

Part Count and Design of Robust Systems

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Abstract. Systems engineering frequently includes efforts to reduce part count with the goal of cutting costs, enhancing performance, or improving reliability. This paper examines the engineering practices related to part count, applying three different theories -- the Theory of Inventive Problem Solving, Axiomatic Design, and Highly Optimized Tolerance. Case studies from the jet engine industry are used to illustrate the complicated trades-offs involved in real-world part count reduction efforts. The principal conclusions are that: 1) part consolidation at the component level has generally been accomplished as technological advancements enable them which is consistent with the “law of ideality” in the Theory of Inventive Problem Solving; 2) part count reduction frequently increases coupling among functional requirements, design parameters, and processing variables while also delivering higher reliability which conflicts with the theory of Axiomatic Design and; 3) at the overall system level, jet engine part count has generally increased in response to escalating demands for system robustness as suggested by the theory of Highly Optimized Tolerance.

Keywords: Robust Design, Theory of Inventive Problem Solving, Axiomatic Design, Highly Optimized Tolerance

1. INTRODUCTION

The purpose of this paper is to study the role of part count in systems engineering, particularly in the long-term evolution of technologically advanced electromechanical systems. In particular, this paper will explore and contrast the implications of three different theories of systems engineering as they are related to part count. Also, this paper will examine the technological evolution of jet engines in an effort to test the predictions of the theories.

Part count is defined, for the purposes of this paper, as the total number of physically separate parts in an engineering system. By this definition, a complex part with many features will count as only one part as long as it is made in a single processing step without first creating many smaller parts that are later assembled. Part count is useful to track in studying an engineering system because it is related to the challenges of initially launching a system (e.g., to manufacturability) and to the challenges of keeping a system in service (e.g., to reliability). Part count can be viewed as a surrogate for more directly useful system properties but it must be acknowledged that it can, under some circumstances, be a misleading surrogate (as will be discussed in subsequent sections).

Unique part count is defined, for the purposes of this paper, as the total number of parts with a separate identity as typically indicated by a part number on an engineering bill of materials. By this definition, an array of identical parts may contribute greatly to part count yet contribute only a little to unique part count. On the other hand, even parts made by an identical manufacturing process may take on a separate identity such as when parts are inspected and then binned according to the tolerances held. Unique part count is important in systems engineering because it creates demands on inter-functional coordination (e.g., all drawings must be signed off) and in logistics and supply chain management (e.g., unique parts must often be kept at maintenance and repair facilities).

Systems engineering efforts are frequently made to reduce part count and/or unique part count while maintaining or improving system functionality, reliability, and robustness. Part count reduction efforts are carried out by many means including:

- Consolidating multiple parts into one, more complex part,
- Eliminating a part and forcing other parts to take over its functions, and
- Dramatically re-conceptualizing the system design to reallocate functions across the subsystems and components.

Technological advances frequently enable part count reduction by some combination of the means listed above. For example, integrated circuits replaced myriad separate resistors, transistors, and diodes with a single wafer and injection molding technologies enabled scores of bosses, holes, snaps, and other functional features to be incorporated into a single part. Despite such broad trends toward part consolidation, it must be emphasized that not every reduction in part count is a step in the right direction. The systems engineering decisions regarding part count must balance issues throughout the system life cycle including technology maturity, time to market, cost (both fixed and variable), reliability, serviceability, supportability, and recycling. In particular, reliability is in direct conflict with part count when parallel redundancy is being considered.

Systems Engineers therefore seek guidance in these decisions. Design handbooks articulate simple heuristics for part count reduction. For example, Anderson (1990) defines three questions to be asked during redesign:

- When the product is in operation, do adjacent parts move with respect to each other?
- Must adjacent parts be made of different materials?
- Must adjacent parts be able to separate for assembly or service?

Such rules help the novice engineer avoid mistakes, but they fall short of what is needed in advanced systems engineering. Such simple rules admit many exceptions such as when relative motion is afforded without separate parts through elastic deformation. They also frequently fail to provide adequate guidance when different system attributes are in tension. Theories of system design might assist engineers by offering a more coherent and consistent view. The next section reviews three currently existing theories and their relationship to part count reduction.

2. PART COUNT REDUCTION IN THEORY

This section reviews three different theories related to systems engineering with a selective focus on their implications regarding part count. The three theories are: 1) Theory of Inventive Problem Solving, 2) Axiomatic Design, and 3) Highly Optimized Tolerance. This set of theories is not intended to be comprehensive, rather it is a sample of three particularly prominent theories, widely cited in the literature, that also have specific implications regarding part count.

2.1 THEORY OF INVENTIVE PROBLEM SOLVING

Altshuller proposed that engineering creativity could be made an exact science. His algorithmic approach is known as the Theory of Inventive Problem Solving, frequently referred to by the Russian acronym TRIZ or alternately referred to as TIPS. Starting in 1946, Altshuller and his collaborators studied hundreds of thousands of patents seeking patterns of innovation that would lay the basis of this theory. Since Altshuller's initial publications, there has been considerable additional development. A complete description of TRIZ and all its full state of current development would require volumes covering SuField analysis (Fey et al, 1994), the algorithm for inventive problem solving (Ariciszewski, 1988), and technology forecasting (Fey and Rivin, 1999, Mann, 2003). As TRIZ has developed, there has also been substantial divergence which by one account has resulted in 15 distinct versions of the development laws (Cavallucci, 2005). Due to these factors, a comprehensive review of the entire TRIZ literature is outside the scope of this paper. The goal of this section is rather more limited. This section presents the main ideas of TRIZ and a few details and recent developments related to part count reduction.

In the view of the authors, TRIZ was strongly influenced by the ideas that dominated the Soviet Union in the mid-twentieth century when Altshuller developed his theory. The Soviet perspective on history and social organization was based on dialectical materialism, the notion that historical and social developments are explained by clashing of theses and antitheses resulting in synthesis. Lenin wrote in the *Communist Manifesto* that repeated cycles of these conflicts would eventually lead to a perfect system of social

organization wherein no government was needed. Altshuller appears to have adopted this philosophical framework as the basis of TRIZ stating that “development of technical systems, like all other systems is subject to the general law of dialectics” (Altshuller, 1984).

A major organizing concept of TRIZ is the “law of ideality.” Just as the Soviets viewed history as a progression toward an ideal state with no need for government, Alschuller proposed that technical systems tend toward an ideal final result which “requires no material to be built, consumes no energy, and does not need space and time to operate” (Altshuller, 1984). Altshuller’s “law of ideality” is frequently interpreted as governing a ratio of useful functionality to a sum of harmful effects and/or costs (Cavallucci, 2001, Clausning and Fey, 2004,). Thus, TRIZ allows for part count increase if the additional parts adequately compensate for their presence by means of greater function or reduced harmful effects. Salamatov (1999) noted that technical systems frequently exhibit and “expansion period” (in which function expands ad the expense of simplicity) followed by a “convolution period” (which superficially appears to be simplification but in reality retains useful functions while better respecting constraints on physical, economic, and ecological complication. Mann (2000a) hypothesized that part count should reach an apex at the time marked by an inflection in the technology “S-curve.”

To accelerate the progression toward ideality, TRIZ includes a great deal of supporting detail. Consistent with the framework of dialectics, in TRIZ, inventions are classified according to how they resolve underlying conflicts or contradictions. For example, one major class of conflicts involves a tool acting usefully on an object, but such action is accompanied by a harmful action as well. Three major tactics for resolving this conflict are listed below and depicted in Figure 1:

1. Eliminate the object so the tool is not needed anymore.
2. Eliminate the tool and assign the useful action to the object.
3. Eliminate the tool and assign the useful action to the environment.

These three major tactics are all consistent with part count reduction, but the next levels of supporting detail are mixed in this regard. Altshuller proposed 40 inventive principles for conflict elimination. Some of these principles are consistent with part count reduction. For example, the principle of joining suggests “joining homogeneous objects or those destined for contiguous operations.” However, many of the conflict resolution “principles” in TRIZ involve increased part count. For example, the “principle of fragmentation” includes “dividing the object into independent parts” (Altschuller, 1984). Similarly,

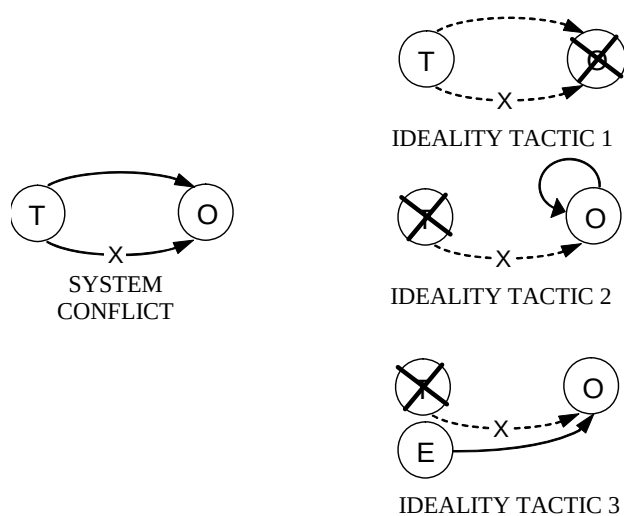


Figure 1. Tactics for resolving system conflicts (adapted from Clausning and Fey, 2004).

the principle of the “previously placed cushion” states that one may “compensate for the relatively low reliability of an object by accident measures placed in advance” (Altschuller, 1984). By one account, the inventive principles that increase part count outnumber those that reduce part count (Mann, 2000b). Nevertheless, when a product is sufficiently mature, it is generally held that TRIZ provides a useful set of tools to aid in part count reduction, especially when used in concert with analysis strategies such as Design for Manufacture and Assembly (Lucchetta et al., 2005).

As discussed in this section, relating TRIZ to part count is challenging. As Cavallucci (2005) noted “the original texts on the subject are vague” and the views of the theory are manifold. In addition, the supporting details of TRIZ are mixed with regard to part count. However, the “law of ideality” strongly supports part count reduction, at least over the long term. In the near term, part count increases can be consistent with TRIZ if performance or side effects are improved enough to warrant the additional parts. But if a technology becomes mature so that increments in performance are necessarily small, then the additional improvements in the ratio of functionality to harmful effects and costs would seem to require part count reduction. More specifically, Mann (2000a) hypothesized that part count should reach an apex at the time marked by an inflection in the technology “S-curve.”

2.2 AXIOMATIC DESIGN

Axiomatic Design (AD) is a theory of design proposed by Suh (1990). Just as TRIZ seeks a scientific foundation for creativity, AD seeks a scientific basis for engineering design but on an axiomatic rather than an algorithmic basis. An algorithmic approach, such as TRIZ, defines step-by-step procedures for a designer to follow. By contrast, an axiomatic approach identifies primitive propositions and seeks to develop theorems from the primitive propositions by deduction.

Axiomatic Design posits the existence of four domains (Suh, 1990) – the customer domain, the functional domain, the physical domain, and the process domain. Design is viewed as mapping between pairs of domains where (in Fig. 2) the domain on the left is “what we want to achieve” and the domain on the right is “how we propose to achieve it.” For example, the functional requirements (FRs) are the minimum set of independent requirements that characterize the design goals. The design parameters (DPs) are the key variables that characterize the physical entity created by the design process to fulfill the FRs. Therefore, the design of a product is the mapping from FRs to DPs. Similarly, the design of the manufacturing system involves selecting process variables (PVs) to satisfy the DPs.

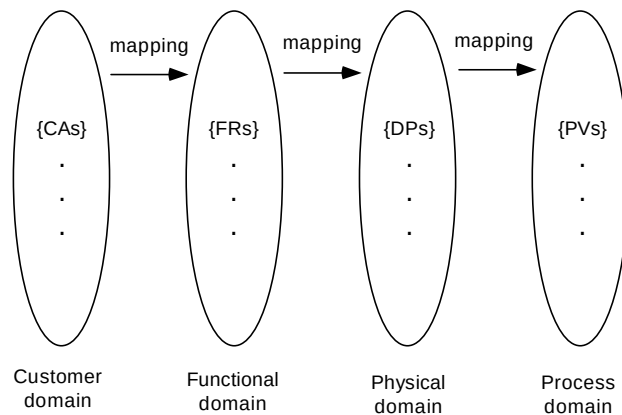


Figure 2. The four domains in Axiomatic Design.

According to Suh, the mapping from the functional domain to the physical domain can be represented by the design equation $\{\mathbf{FR}\} = [\mathbf{A}]\{\mathbf{DP}\}$. The elements of the design matrix are defined as the partial derivatives of the functional requirements with respect to the design parameters $\mathbf{A}_{i,j} = \partial \mathbf{FR}_i / \partial \mathbf{DP}_j$.

Suh defines an *uncoupled design* as a design whose $\mathbf{A}$ matrix can be arranged as a diagonal matrix by an appropriate ordering of the rows and columns. He defines a *decoupled design* as a design whose $\mathbf{A}$ matrix can be arranged as a triangular matrix. He defines a *coupled design* as a design whose $\mathbf{A}$ matrix *cannot* be arranged as a triangular or diagonal matrix. Based on the structure of this design matrix, $\mathbf{A}$, Suh defines what he calls the “independence axiom.” He states that an *uncoupled design* satisfies the independence axiom, that a *decoupled design* satisfies the independence axiom as long as changes in the DPs are performed in the appropriate order, and that a *coupled design* does not satisfy the independence axiom.

In addition to the “independence axiom,” Suh (1990) proposes the “information axiom” embodied by the imperative to “minimize information content.” This axiom is frequently misinterpreted as governing descriptive complexity of the design, but in fact, it has quite different implications. The information axiom depends on Suh’s definition of the information content of a design. Within Axiomatic Design, the probability that a product can satisfy *all* of its FRs is called the probability of success (p_s). Based on the notion of probability of success, information content I is defined as $I = \log_2(1/p_s)$. Given the definition of information content, the theory of axiomatic design includes the following “theorem” – “The sum of information for a set of events is also information, provided that the proper conditional probabilities are used when the events are not statistically independent” (Suh, 1990).

The independence axiom and the information axiom are interrelated. For example, Suh states that the “information content of an uncoupled design is independent of the sequence by which the DPs are changed to satisfy the given set of FRs.” An even stronger claim relating the independence and the information axioms is “when the state of FRs is changed from one state to another in the functional domain, the information required for the change is greater for a coupled process than for an uncoupled process” (Suh, 1990).

There has been an effort to relate Axiomatic Design and TRIZ. Mann (1999) explored the compatibility between the two theories concluding that: 1) Axiomatic Design offers TRIZ practitioners a means for problem definition and the handling of multi-layered problems; and 2) TRIZ offers practitioners of Axiomatic Design a means to develop candidate DPs once FRs are defined. Along similar lines of reasoning, a hybrid methodology has been proposed merging Axiomatic Design with TRIZ and also with robust design and Reliability Centered Maintenance (Sarno, et. al, 2005). In this hybrid, once again, TRIZ is primarily employed as a tool for developing solutions within a process structured via Axiomatic Design.

The theory of Axiomatic Design has specific implications for part count reduction. It is clear that any design having fewer DPs than FRs must be coupled and hence unacceptable according to the theory. However, the theory does not hold that each DP requires a separate part. This is made more explicit in Suh’s “Corollary 3 (Integration of Physical Parts)” which calls for integrating design parameters into a single physical process, device or system, but only when the Independence Axiom can be satisfied. In

other words, part count reduction can and should proceed by consolidating multiple DPs into a single part but only if the resulting design matrix has the required structure. Therefore, Axiomatic Design makes a specific prediction about part count reduction and system reliability -- that part count reduction will reduce system reliability if brings about coupling of the design.

2.3 HIGHLY OPTIMIZED TOLERANCE

Carson and Doyle (2000) have offered a vision of technological evolution based on Highly Optimized Tolerance (HOT) -- a term “intended to reflect systems designed for high performance in an uncertain environment...” This conception of HOT systems stands in contrast to other contemporary complex systems theories which generally emphasize “self organized criticality” – the idea that complex behavior emerges from a set of simple components. By contrast, HOT emphasizes configurations due to deliberate design or biological evolution rather than emergence from physical processes only. These HOT systems have heterogeneous, self-dissimilar structures and attain higher levels of performance and robustness than usually observed in self-organized systems.

The theory of HOT has significant implications for part count reduction. Carson and Doyle note that modern engineered systems are characterized by tremendous complexity. For example, comparing a car manufactured today and a car manufactured thirty years ago with a similar list of additional features such as radios, most would agree that the newer automobile has substantially more parts and a greater variety of parts. At the highest level of abstraction, the function of the car has not changed, it still must apply power to the wheels, enable the driver to steer and brake, and handle the bumps in the road. This raises the question of what this increasing complexity serves to achieve. Comparing the earlier systems with low part count to the newer systems, Carson and Doyle (2000) observe “what is lost in these simpler systems is not their basic functionality, but their robustness.” Most people who have recently driven an older car will agree that they are far less robust than their modern counterparts. For example, they may start easily enough on a warm day, but are generally hard to start in cold weather. In other words, the function of starting in an older vehicle design is not as robust to ambient temperature as in a more modern vehicle design.

With the theory of HOT, Carson and Doyle challenge notions from TRIZ. While TRIZ predicts that technological evolution leads to simplification in the long term (at least after the inflection in the “S-curve” according to Mann (2000a)), Carson and Doyle take an opposite stance “while it has become cliché that greater complexity creates unreliability, the actual story is more complicated... The essence of this robustness, and hence of complexity, is the elaboration of highly structured communication, computing, and control networks that also create barriers to cascading failure events.”

As an example of such barriers to cascading failure, consider the introduction of airbags in passenger cars. Figure 3 depicts the state space of the vehicle and the airbag. A set of cascading failure events begins with a change from a normal driving condition to a dangerous one. If the actions of the driver are inadequate, this results in a crash. Without an airbag, the driver’s head is likely to contact the car leading to trauma, but the airbag senses the crash and deploys. This leads to the driver’s head contacting the airbag rather than the car.

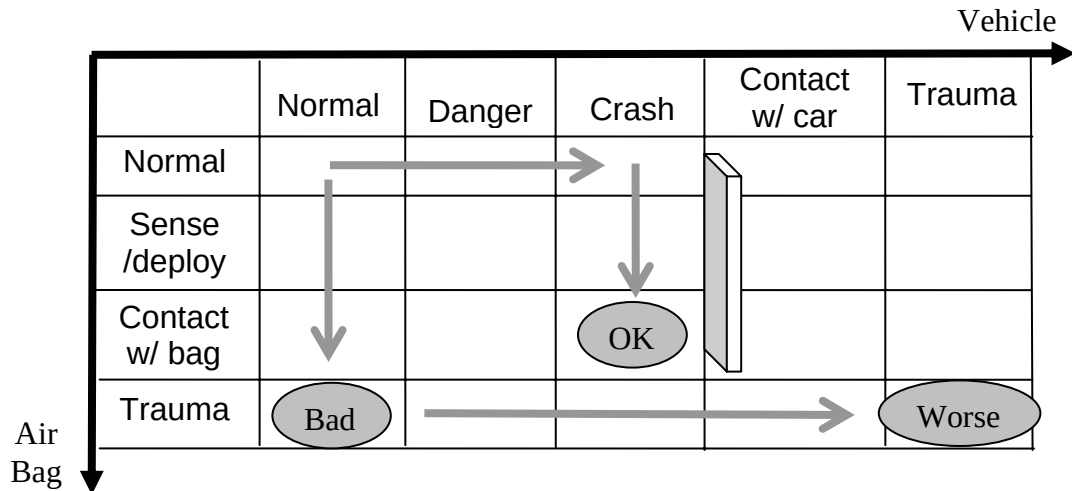


Figure 3. The use of airbags to interrupt a cascading failure (adapted from Doyle, 2004).

It is important in this context to draw a distinction between adding a new function and making an existing function more robust. The example of air bags is useful for illustrating our position on this. One may argue that the function of seat belts is to enable the driver to experience a collision without injury. Seatbelts can enable this function fully under the right conditions. However, as the range of conditions is expanded to include more angles of impact, locations of impact, seating positions of the driver, etc., the seatbelt alone frequently appears inadequate. Adding front and side airbags enables the basic function previously provided by seatbelts to be delivered across a larger range of uncertain or variable factors. According to the definitions proposed by Clausen and Frey (2005), the operating window of the system has been expanded and, if it holds the previous operating window as a subset, the system robustness has surely improved. This is the interpretation we propose here regarding the theory of HOT. As long as the previous design can carry out the basic function under consideration, at least under ideal conditions, and the design changes proposed only serve to enable the function over a larger operating window of uncertain or variable conditions, then we propose that this design change was driven by robustness as conceptualized in HOT.

Perhaps making a function more robust by additional networks and barriers can also be accounted for under the TRIZ “letter of the law” by allowing some rise in the numerator in the “law of ideality” to offset the rise in the denominator. However, the “spirit of the law” -- progression toward a state that “requires no material to be built, consumes no energy, and does not need space and time to operate” seems to be clearly at odds with the predictions of HOT. Further, there is a specific conflict with the prediction by Mann (2000) that part count will reach an apex at the inflection point in the technology “S-curve” whereas HOT suggests complexity continues to rise without ever reaching an apex.

The theory of HOT also challenges notions from Axiomatic Design. Axiomatic Design holds that information content of a system is summative. Thus it follows that probability of success must decline with addition of Design Parameters to a design that meets the “independence axiom” unless that addition not only adds columns to the design

matrix but also alters the structure of the current design matrix elements. In apparent contrast, Carson and Doyle argue that “advanced technologies and organisms, at their best, use complicated architectures with sloppy parts to create systems so robust as to create the illusion of very simple, reliable, and consistent behavior apparently unperturbed by the environment.” This idea goes back at least as far as John von Neumann’s 1952 lectures on “Probabilistic Logics and the Synthesis of Reliable Organs from Unreliable Components.” In this work, von Neumann proved that multiplexed “bundles” of basic organs can be arranged so that the system error rate decreases monotonically with the number of parts as long as the component reliabilities are better than 1/6. These results are not consistent with a procedure of summing information content defined as it was by Suh (1990) but they were shown by von Neumann to be consistent with information as defined by Shannon (1948).

According to von Neumann’s theorems, the number of “basic organs” needed, although large (~20,000) is remarkably insensitive to the escalation in system requirements (von Neumann, 1952). The theory of HOT builds upon this idea, but says something different too. While von Neumann analyzed parallel structures of organs of the same kinds, the theory of HOT holds that systems will evolve to become more heterogeneous (parts should generally not all be the same) and be formed of complex architectures (not merely parallel structures). Therefore, the theory of HOT suggests that not only part count rises, but the number of unique parts will also frequently rise in order to accomplish robustness. Perhaps the heterogeneity also enables the total part count increases to be less than the huge increases described under von Neumann’s schema.

To illustrate how HOT is related to a rise in unique part count, again consider Figure 3. The automotive airbag, while adding unique parts, reduces the severity of one cascading failure. At the same time, the new parts create another possible cascading failure event in which the airbag deploys under normal driving conditions leading to a crash and trauma. However, good design of the sensing and deployment systems can make this cascading failure highly improbable. A car with an airbag is both more complex and more robust than a car without an airbag, which is why insurance companies offer financial incentives for drivers to purchase vehicles with airbags. However, this is accomplished not by massive parallelism of identical “sloppy” parts as often observed in biological systems, but by judicious addition of a modest number of highly-engineered, unique parts.

As observed by Carson and Doyle, part count reduction is not the rule in technological evolution. Even if baseline system performance becomes stable, escalating demands for robustness will frequently drive higher system complexity both in part count and in unique part count. Due to these trends, it seems that a full theoretical understanding of part count changes in systems engineering must include considerations of system robustness.

3. CASE STUDIES: PART COUNT AND GAS TURBINE ENGINES

This section is comprised of case studies intended to illustrate the benefits and pitfalls of part count reduction. All the case studies are from a single industry, gas turbine engines. This strategy was employed so that a team of experienced engineers could be assembled with deep working knowledge of the subject including experiences at all three major manufacturers -- General Electric, Pratt & Whitney, and Rolls Royce. Although the cases all concern gas turbine engines, they are intended to span a wide range of systems engineering considerations.

A brief introduction may be in order for those unfamiliar with jet engines. Figure 4 is a simplified schematic of a turbofan engine. Air enters from the left and flows into the inlet where it is compressed and accelerated by the fan. The air often splits so that a portion flows into the core of the engine and a portion bypasses the core enabling a larger total mass flow. The core of the engine is comprised of the compressor, combustor, and turbine. The function of the compressor is to increase the air pressure. The combustor adds fuel to the flow where it is burned, greatly raising its temperature. The turbine then extracts some of the energy from the flow, lowering its pressure and driving the compressor through a shaft connecting the two. A nozzle then accelerates the flow.

The remainder of this section is a set of discussions of major part count reduction efforts in gas turbine engines and their relationships to the three system design theories introduced in Section 2.

3.1 SEPARATE BLADES AND ROTORS VERSUS AN INTEGRAL DESIGN

Conventionally, axial flow compressors have had separate blades and rotors, most often with “fir tree” connections such as those depicted in Figure 5. However, there has recently been a trend toward consolidation into a single part. This technical innovation is known variously as a “blisk” at General Electric or an “integrally bladed rotor” at Pratt and Whitney.

The consolidation of blades and disks in a single part is not new. Centrifugal

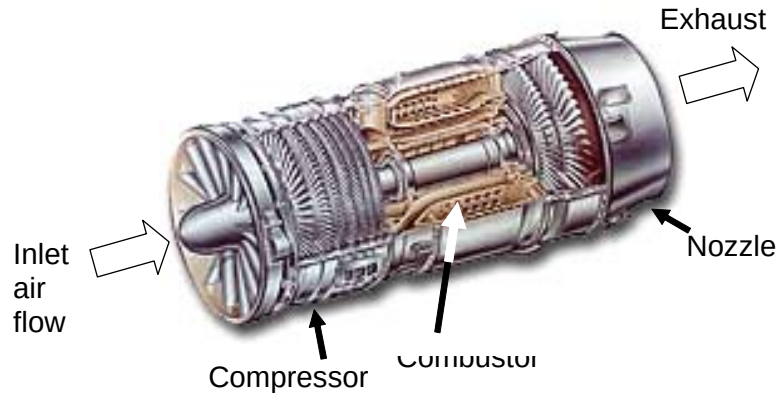


Figure 4. Schematic of a jet engine showing its major components.

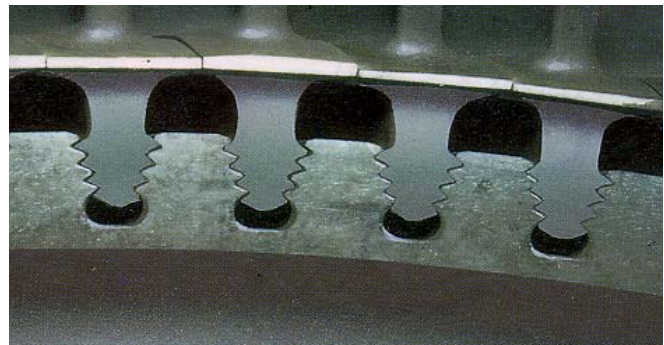


Figure 5. The blade - disk interface is often shaped like a fir tree.

flow compressors have conventionally been cut out of a single block of material. But axial flow compressors require a large number of closely-spaced blades with complex, tightly-toleranced geometry and extreme strength due to high centrifugal loading. The TRIZ principle of local quality suggests that making the blades separate affords some advantages. Separate blades can be forged, machined, and inspected separately and also can be replaced individually if they are damaged in service. Therefore we see that initial trends in compressor design (resulting in part count increase) are consistent with TRIZ.

Despite the advantages of separate blades, there is increasing pressure to consolidate blades and disks into a single part, and this has been accomplished in many designs. In one specific example, a mid-stage compressor bladed disk employed 75 airfoils, a corresponding number of front and rear seals, and blade locks, in addition to the disk, resulting in over 230 parts for the one disk alone, all of which were consolidated into a single part leading to the following advantages:

- 1) **Lower lifecycle cost.** The cost associated with delivery, inspection, handling, and inventory holding for all 230 parts was enormous. Despite higher initial cost of the integrated part, the lifecycle costs decreased dramatically with part consolidation.
- 2) **Reduced weight.** The need for attachment features adds significant mass to the outboard region of the disk. In modern compressors, the overall weight penalty as compared with an integrated part is 5-10%. This percentage savings is very large by aerospace industry standards.
- 3) **Lessened leakage flow.** The radial gap between the airfoil root and the root of the disk slot provides a path for leakage from high pressure regions to low pressure regions. This leakage reduces compressor efficiency, cuts stall margin, and increases disk rim temperatures. Essentially all of the leakage associated with attachment features was eliminated by part consolidation enabling improved performance and robustness to inlet flow disturbances.
- 4) **Improved reliability and simplified maintenance.** The blade/disk interface is a major source of stress concentration and also a locus for fretting and cracking. As a consequence, blade attachments are a likely region for failure and must be inspected periodically. These reliability and maintenance issues were greatly mitigated with part consolidation.

While the consolidation of blades and disks into a single part has provided significant advantages, it has also created daunting design challenges at both the component level and at the system level.

First, consider the manufacturing issues. Attaining tight spacing of the blades has pushed manufacturers toward flank milling in which the side of the cutter is in contact with the work rather than the tip (Fig. 6). But flank milling restricts the geometries one can produce which might compromise aerodynamic performance. Adequate solutions could only be found by multiple iterations of aerodynamic design and manufacturing process design (Wu, 1995). This is clear evidence that part count reduction caused aerodynamic design and manufacturing to become coupled. From the perspective of Axiomatic Design, this fact would be evidenced by a non-triangular matrix **AB** representing the product of the matrix **A** mapping from aerodynamic FRs to blade

geometry DPs and the matrix **B** mapping from blade geometry DPs to tool path / tool shape PVs. The challenge of executing this coupled design has been met through new CAD tools capable of modeling the flank milling process and tying together milling simulations and computational fluid dynamics. By this means, the design iterations required to execute the flank milled blades were greatly accelerated and so despite the coupling which creates a need for iteration, good designs could be developed quickly (Wu, 1995). The coupling of design and manufacturing, which was evident in the case of flank milled blisks, is specifically precluded by Theorem 9 in Axiomatic Design which holds that the manufacturing process parameters should be arranged so that they can be decided in a single iteration once the best ordering is determined. Despite design/manufacturing coupling, the jet engine industry has succeeded in implementing flank milled integrated blades with excellent results. This verifiable, observable phenomenon is not consistent with Axiomatic Design; it is a counter example to the theory.

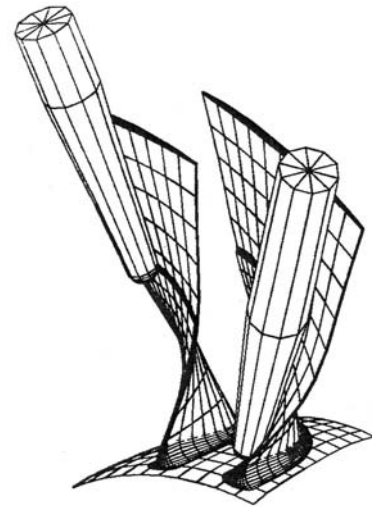


Figure 6. Flank milling of complex compressor blades (from Wu, 1995).

While the manufacturing issues serve to illustrate the component-level design challenges, Foreign Object Damage (FOD) nicely illustrates the system-level considerations. In a bladed disk design, the blades can often be repaired on-wing. By contrast, once an integrated blade is damaged beyond repair limits, the engine must be removed. Because an engine removal is both disruptive and costly, either separate blades are needed or else countermeasures against FOD must be adopted. One countermeasure to FOD is increased blade leading edge thickness, but this is detrimental to compression system performance whose effects can only be fully evaluated through engine-level trade studies. Another option is to "hide" the core flow path from the fan and/or design the fan to act like a centrifuge to force FOD outward and away from the high pressure system. These design decisions usually involve performance, weight, and cost trades. Increased repair limits will likewise be detrimental to compression system performance and will result in increased fuel burn and a reduction in temperature margin which could result in early engine removal. Repair technology improvements are being developed such as welding technologies to repair damage on-wing. Even if this problem is solved, integrated blades and rotors must be carried as spares inventory and this cost is much greater than the inventory cost of individual blades.

Part count reduction at the component level via integration of blades and disks into a single part has been accomplished and successfully fielded. The result has been dramatically improved thrust to weight ratio and improved reliability. This evolution toward fewer parts and better performance is broadly consistent with the TRIZ "law of ideality." But, these benefits were attained at the cost of greatly increased coupling of design and manufacturing, in apparent contradiction of Axiomatic Design (especially Theorem 9). Aerodynamic design and blade milling became inexorably intertwined demanding iterative solutions made practicable by specially tailored computerized design tools. Even though the industry has overcome the coupling in the design process, other

challenges still remain. As with many other innovations new system-level factors need to be considered such as repair and supply chain logistics. The trade-offs involved in these system-level design challenges seem to defy explanation by any simple theory and create a demand for experienced professionals whose judgment is needed to create commercially competitive systems.

3.2 BLADE COUNT REDUCTION IN COMPRESSOR DESIGN

Improved aerodynamic technology, especially computer aided engineering, has resulted in three trends in the design of compressors and turbines each of which has contributed to part count reduction.

1. Fewer blades per stage.
2. Fewer stages to achieve the desired overall performance.
3. Counter-rotating turbines which allow the elimination of stationary stages (nozzles) between stages.

These three strategies have all been employed widely in design of turbo-machinery, but are usually not all found in a single design. Choices among these strategies involve trade-offs and systems-level studies to determine the optimum design for a given set of engine requirements. Details of each approach are discussed in turn below.

Improvements in Computation Fluid Dynamics (CFD) have enabled design of 3D airfoil shapes with increased loading per blade with the result that fewer blades per stage are required to achieve the desired pressure rise. However, these shapes have greatly increased the challenges of compressor design. The 3D airfoil shapes tend to be more sensitive at the tip sections to vibratory forces because the blade tip chord is usually greater than that of a conventional airfoil increasing the tip vibratory stresses caused by aerodynamic forces and blade-to-casing rubbing. Tip vibratory stresses require a better understanding of vibration modes, aerodynamic forcing functions, and improved means of measuring blade tip stresses. Further, to produce these complex shapes, new manufacturing technologies have been required such as electro-chemical machining and electric discharge machining. Implementation of these technologies requires capital investment for new equipment and, in some case, consideration must be given to hazardous waste products. There is also a new “learning curve” for production of the airfoils including training of operators, inspection techniques and rework procedures to avoid scrapping of expensive parts. The benefits of fewer parts, lower weight and the resulting reduction in operating and maintenance cost must be evaluated against the increased cost per blade and new vibratory failure modes which occur because of the 3D shapes.

The evolution toward fewer blades per stage is generally consistent with the TRIZ “law of ideality” since part count reduction can be achieved with no change in basic system functionality. However, a major cost is paid in the complexity of the design process itself. Where design could previously be handed sequentially from aerodynamics to structures, today the two domains are more strongly coupled. Viewed from the perspective of Axiomatic Design, there are no changes in the functional requirements nor in the high level design parameters, but the mapping between the two domains has evolved toward tighter coupling demanding more design iterations. In general, industry

has found that the benefits of fewer blades per stage outweigh the drawback of more coupled design. This trend therefore generally supports the TRIZ principle of ideality and appears to be inconsistent with Axiomatic Design.

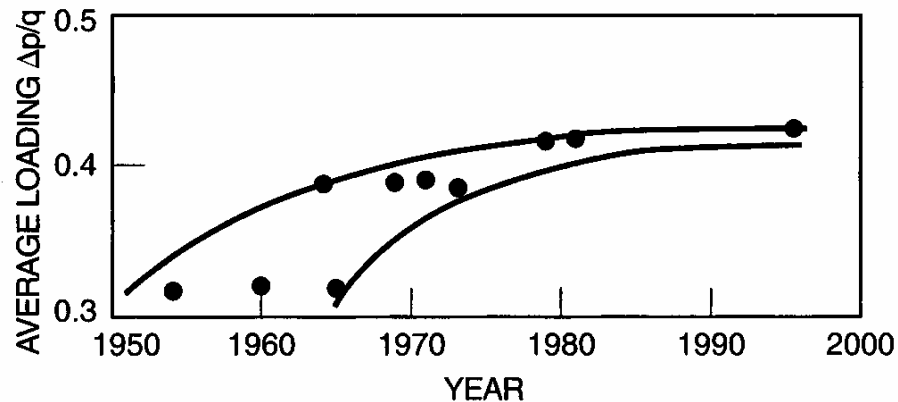


Figure 7. Increase in stage loading as an industry trend (from Wisler, 1998).

As industry has evolved toward fewer blades per stage, it has also evolved toward fewer stages per engine by a trend toward higher stage loading (see Figure 7). As before, improved CFD technology has been a key driver. Improvements on aerodynamic design have led to typically one or two stages being eliminated with a constant overall compressor efficiency. Alternatively, CFD can provide one to two points in overall efficiency for a constant stage loading. Generally, the industry has chosen to increase stage loading and reduce the number of stages. Reducing the number of stages gives the added benefit of reduction in engine length which reduces engine weight and assembly time and also results in a stiffer engine making deflection control easier and reduces sensitivity to rotor imbalance. However, higher stage loading generally demands better compressor clearance control. Because of the higher stage loading, there is increased sensitivity to tip clearances which impact both efficiency and surge margin. Even though reduced engine length improves the ability to control clearances, better 3D heat transfer and deflection technologies are required to understand and set engine clearances over a wide range of operating conditions. In addition, there is the need for more complex control functions to ensure sufficient surge margin. These functions may result in greater hardware complexity (such as variable geometry, bleed valves, and/or clearance control) or additional software (for refined control of acceleration rates).

The evolution toward fewer stages is generally consistent with the TRIZ ideality principle. This trend is particularly interesting since there has been a clear alternative – to maintain the same part count and improve efficiency. Yet faced with the alternative, the benefits of part count reduction for cost, weight, maintenance, inventory, etc. are difficult to resist. However, in this case, the evolution toward a simpler compressor has driven up overall system complexity due to the need for tip clearance control. This trend is generally consistent with HOT theory.

Counter-rotating turbines are a major advance in engine technology providing roughly a “four fold greater work capacity at a given rotation speed” (Adamson, et. al. 1991). However, taking advantage of this potential benefit requires a better

understanding of the exit conditions of the high pressure turbine and, thus, the entrance conditions of the low pressure turbine. The first generation application of this technology has resulted in the elimination of the nozzle between the high and low pressure turbines. Elimination of this part and the associated seals and attachments has yielded a major reliability improvement since these parts are subjected to high thermal stresses and are a frequent source of failures. The trend toward adoption of counter-rotating turbines illustrates how strongly reliability can serve as a driver of part count reduction. However, the benefits of counter rotating trubines have come at the expense of much greater design difficulty. Two effects, in particular tend to become intertwined. First, the change in high pressure turbine exit conditions must be thoroughly evaluated over the entire operating range since the performance benefits of counter rotation can be lost if the matching of the two turbines is not correct. Second, the gyroscopic effects on rotor dynamics and engine mechanical loads will be more complex. This is particularly important for engines which have an intershaft bearing which ties the high and low pressure rotors together mechanically.

Use of counter-rotating turbines, like many other part count reduction strategies so far discussed, tends to support the TRIZ ideality principle and challenge the theory of Axiomatic Design. The functions of the nozzle are taken up by the rotating stages of the turbine leading to part count reduction. However, the mapping among FRs and DPs becomes increasingly coupled requiring an iterative design process. According to Axiomatic Design, the probability of success should have been reduced, but in fact the system reliability improved because a high failure rate part was eliminated.

3.3 ENGINE CONTROL SYSTEMS

The control systems of modern gas turbine engines consist of a large number of interacting parts. The high-level functions of the control system include starting and shutdown control, thrust management, acceleration and deceleration control, protection from exceeding engine operating limits, and communications with aircraft systems including cockpit displays and pilot commands. The technologies have evolved from purely hydro-mechanical systems, to mixed systems with hydro-mechanical and electronic supervisory controllers (analog or digital), leading to full authority digital engine controls (FADEC). The evolutionary path for Rolls Royce engines is presented in Table 1.

Engine	Fuel flow	Bleed valve	Variable Stator Vanes	Fuel trimming	Overspeed Limiting	
					Shaft speed limiter	Shaft breakage protection
RB211-524C/D (1970s)	Hydromech (FFG)	Pneumatic	Pneumatic	N/A	Mechanical	Mechanical
RB211-535 (1983)	Hydromech (FFG)	Analog (BVCU)	N/A	Digital (ESC)	Mechanical	Mechanical
RB211-524G (1989)	Digital (FAFC)	Pneumatic	Pneumatic	Digital (FAFC)	Mechanical	Digital (FAFC)
Trent (1990s)	Digital (EEC)	Digital (EEC)	Digital (EEC)	Digital (EEC)	Digital (EEC)	Digital (EEC)

Table 1. Principal parts in engine control systems with type of computation technology used, adapted from Prencipe (2000).

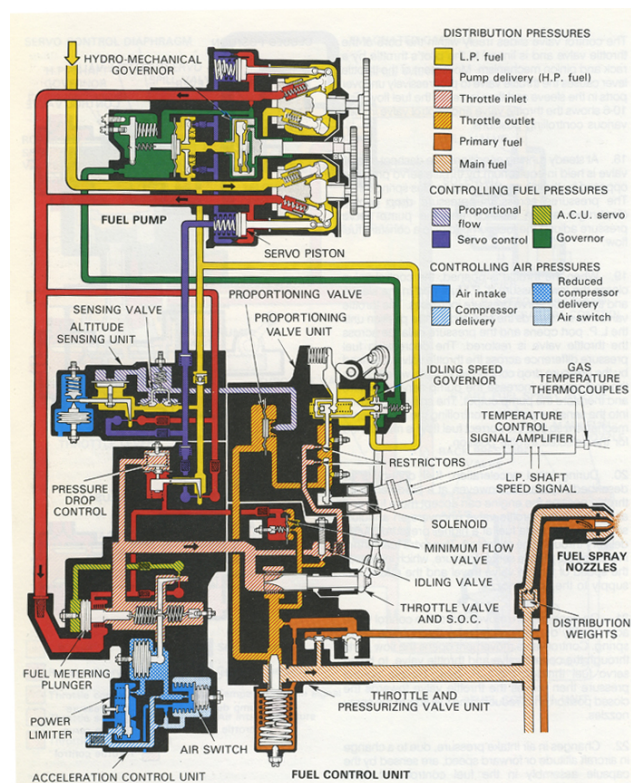


Figure 8. Example of a hydromechanical control system (Rolls-Royce, 1986).

Rolls-Royce used hydro-mechanical control systems on the early versions of the RB211-524 and the Spey and Tay engines. These systems contained different parts for achieving specific functional requirements. Separate components were required for altitude sensing (adjusting fuel flow to match the inlet air pressure), acceleration and deceleration control, shaft speed governing, idle setting, etc. The resulting systems were highly complex with hundreds or thousands of parts including valves, springs, levers, cams, shafts and seals. Although the early systems had high part count, they had a relatively simple mapping between functional requirements and design parameters. Figure 8 shows many parts or subsystems related directly to a single functional requirement, such as the 'idling valve' or 'acceleration control unit'. This trend suggests the early designs were generally consistent with the Independence Axiom in Axiomatic Design.

As engine systems evolved in the 1970s and 1980s, higher by-pass ratios needed for fuel efficiency were demanding more sophistication in thrust management and cockpit interfacing which could not be met with hydro-mechanical control systems. This led to the introduction of electronic supervisory systems. The RB211-535 supervisory control is an example. On this engine, an Engine Supervisory Controller only provided limited authority to trim fuel flow to optimize engine thrust, and hence reduce specific fuel consumption. In this case, the addition of the supervisory controller increased the part count because a fully capable hydro-mechanical fuel flow governor was maintained. Additionally, a separate Bleed Valve Control Unit was developed for controlling compressor bleed valves. This used analog electronics for control, with digital fault detection. All jet engines need a system for protecting the engine from a hazardous shaft over-speed condition, and the RB211-535 included a separate mechanical system to achieve this.

The next evolutionary step emerged when the first dual channel full authority digital electronic control (FADEC) for a commercial engine was introduced on the Pratt and Whitney PW2037 in the early 1980s. By the 1990s all large engines were being developed with FADEC controls. The Rolls Royce Trent engines are typical of how these control systems are designed. At the heart of the FADEC system is an Electronic Engine Controller, which performs all the computation previously dispersed among several units. A Fuel Metering Unit receives an electrical command to control the position of a fuel metering valve. The position of the valve is sensed and fed back to enable closed loop control. There are no longer any parts specifically associated with functions such as acceleration control or speed governing; The electronic controller manages all of these functions in software. Therefore the introduction of FADEC control systems reduced the physical part count by integrating many functions into one unit. The integration of information and the increases in processing power also create an opportunity to expand the functional capability of the system. This tends to increase the part count again. For example, in older engines, the air cooled oil cooler had no regulation capability and was designed to provide cooling air sufficient for the worst case oil cooling demand. The valves could not be regulated and hence for much of the time the oil was being cooled more than needed, with a consequent loss in fuel efficiency. The introduction of FADEC control provided an opportunity to control the oil cooler in response to oil temperature

measurement. This allowed the bleed air demand to be reduced and improved fuel efficiency at the cost of added actuators and sensors.

[illegible]

The history of jet engine controls also sheds some light on Axiomatic Design. The long term trend in engine control has been to achieve part count reduction at the component level by moving away from largely uncoupled mechanical and hydraulic systems towards electronic controls. Figure 9 presents a Design Structure Matrix (DSM) for a modern jet engine, the Pratt & Whitney PW4098 (Sosa et al, 2000). Although a DSM is not the same as a design matrix within Axiomatic Design, it does present information sufficient to infer whether coupling exists. Elements in the DSM above the diagonal indicate flows of information from a later design task to a previous design task and therefore represent a potential for rework cycles. Since only designs that are “coupled” according to the “idependence axiom” require rework cycles, elements above the diagonal of a DSM are evidence of coupling as defined within the theory. It is clear from this DSM that modern jet engines are more nearly block diagonal than lower triangular. Certain sets of design tasks are strongly coupled to one another. In addition, control systems and other integrative systems are associated with especially dense bands of the matrix far from the diagonal. As a practical matter, this introduces the possibility of fairly large blocks of rework. In fact, these rework cycles are made less likely or less severe by either an evolutionary approach, avoiding designs very far from current experience, or else very good predictive modeling capabilities. Notwithstanding this, Figure 9 presents strong evidence that modern jet engine control systems are a particularly strong source of coupling. These facts clearly conflict with the predictions of Axiomatic Design.

3.4 OVERALL JET ENGINE TRENDS

The three previous sub-sections have been just a sample of the many technological and design advances made in the past several decades. These advances have all contributed to improvements in overall performance, cost, and reliability.

One of the key indices of overall performance is thrust to weight ratio -- high ratios are especially valued in military applications. Figure 10 presents data from 25 military jet engines produced since 1960 (Younossi et al., 1991). It also presents a line indicating the overall trend based on statistical analysis of this data. This line suggests that, as far as thrust to weight ratio is concerned, jet engines have long since passed the inflection point on the “S-curve” if there ever was one.

Similarly, Figure 11 presents data on thrust specific fuel consumption. Reductions in this figure of merit are valued in commercial transport applications. To this Figure we added a curve that bounds the data from below. There appears to be an asymptotic improvement over time in the best available performance. Again, it appears that an inflection point on the “S-curve” is decades in the past.

A reason for this continued rise is that even small improvements in performance can result in large differences in market share within a competitive industry. Therefore the high part count and its attendant costs are justified economically. As a result of the competitive environment, part count and other measures of complexity seem to keep rising. As Arthur (1993) observed:

... over the years, jet engines steadily become more complicated. Why? Commercial and military interests exert constant pressure to overcome limits ... and to handle exceptional situations. Sometimes these improvements are achieved by using better materials, more often by adding a subsystem... But all these additions require subsystems to monitor and control them and to enhance their performance when they run into limitations.... On the outside, jet engines are sleek and lean; on the inside, complex and sophisticated. In nature, higher organisms are this way too. On the outside a cheetah is powerful and fast, on the inside, even more complicated than a jet engine. A cheetah, too, has temperature-regulating systems, sensing systems, control functions, maintenance functions-all embodied in a complex assembly of organs, cells and organelles, modulated not by machinery and electronics but by interconnected networks of chemical and neurological pathways. The steady pressure of competition causes evolution to "discover" new functions occasionally that push out performance limits.

This analysis is almost precisely the one offered by HOT, especially if we replace the emphasis in the last sentence on “new functions” and performance with an emphasis on robustness more in line with the previous comments about handling exceptions.

4. CONCLUSIONS

Part count reduction, at the component level, is among the most prevalent engineering strategies, especially within highly evolved, stable engineering systems undergoing evolution over long periods of time (such as jet engines). System design theories make various predictions concerning part count. The TRIZ “law of ideality” suggests that, in the long-term, part count reduction will be observed to approximate and ideal final result. Axiomatic Design suggests that part count reduction should only be effective if functional coupling can be avoided. The theory of Highly Optimized Tolerance suggests that systems will evolve towards more complexity as robustness demands require countermeasures against failure modes. An examination of major trends in the jet engine industry suggests that, although none of these theories is borne out with perfect consistency, each theory provides some useful insights.

As predicted by TRIZ, opportunities for part consolidation have consistently been adopted in the jet engine industry as technological advancements have rendered them practicable. As part count has been reduced at the component level, significant benefits have been attained, especially when low reliability parts are eliminated. However, at the

system level, overall jet engine part count is still rising, despite the fact that the inflection point on the S-curve is long past. Therefore, we conclude that the “law of ideality” in TRIZ must be viewed only as a component-level evolutionary principle. For engineering complex systems we require other theoretical bases.

In contradiction with the theory of Axiomatic Design, part consolidation in jet engines has frequently made the design more coupled while nevertheless improving probability of success. The coupling of modern jet engines is observed at the component level in modern compressor design, across design and manufacture as observed in blisks, and at the system level as observed in engine control systems design. This coupling has increased the difficulty of executing the design and has led to much greater reliance on iterative approaches to subsystem optimization and system-level trade studies. However, the jet engine industry has largely succeeded in overcoming the challenges of executing coupled designs, mostly by means of computer aided engineering. Large investments have been made in specialized software tools for detailed modeling of fluids, structures, thermodynamics, manufacturing, etc. and all these disciplines are become more fully integrated via computer models. Furthermore, the reliability of jet engines has risen as coupling has become stronger which is clearly counter to Axiomatic Design. Therefore, we propose that the independence axiom should be viewed as a caution against the design challenges posed by coupling rather than as a strict prescription to avoid coupling at all costs. We also propose that the information axiom and its related theorems regarding summative information require major rework since the restrictions to independent events renders them of little use in tightly interconnected systems such as jet engines.

In accordance with the theory of Highly Optimized Tolerance, even as parts are consolidated at the component and subsystem levels, recent history of jet engines reveals a fairly consistent trend toward rising system part count. Despite common sense notions such as the “KISS principle” the rise in complexity of jet engines has improved system reliability and robustness. The myriad components of jet engines have co-evolved into tightly coupled system approaching theoretical performance limits. Due to escalating demands for robustness, the components and subsystems are architected in layers creating barriers to cascading failure. As a result, the modern jet engine is among the most complex, yet most reliable engineering systems in existence today.

To summarize, although part count reduction is eventually observed at the component level as suggested by TRIZ, when the scope is enlarged to the system context, escalating demands for system robustness have generally resulted in increased number of parts and number of unique parts in jet engines. Further, this part consolidation at the component-level and layering of barriers to cascading failures at the system-level have increased coupling and simultaneously improved reliability in direct conflict with the predictions of Axiomatic Design. We regard Highly Optimized Tolerance as a more useful framework for understanding technological evolution at the system-level.

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