.172 * 100/70 = 73.10;$$

$$73.10 * 0.3 = 21.93\ m^3;\ 423 / 21.93 = \underline{\underline{19.3}}\ \text{parts}/m^3$$

Table E7 Integration densities

	A	B	C	D	E	F
Total fuel capacity [litre]	61090 = 61.09 m^3	139560	194878	310000	64030	139560
total parts (in MU)	350	423	566	1018	324	578
density [parts/m^3]	**40.5**	**19.3**	**18.5**	**20.9**	**36.8**	**27**

- Calculation of *(non-recurring) costs*: Reliable cost data were only partially available, and only for a few campaigns. Therefore, some reasonable extrapolations had to be made. Real data came from written evidence of expenditures for *material* and *labour*. Some cost indications were taken from the *hours* spent for design and manufacturing work and for quality assurance (especially for EMUs), and some from *planned* costs and hours. Several factors were taken into account: *size* of the wing (taking respective *reference part counts), mock-up category*, and money *inflation* over the years (in average 2% p.a.). Results were rounded off. Values are equivalent to economic conditions as of 2005 to compare what the campaigns would cost in that year. Program A was calculated backwards with B as basis, C acts as fix-point for forward calculations (or better: estimations) of D, E and F.

What was reliably known:

1) Expenditures for B1 (9); B2, the refurbishment for twin-engine plane (4.5); all in all B cost about 13.5; B2 however, isn't taken into account for the statistics, as a refurbishment of a mock-up was unique and limited to program B;

2) DMU campaign C was *planned* to cost half as much as the EMU campaign B1 did cost (= 4.5), which would actually have been the price tag, if not:

3) C in the end cost more than double the estimation due to unplanned expenditures for the additional generation of 2D drawings of which the 3D CAD system was then not capable => denoted "<u>C</u>"

Further assumption: expenditures depending on mock-up category factor: Cat I = 0.8, Cat II = 0.9 and Cat III = 1; This means less detailed Cat I mock-ups consume less budget than higher category mock-ups.

For instance, calculation of costs for A; (for D, E and F costs of program C are taken):

$$\text{cost(A)} : \text{size(A)} * \text{MU cat.(A)} = \text{cost(B1)} : [\ \text{size(B1)} * \text{MU cat.(B1)} + \text{cumul. inflation}]$$

with 10 years and in average 2% inflation each => 20% of 9 => 1.8;

$$\text{therefore: cost(A)} = 9 * [0.61 * 0.85 / (0.74 * 0.95 + 1.8)] = \underline{1.85} \text{ (then-year)}$$

Table E8 Costs and cost factors

	A	**B1**	**C**	**<u>C</u>**	**D**	**E**	**F**
Reference time scale	1980	1990	2000	2000	2005	2005	2005
Delta years	-10	Basis pre B	Basis post C		+5	+5	+5
MU category	I/II	II/III	III	III	III	III	III
Category factor	**0.85**	**0.95**	**1**	**1**	**1**	**1**	**1**
Part count (MU)	350	423	566	566	1018	324	578
Size factor	**0.61**	**0.74**	**1**	**1**	**1.79**	**0.57**	**1.02**
2% Inflation p.a. cumulated	**50%**	**30%**	**10%**	**10%**	**0%**	**0%**	**0%**
Then-year result	1.85	9	4.5	10	5.5	1.77	3.16
EC 2005 Result	**1.4**	**6**	**2.5**	**5.6**	**2.8**	**0.9**	**1.6**
Relative to B	**0.23**	**1**	**0.42**	**0.93**	**0.47**	**0.15**	**0.27**

- *Mock-up campaign time*: That's the time from start of the campaign to its formal end, or to a defined end-point, in this case the start of final assembly. Mock-ups, in reality were often used further on, especially when regarding the CDMU, which is constantly updated in the wake of the programs' life cycle. Dates are taken from official planning schedules.

Table E9 Campaign times

	A	**B**	**C**	**D**	**E**	**F**
months	25	32	23	30	42	37

Appendix F The Cross Impact Matrices for campaigns B and D

	B		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
	0=neutral/no 1=weak 2=medium 3=strong impact		Type of parts in mock-up	Integration density A/C-Mock-up	Design-in-Context	Draw-ing tool use	Mock-up Class Category	MU Operat-ional policy	Kinematic com-plexity	Mock-up tasks to be fulfilled	Develop-ment software toolset change	software tool environ-ment and maturity	CAD-PDM inte-gration	Team organisa tion	A priori in-house mock-up experienc e	Number of comp. ratio	Moving comp. ratio	Config-uration simi-larity	Part commun-ality	Number of partners & subcon-tractors	Passive Sums
		Sub-div.	243.2	19.3	0.66 irreg. Incompl.	0.5 2D CAD	0.75 class II/III	0 def/impl.	24.5	0.75 tasks 1-4	0 no change	0 homogen/ establ.	1 no integ	1 no-col. funct.	0.33 exper.	0.7	0.196	0.75 low simi	1 no comm.	0.5 5-10 suppl	
1	Type of parts in mock-up	243.2		0	0	0	3	3	0	2	0	0	0	0	0	2	1	2	1	0	14
2	Integration density (A/C-Mock-up)	19.3	1		0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	0	6
3	Design-in-Context	0.66 irreg. Incompl	0	0		3	0	1	0	0	1	3	3	2	0	1	0	0	0	3	17
4	Drawing tool use	0.5 2D CAD	0	0	3		0	3	0	1	0	3	0	0	0	0	0	0	0	0	10
5	Mock-up Class Category	0.75 class II/III	3	2	0	0		3	3	3	0	0	0	0	3	3	3	2	2	0	27
6	MU Operational Policy	0 def/implem.	3	0	3	2	2		2	3	0	0	0	1	2	2	2	1	1	1	25
7	Kinematic complexity	24.5	1	2	0	0	0	0		0	0	0	0	0	1	3	3	0	0	0	10
8	Mock-up tasks to be fulfilled	0.75 tasks 1-4	3	2	3	0	3	3	2		0	0	0	0	3	3	2	2	1	0	27
9	Development software toolset change	0 no change	0	0	0	0	0	0	0	0		3	0	0	0	0	0	0	0	0	3
10	software tool environment and maturity	0 homog/estab	0	0	0	0	0	0	0	0	3		2	0	0	0	0	0	0	1	6
11	CAD-PDM integration	1 no integr	0	0	0	0	0	0	0	0	2	0		0	0	0	0	0	0	0	2
12	Team organisation	1 no-col. funct.	0	0	1	0	0	0	0	1	0	0	0		1	0	0	0	0	1	4
13	A priori in-house mock-up experience	0.33 experi.	0	0	0	0	1	0	0	2	0	0	0	2		0	0	0	0	1	6
14	Number of components ratio in MU	0.7	0	1	0	0	3	3	1	3	0	0	0	0	0		3	1	2	0	17
15	Moving comp. Ratio	0.196	0	1	0	0	3	3	3	3	0	0	0	0	0	3		1	1	0	18
16	Configuration similarity	0.75 low simil.	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0		2	0	3
17	Part commun-ality	1 no comm.	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	2		0	4
18	Number of partners & subcon-tractors	0.5 5-10 suppl	0	0	0	0	2	2	0	2	0	0	0	2	1	0	0	0	0		9
	Active Sums		**11**	**8**	**10**	**5**	**18**	**21**	**11**	**20**	**6**	**9**	**5**	**9**	**11**	**20**	**16**	**11**	**10**	**7**	
	Active Mean	**11.555556**																	Passive Mean:		**11.55556**

	D		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
	0=neutral/no 1=weak 2=medium 3=strong impact		Type of parts in mock-up	Integration density A/C-Mock-up	Design-in-Context	Drawing tool use	Mock-up Class Category	MU Operat-ional policy	Kinematic com-plexity	Mock-up tasks to be fulfilled	Develop-ment software toolset change	software tool environ-ment and maturity	CAD-PDM inte-gration	Team organisati on	A priori in-house mock-up exper.	Number of comp. ratio	Moving component s ratio	Config-uration simi-larity	Part commun-ality	Number of partners & subcon-tractors	Passive Sums
		Sub-div.	535.5	20.9	0.33 reg. Update	0 3D CAD	1 class III	1 case by case	71.5	1 tasks 1-5	1 change	1 heterog./ new	0.66 partial integr.	0.33 co-col. multidisc.	0.33 exper.	1	0.192	0.25 high simi	1 no comm.	1 > 10 suppl.	
1	Type of parts in mock-up	535.5		0	0	1	3	0	0	2	0	0	0	0	0	2	1	3	1	0	13
2	Integration density (A/C-Mock-up)	20.9	1		0	1	0	0	0	0	0	0	0	0	0	3	2	1	0	0	8
3	Design-in-Context	0.33 reg. update	0	0		1	0	3	0	0	3	3	3	2	1	1	0	0	0	3	20
4	Drawing tool use	0 3D CAD	0	0	0		1	3	1	3	3	3	1	0	3	0	0	0	0	0	18
5	Mock-up Class Category	1 class III	3	3	2	3		3	3	3	0	0	0	0	2	3	3	1	1	0	30
6	MU Operational Policy	1 case by case	1	1	3	3	2		2	3	3	3	2	3	2	3	2	0	1	3	37
7	Kinematic complexity	71.5	1	2	0	1	0	0		0	0	0	0	0	0	2	3	2	0	0	11
8	Mock-up tasks to be fulfilled	1 tasks 1-5	3	2	3	3	3	3	2		2	2	0	3	3	2	2	2	1	0	36
9	Development software toolset change	1 change	0	0	0	0	0	0	0	0		3	0	0	0	0	0	0	0	0	3
10	software tool environment and maturity	1 heterog./new	0	0	3	0	0	0	0	0	3		1	0	0	0	0	0	0	3	10
11	CAD-PDM integration	0.66 partial integ.	0	0	3	2	0	2	0	0	3	3		0	0	0	0	0	0	2	15
12	Team organisation	0.33 co-loc. mulitdisc.	0	0	1	0	0	3	0	2	2	1	0		3	1	0	0	0	3	16
13	A priori in-house mock-up experience	0.33 experi.	0	0	1	0	0	1	0	2	2	2	0	0		0	0	0	0	0	8
14	Number of components ratio in MU	1	0	3	0	3	3	3	1	3	0	0	0	0	0		3	0	2	0	21
15	Moving components ratio	0.192	0	3	0	3	3	3	3	3	0	0	0	0	0	3		2	1	0	24
16	Configuration similarity	0.25 high simil.	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0		1	0	3
17	Part commun-ality	1 no comm.	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1		0	2
18	Number of partners & subcon-tractors	1 > 10 suppl.	0	0	3	0	2	2	0	2	2	2	1	3	2	2	0	0	0		21
	Active Sums		**10**	**14**	**19**	**21**	**17**	**26**	**12**	**23**	**23**	**22**	**8**	**13**	**16**	**22**	**16**	**12**	**8**	**14**	
	Active Mean	**16.444444**																	Passive Mean:		**16.4444**