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ON THE ADVERSE CONSEQUENCES OF COST-PERFORMANCE METRICS USURPING THE ROLE OF GOALS THEY WERE SUPPOSED TO SUPPORT

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ABSTRACT

This paper shows how many of today's zealously applied cost-saving techniques have been counterproductive, when assessed at a higher level. The separate minimization of *individual* costs is shown to usually *inevitably prevent* the overall minimization of *total* costs, whenever the individual costs interact with other costs. *Any* goals defined at a lower level than for an entire organization are actually *constraints*, which can only rarely achieve anything better than a sub-optimum solution. What is needed, instead, are more scientific metrics that relate the performance of an individual, or department, to the *common* goals, explaining why it is *necessary* that some individual costs should *not* be minimized. Specific examples are included to show how and why many contemporary management techniques that are successful under some circumstances have failed to deliver what they promised under others. Hope for the future is provided by identification of those distinguishing characteristics that have enabled some recent programs to succeed when others have failed. The paper also contains examples, at the technical level, of ideas that can save cost, or have already done so.

INTRODUCTION

A strong case can be made that many of today's cost-saving initiatives, launched with the most noble of intentions, are often counterproductive because they are not universally applicable, particularly when they focus on minimizing only one cost at a time, in isolation. Even when that goal is achieved, there can be *consequential* increases in the cost of *other* activities that had not been accounted for. What is needed, in the aircraft industry and elsewhere, is reductions in *overall* costs – of production and of ownership. If this were the *only* goal, sub-optimum solutions would become more apparent, as would the necessity that *some* incremental costs *must increase* if the *total* costs are to go down. Today's procedures break down whenever *techniques* for satisfying high level goals become *goals* in their own right, and are applied unthinkingly to situations in which they do as much harm to overall performance as they do good elsewhere.

One may wonder why what seems, at first sight, to be a paper focussing on management belongs in a technical conference. The reason is that every false economy not only achieves a sub-optimum economic solution, it also creates a technically sub-optimum product. More than ever before, technical development today is conducted within tight economic constraints. The performance of a typical department in an aircraft factory is measured against its assigned schedule, and costs within each department are limited primarily by head-count. If schedules and budgets are realistic, the kind of anecdotes related here should not occur. The primary reason for including them is that examples like these, whenever and wherever they are observed, can act as a warning that the focus of the organization has strayed. It is hoped that this paper, by logical deductions and by anecdotal evidence, will provide significant feedback to those who manage technical projects. It is also hoped that the specific examples will encourage more 'lateral thinking'. The examples cited are real, rather than hypothetical, to better convey the message that there are many cost-saving opportunities available for the future.

It is necessary first to distinguish between two kinds of cost reductions. The first is an improvement in departmental efficiency that has no effect on the operations of any *other* department. Such cost savings obviously benefit the corporate bottom line directly. This paper does not address such cost savings, which are most pronounced in manufacturing and final assembly, these being the

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[*] The views and observations expressed here are those of the author and do not necessarily represent those of The Boeing Company.

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operations that are done *last*. The concern addressed here is about what happens *earlier* in the creation of the product, particularly with those tasks done only the once, which have a very strong bearing on the costs incurred, and time span, in every department involved *later* in the process and, most importantly, on the recurring production costs.

Obvious examples of this kind of interactive problem include attempts to minimize the cost of design, rather than to design the minimum-cost parts, structures, and systems to manufacture or operate. Similarly, efforts to minimize the cost of tooling, to the detriment of the assembly processes carried out in those tools, can add even more to the total cost of production, and maintenance. Insufficient money spent on modern machinery would have the same adverse effect, even if it did decrease capital expenditures. Development costs can be as low as 10 percent or so of the total production costs for large jet transport aircraft, yet they are commonly cited as being responsible for some 80 percent of the cost of production. Once a design has been completed, manufacturing has very few variables left under its control with which to make deep inroads into the 90 percent of the budget that it consumes. It is within its power to *reduce* its costs by its own actions, but not to *minimize* them. It stands to reason that restricting the design effort, (and any other once-only cost) to minimize costs incurred early in a program, will almost always be counterproductive, even if the value of money spent first is greater than that spent later, because of inflation. Merely spending more money up front will not solve the problem, either. It needs to be focussed on specific vital tasks that can produce downstream savings. Preliminary conceptual designs, covering *all* aspects of production from tooling to subcontracting, need to be *completed* by small teams *before* the tasks are passed to large organizations for the details to be carried out. Such 'advanced planning' costs relatively little money, but there does need to be a provision of sufficient time to complete it, since it is at this stage that 'interdepartmental' communications can be the most effective.

Another powerful technique with which to reduce production costs is to prepare detailed plans for the *sequence* of operations, part by part, so that the need for intermediate assembly tools and unnecessary precision can be avoided by using design features or previously installed components to locate those added later. This is referred to as determinate, or jigless, assembly. It is also very important, in planning the assembly sequence, to identify which holes must *not* be drilled and which fasteners must *not* be installed at the sub-assembly stage, to permit the assembly of the subassemblies without first removing fasteners and drilling out their holes so that the interfaces can be made to meet. Achieving *this* cost saving means drawing *more* than the finally assembled product. Definition of the products at *intermediate* stages of production has often not been done. It is an integral part of the Design For Assembly (DFA) method, but is still often thought of as an *added* task for design and, in some factories, is the first casualty when design budgets are reduced. It is not a task that should be left to a *separate* planning department once drawings of the assembled structures have been released; it should be regarded as an *integral* step in the design process, to be released *simultaneously* with the definition of the product. Nevertheless, some of the enormous unplanned expenditures caused by omitting such 'interdepartmental' activities have now become apparent. It remains only to link the two events together, and to do better the next time.

Within large organizations, global, rather than individual (or departmental) incentive compensations may be needed to discourage too narrow a focus on cost saving. A reward system whereby people benefit from doing their *own* work in such a way as to help *others* to minimize *their* costs is more likely to yield the better outcome for the enterprise than has the traditional approach of rewards for minimizing costs in isolation. But even without this better focus, successful products have been developed and profitably marketed. Within the author's working career, this has been observed in the form of X-shop or Skunk Works operations. It has also happened when 'second teams' have been given an opportunity to shine because the 'first team' was pre-occupied on other projects. What these successes have in common is that a small *enthusiastic* team of individuals, led by a *single* capable leader, often accomplishes what the entire organization cannot. Smallness is essential for establishing the same kind of co-ordination as existed when an industry was first created. But, today, smallness is frequently not sufficient; a small team often needs access to the *expertise* of a large, established, organization, but would collapse under the weight of that organization if the new development were not isolated. Modern management is correct in recognizing that reduced costs require that fewer people be involved in development and production. The problem is that the successful small teams are frequently stocked with 'volunteers' who spend long hours to make a project succeed. It is difficult to *create* such teams; but we need to be smart enough to *nurture and support* them. The last 30 years of industrial experience clearly shows that such undertakings are, on average, far more frequently technically, and financially, successful than those where entire large organizations were involved. Better organization, to break down the interdepartmental barriers that exist in large organizations can help, but nowhere near as much as *eliminating* them by working with a team so small and focussed as not to need them.

DIFFERENCES BETWEEN GLOBAL AND SUB-OPTIMUM (LOCAL) MINIMA

The perverse nature of a plan focussing on easily *identifiable* incremental (individual) cost savings is that, in a complex society or business organization, actually succeeding in satisfying *some* such goals virtually *guarantees* an even greater *increase in other costs.* The underlying problem is that *total* costs, or profits, are the result of a complex interaction between *many* costs internal to the producer of a product and of other costs of operation beyond his control. The *absolute* minimum cost of production is *NEVER* associated with a simultaneous minimum in *every* individual cost comprising that total. A simplified presentation of this state of affairs is depicted in Figure 1, which shows the effect on *total* costs (vertical axis) of three *interactive* but separately controllable *incremental* costs (horizontal axis). The drawing is schematic only, and not to scale. (Completely characterizing the system requires many such charts, one for each seemingly independent variable. This is really an *n*-dimensional problem, but the characteristics can be clarified on a 2-dimensional chart.)

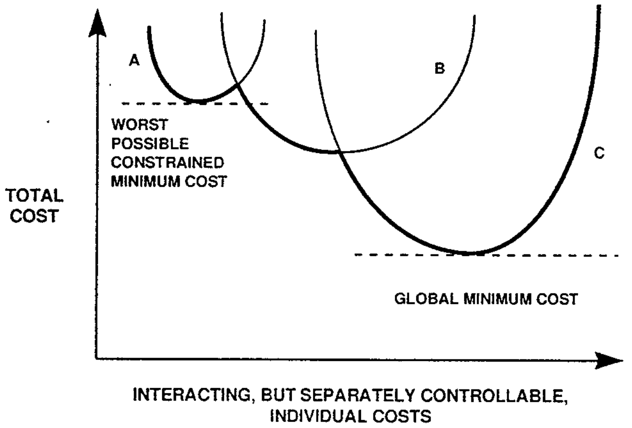

FIGURE 1 - Difference Between Local and Global Optima, and Between Constrained Optima and Those Defined by Minimizing Single Variables

This problem is not new; it was well known to the man recognized as the father of Total Quality Management, W. Edwards Deming who, in his book *Out of the Crisis,*(1) recommended very strongly *AGAINST* performance evaluations based on the setting of *individual* goals. Whenever their output influences the activities of *other* groups, tying the *measurement* of the performance of each individual, or small group, to a reduction in some incremental cost in their own department which he or they *visibly,* and directly, affect almost always ensures that there is then *no possibility for the entire operation to achieve what ought to have been* its *goals.* With reference to Figure 1, what this policy ensures is that, if *every* such (individual or departmental) goal *is* achieved, the corporate performance can *NEVER BE ANY BETTER THAN PERMITTED BY THE HIGHEST **(WORST)** CONSTRAINT RESULTING FROM MINIMIZING THE **MOST** INAPPROPRIATE OF THE INDIVIDUAL COSTS* (Curve A). When strong interactions exist between departmental costs, only if many departments ***FAIL*** to attain their individual goals can overall costs be minimized, (Curve C). (The total cost may be *diminished* by independent reductions, but only rarely can it thus be *minimized.*)

There is nothing wrong with setting performance goals and measurement criteria at the *highest* possible level in an organization and applying these *very same* goals at *every* lower level. What Deming warned us against was the creation of *secondary* goals, at lower levels, which, while appearing to be worthwhile when assessed in isolation, either failed to support or even directly contradicted the *overall* (primary) goals. Only when there is *ONE* common goal, and it is the *correct* one, is it possible to truly minimize overall costs, or maximize overall performance or whatever the enterprise-wide single goal might be. In the context of Figure 1, this means *starting* the search for the optimum solution in the *deepest* of the troughs, i.e. the organization in which *most* of the money is spent, or that has the *greatest* influence on performance. Satisfying *any* additional goals will, by definition, *prevent* the attainment of the primary goal. The *more* such secondary goals are satisfied, the *higher* will the margin whereby the primary goal is missed, whether it is one of cost or performance. Instead of making every department responsible for minimizing its *own* costs, or allowing it *sole* authority to influence the activities carried out within it, industry must put the effort into developing the far more difficult metrics that relate each *individual* performance to satisfying the *overall* goals – and allocate resources accordingly.

AN OBJECT LESSON IN THE GLOBAL CONSEQUENCES OF FOCUSSING ON AN INAPPROPRIATE INCREMENTAL COST SAVING

It is commonly accepted than actually achieving *any* validated cost-saving must be a 'good thing'. Nothing could be further from the truth, as the following example should show. In this case, the stipulated goals *were* achieved, but at what cost! During World War II, The Boeing Company designed and produced the B-29 bomber in large numbers, with the demand always outstripping the supply. The saga about to be discussed concerns an effort to increase the production rate in response to this demand, the consequences of which were revealed in a letter to the editor published in *Airpower*(2). The letter, concerning the differences between the B-29A produced at Renton and the B-29 and B-29B produced at Wichita, is reproduced in the footnote below*. A little clarification may be needed for those not familiar with the design details alluded to in this letter. On the *original* B-29, the primary wing box was made in 3 pieces, 2 tip sections and a *center* section extending from beyond one outboard engine nacelle, straight through the fuselage, to beyond the other outboard nacelle. The *revised* design, implemented *only* on the B-29A, added 2 more manufacturing breaks in the wing, 1 at each side of the fuselage, with a dry bay on the inside and outside of both sides of the fuselage, displacing fuel tanks that existed on the original B-29. This permitted the wing/fuselage join to be deferred until later and meant that better use could be made of the factory floor space. Unfortunately, it required that the B-29A had to sacrifice *HALF* of the *payload of bombs* with respect to the original B-29 design, when both were flying on long-range missions.

It is probable that all of this was done at the request of the US Army Air Corps and that Boeing was merely responding to the requests of their *customer*. However, the *high-level* goal in this scenario was to maximize the number of bombs dropped on the enemy. The aircraft were merely the *instruments* by which they were delivered. The focus on maximizing the number of aircraft built, rather than the tonnage of bombs dropped, meant that *twice as many* B-29A's needed to be built as would otherwise have been necessary, *twice as many engines* (of which there was an even greater shortage), and the training of *twice as many crews* – and, presumably, the need to therefore build twice as many factories!

The purpose of telling this saga is to emphasize what can happen when decisions are based on a lower-level criterion, rather than on the highest level goal. Surely someone could have foreseen the consequences of this decision *before* it was implemented.

ON THE EVILS OF MINIMIZING INDIVIDUAL COSTS AS THEY OCCUR

The need for looking at the *whole* picture, rather than at *incremental* tasks, is typified by the process of design, and of the concerted efforts customarily devoted to minimizing its cost – in isolation. Some decades ago, it became standard practice in the aircraft industry to design only the *left* side of it and to *define* the right-hand side to be its mirror image†. This reduces the cost of preparing the drawings but precludes the even greater savings derived by the very different approach to this issue in the automobile industry. The outside panels on cars are visibly symmetric, but the mechanisms underneath are not. The auto industry *minimizes* the total number of *different* parts it has to make by designing *both* sides of the automobile to make the greatest possible use of *common* parts. The remaining parts are made *asymmetrically*, if necessary, because it takes the same amount of tooling to create two asymmetric parts, by stamping or forging, as it does to make two symmetric ones. If they are not identical, they must be different. To be fair, the aircraft industry has become very efficient in making symmetric *machined* parts from a single NC tape, merely by identifying a left or right configuration. However, there is more paperwork associated with symmetric components than with ones that are common. Parts shortages are usually reduced when common parts are used. The number of *different* parts is usually more critical than the *total* number of parts. Ref.'s 3 and 4 contain examples of such real cost-saving ideas used in the automobile industry, so they are not repeated here.

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* Though a subsequent version of the B-29, the "A" variant was not an improvement or even an immediate equivalent (photo caption no. 2, page 24, Feb. 1995, "*Wings*").

To facilitate greater volumes of B-29 production, Boeing's Renton plant used a peculiar assembly method whereby the center wing section panel, originally a single unit, was redesigned to provide a stud assembly joint on each side of the fuselage. This was the major reason for the Renton site receiving the "A" series letter.

Since these stud joints occurred at the most severely stressed portions of the wing, approximately 700 lbs. of structure had to be applied in this area. Compounding this weight penalty, the volume of this structure displaced a 215-gallon center wing fuel tank. The direct loss of 215 gallons, combined with the elevated fuel consumption rate necessary to support the added 700 lbs. in weight empty, placed the B-29A at an operational disadvantage to the original.

Ed Wells, Chief Designer at Boeing, states that at the time of its combat introduction, the B-29(A)'s bomb load capacity was necessarily half that of the original B-29; the "A" variation requiring an additional bomb bay fuel tank during joint operations with conventional Superforts.

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† This standard procedure has even been known to interfere with the *function* of parts of the structure. Perhaps the best known example concerns the five totally different designs implemented for the waist-gun positions on the famous B-17 Flying Fortress bomber of World War II. Only after the production of the *final* model, the B-17G, had begun were the positions staggered fore-and-aft to prevent the gunners on each side bumping into each other all the time. The author can only admire the designers of some Grumman carrier-based aircraft, in which the wing-fold axes were skewed so that one wing folded forward of the other, sitting snugly over the fuselage, instead of colliding with each other at such a great height that the aircraft could not have been stored below decks if the wings had folded symmetrically.

'Saving' on the cost of design has other adverse cost implications in terms of higher manufacturing and tooling costs. The following saga, relating to aircraft spoilers, illustrates the kind of opportunities to minimize *large* costs that are lost whenever too much effort is devoted to minimizing *small* ones that occur first, instead. Spoilers are traditionally constant-chord devices, even when the wing plan-form is tapered. This permits each spoiler, or at least the main structural box, to be used at more than one location. Consequently, there must be a very slight twist, along the span. This minute difference, from side to side, is all that stands in the way of having totally common components. On one aircraft, the spoilers actually are symmetric and the twist is created by distorting the spoilers as they are pulled up hard against rigid stops at each end when retracted. The twist is so minuscule as to have no effect on their performance when they are deployed. This philosophy could not be followed on another aircraft, in which the spoilers were pulled down to seal tightly on the top of the flaps, rather than against stops on brackets attached to the rear spar. Nevertheless, there was still an opportunity for making the spoilers from *common details* from side to side, with the twist incorporated only at the final step in assembly, when they were all bonded together. Had this philosophy been adopted, the inboard rib of the spoilers on one wing would be the same as the outboard rib on the spoilers of the other wing, and vice versa. The spars would have been common, without twist at the detail stage. But, more importantly, it would have permitted the honeycomb core to be carved by an inexpensive *single*-axis numerically controlled carving machine. Doing so would have needed the minutest of a twist in the spar webs, resulting in the areas covered by the hinge fittings being no more than *half a thousandth of an inch out of flat.*

Unfortunately, this would have been contrary to drafting policy, so the spar webs were drawn with no twist. This meant that, since the *rest* of each spoiler was lofted with the appropriate minute aerodynamic twist, that the opportunity to build inexpensive constant-cross-section spoilers was lost. Worse, as a direct consequence of this, the core was no longer of constant cross-section, either, and it therefore became necessary to purchase a 5-axis carving machine. The added expenses did not end there, either. Instead of curing the detail parts on *common* tooling, and having the final bonding fixtures as the only twisted tools, every tool for a detail part was replicated to incorporate left or right twist, of no more than half a degree over a 300-cm (10-foot) length. This policy *did* succeed in minimizing the relatively insignificant cost of preparing the drawings which, under conventional sequential scheduling, was the first task to be done. It also had them completed quickly, which was important in view of having to make twice as many tools as should have been necessary. But was it the best goal to have been assigned to the design department?

Such dedication to minimizing the cost of the design, rather than of the part, did not end there. While the spars in the outboard spoilers were absolutely straight, those for the inboard spoilers were slightly crowned, by 0.5 mm (0.020 inch) over their 300-cm (10-ft.) span. Since the drawing tolerance was 0.81 mm (0.032 in.), it could have been 'legal' to make one straight spar tool. It would have made more sense to *average* the two sets of loft data, and to make one common tool acceptable to the aerodynamics department however, because the deviation from symmetry, from end to end, was only 0.02 mm (0.001 in.)! However, yet again, the *first* cost saving was seized instead of the much *larger*, but *later* one.

One must surely question the wisdom of such priorities. To paraphrase astronaut Neil Armstrong; "One small cost minimized for a man; one large cost maximized for mankind!" There are *many* components on aircraft structures that are not common when completed, but which contain individual components that *could* have been made common, if the scope of the design process were sufficiently expanded. Some such ideas are described in Ref. 3. They include canting spar webs, instead of unthinkingly drawing them in a vertical plane and causing the flange angles at the top and bottom to be different. On control surfaces with no camber, this can, in addition, permit the use of common ribs from side to side. One can also make stiffeners in standard lengths, like the grip lengths of fasteners, so that the same rib stiffener could be used at many locations. All it takes is the creation of constant-depth contours for a wing or tail, like maps of mountains, to identify zones in which a constant-length stiffener could be made to fit. This does not normally happen, because many designers are assigned the task of drawing several complete rib assemblies each, and no one else is budgeted to look for potential commonality on such a scale. What is needed is considerably more lateral thinking than is common today.

The example of the spoilers serves to indicate how, for a little more design effort, it would have been possible to achieve substantial reductions in series production. Saving on the small once-only first cost *excluded* the much greater potential downstream cost savings. There are many more such instances that could be cited to reinforce the point that the focus must be on minimizing *total* costs first, and individual costs *second.* This is not to imply that minimizing individual costs is wrong; the concern is with minimizing them without regard to the consequences *elsewhere* in the organization.

THE BENEFITS OF A GLOBAL PERSPECTIVE ON WEIGHT SAVING

Just as with cost savings, not all incremental weight savings are beneficial. This situation is best known in terms of optimizing wing structure for *several* constraints simultaneously, versus one at a time. Particularly in the case of increasing the flutter speeds, the truly best solution usually differs appreciably from a design focussed on minimizing strength margins to remove apparently 'unnecessary' material. In this situation, the fact that the minimum *overall* weight design is heavier than a design for static strength alone is well understood. But there are similar situations where it does not seem to be.

One common figure of merit for splices is the ratio of pounds of weight transferred per pound of splice. Another is pounds of weight transferred per dollar of splice. While both seem rational, there is a far better metric, related to the weight of the *entire* structure instead. Splices are such a small fraction of an entire structure that structurally more efficient splices can often be justified on the basis that a little extra weight or cost in the splice can permit far more substantial weight and cost savings in the *rest* of the structure. By their very nature, splices tend to be the weak links in structures. It stands to reason that the best criteria for designing splices are those that *minimize* this tendency, and allow the basic structure to be utilized to the *maximum* degree possible. Again, the point at issue is that *greater* benefits can be achieved by assessing the *entire* structure than by focussing on the splices *alone*.

A very similar situation arises in the design of splices themselves. In a multi-row mechanically fastened joint, there are *many* possible first-failure scenarios. Sometimes, the existence of a high margin of safety in regard to one possible mode of failure is responded to by changing the design to reduce *that* margin, in the belief that doing so is simply removing *unnecessary* weight. Particularly in the case of composite structures, this is absolutely the wrong thing to do. The *single* objective of designing splices should be to maximize the operating stress level *outside* the joints, where most of the structure is located. This will come very close to minimizing both the weight and cost of the *entire* structure. Adding further constraints inhibits the achievement of that goal. In particular, trying to operate fasteners at high bearing stresses, to save on the cost of undeniably expensive specialty fasteners, causes a reduction in the skin operating stresses, via the well-known bearing/bypass interaction. This incurs even greater costs in the form of additional plies of expensive composite material. Ref. 5 contains quantified analyses, and the associated formulae, for identifying truly *optimum* joint proportions. Ref. 6 records how successfully these methods were applied to simulated wing-skin splices, with composite laminates up to 2.5-mm (1-inch) thick withstanding gross-section average stresses of 350 MPa (50 ksi) prior to failure. In no case were the optimum joint proportions associated with simultaneously minimizing the margins for net-section tension strength, bearing failures in the laminate, fastener shear or bending failures, etc. As throughout the rest of this paper, the message here is that a clear focus on the *highest*-level goal(s) will yield a better product than allowing the design process to be constrained by a multitude of seemingly plausible lower-level measures of efficiency.

SOME OFTEN UNAPPRECIATED ASPECTS OF COST/WEIGHT TRADE-OFFS

A further source of high product costs which is not understood as well as it ought to be is failure to comprehend the true value to be assigned to cost/weight trade-offs, and how the criteria change during the course of a project. This value *can* be calculated realistically, but sometimes isn't. As before, the author's concern is not with what happens when such criteria are established scientifically, and applied *uniformly* throughout an entire program; it is with what happens when this is *not* done. Unfortunately, rigorously established criteria for this trade-off are, on occasion, replaced by the simplistic perception that the penalty for weight added to reduce manufacturing cost is the cost to the operator of flying a lump of 'lead' around for the entire life of an aircraft. This is actually valid only for the very *last* derivative in a line of aircraft *after* the performance targets have been met. Until then, a more accurate measure of the true cost of a structurally unnecessary pound of weight is the money spent to *remove* a matching pound of weight to meet the specified performance. The second assessment of the cost of added weight usually differs by a large factor from the first.

A proper understanding of this issue almost ensures a complete prohibition on 'saving' cost by adding weight to primary structure, which is usually designed first, unless the benefit is at least as great as has traditionally been paid to take the same amount out of the far more expensive secondary structure, which is the usual location of weight-savings programs. This is because the design of secondary structure is usually left until last, so saving weight there is perceived as saving the cost of repeating the design of the primary structure, or disrupting a production line at its most difficult phase. Somewhere, the message has been lost that there are a lot more pounds of primary structure from which to remove proportionally little weight, and far too few pounds of secondary structure to achieve significant weight savings. This merely compounds the difficulty that secondary structure costs far more per pound than primary structure – and always will. Contrary to the oft-expressed view that it is too expensive to change a drawing after it has been released, saving weight in primary structure is often the *least* expensive option available.

The need for an appropriate cost-weight trade factor can even arise when it would not traditionally be recognized. Suppose that one group of designers has under-run both its 'must-cost' and 'must-weigh' requirements for its component(s), either because of ingenuity or conservatively assigned bogeys. Should they be permitted to increase weight, up to its assigned limit, to reduce cost and to qualify for bonuses? The correct answer is "only if doing so does *not* violate the appropriate equivalence between cost and weight", not "of course they can, as long as they do not exceed their targets". For every situation like this, there will be other components for which one or more targets have not been met. Solving this situation is exacerbated if the *entire* program is denied the benefits from the groups that were able to more than satisfy their requirements. What must be avoided is situations in which the overall aircraft fails to meet its performance targets, but *would* have if it had not been for failure to take full advantage of *all* opportunities to do so.

At the start of a new design, until it is confirmed that all performance objectives can be met, the downstream cost of a pound of weight added to reduce manufacturing costs should be whatever it takes to remove a matching pound of weight from somewhere else. Business plans that permit the addition of a pound of weight for as little a saving as $25 per lb., while tolerating weight-saving programs costing $2,500 per lb. of weight saved, are simply not economically viable. Apart from any other considerations, not all of these plans succeed. Suppose that a careful investigation established that, from an airline customer's perspective, a pound of structural weight added, or deleted, was worth about $1,000 per pound* in terms of its effect on their revenue during the time they owned the aircraft. Then, if the success rate of cost- and weight-saving programs were only 50 percent, weight-saving ideas would need to be estimated as costing no more than $500 per lb. of weight saved, and not be implemented if they cost any more, while cost savings that added weight in the process would need to yield at least $2,000 per lb. of weight added. It is imperative that these two activities *NOT* be administered separately. The need for costly weight-saving programs, to meet specified performances, would often be obviated by *not* having added weight to save on manufacturing cost. (Obviously, this is not intended to discourage saving cost on primary structure whenever doing so does *not* add weight. The concern is about those commonly occurring circumstances in which one is traded for the other.)

Even the preceding trade-off is an oversimplification, albeit a rational one. The four-to-one difference suggested here assumes that all performance objectives have been met for the present aircraft *and will be met for all of its derivatives!* An early production model may be far less weight-critical than the final derivative. Hence, the performance of the final aircraft model can be gravely affected by cost-savings that had actually *met* the criteria for an earlier model. An objective assessment of the cost/weight trade-off for aircraft structures and interiors would indicate that, *at any time prior to the end of the design of the FINAL derivative model,* the value of a pound of weight is what it costs the manufacturer to fail to achieve the promised performance.

On one large transport aircraft, the addition of hundreds of pounds of weight in the primary structure was incurred as the result of design features to reduce the cost of final assembly. Unfortunately, it was subsequently discovered that the aircraft failed to meet its anticipated performance. The cost of the performance-improvement program exceeded by far the original cost savings. In this case, the weight had been *added* consciously. However, equivalent, but so-far unquantified, consequences result from failure to *remove* structurally unnecessary weight that is not identified until after the stress analysis has been completed. This is sometimes done, but only as part of a formal weight-saving program initiated after upper management has acknowledged the existence of what would otherwise be a costly performance shortfall, and usually after series production has commenced. Why is this not an integral part of *all* development programs?

The reason why there *should* be a preference for removing weight from primary, rather than secondary, structure can be confirmed analytically, very simply. Suppose, for example, that a pound of metallic primary structure costs about $100 to produce, a pound of metallic secondary structure costs $250, and that a pound of secondary composite structure costs typically $500. Given that the typical weight savings actually *achieved* on composite structures – when there has been a metallic baseline to actually quantify the benefits – is only some 10 percent, a pound of weight added (or not removed) to save cost in the primary structure of

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* This includes both the fuel needed to fly unnecessary structure around and the loss of revenue associated with the matching decrease in revenue-producing payload. This value is influenced by the nature of the aircraft. It is critical for a long-range aircraft that has to restrict the number of passengers it can carry to meet the range. It is not so serious for small short-range aircraft that have space limits on the number of passengers and any freight that can be accommodated within the aircraft.

a performance-critical aircraft could require that 10 lbs of metallic secondary structure be replaced by 9 lbs of composite structure; in other words, that a possible cost as low as $2,500 be replaced by one of $4,500. (No allowance need be made for probability of success, in this case, because average weight savings have been used.) In short, based on realistic production costs, it has been shown here that a single pound of weight added to simplify production of primary structure would typically need to save at least $2,000* , if the aircraft performance were not to be degraded. This kind of target needs to be remembered by all those who advocate such concepts as integrally stiffened structures to reduce part count, in the fervent belief that this is a 'good thing'.

THE PRO'S AND CON'S OF PART-COUNT-REDUCTION

Perhaps the worst of all modern fads for aircraft design and construction is the belief that parts-count-reduction will *always* save money. The fact that this is *not* so is clarified in Ref.'s 4 and 7. The author's assessment of the situation is that there is no one-to-one correlation between parts count and cost. In some instances, an inverse relationship is to be found. As noted earlier in this paper, in regard to another false economy, the concern expressed here is not with those situations where parts integration actually *does* save money; it is with what the author sees as a pre-occupation with reducing parts count without looking at the entire picture first. Parts-count reduction, when it works, is a *technique* for reducing costs. Far too often, it has become a *surrogate goal* whenever the real goal is difficult to quantify.

Parts integration has worked brilliantly in the electronics industry. Tubes were replaced by transistors, and resistors by integrated circuits, resulting in decreased costs and increased reliability. However, if this concept *were* universally applicable, the fuselages of 747 airliners would be hogged out of a single billet of aluminium. It is conceded that applying the concept to the swept wing on a C-5 aircraft, from tip to tip, would be as impossible as it is illogical. Why, then, is there so much support for efforts to reduce part count, without first establishing that doing so, *in each case*, will actually save money?

The objective readers of Ref.'s 4 and 7 will conclude that some parts should be integrated, while others should not. Parts-count reduction is no more universally wrong than it is universally right. But there is definitely *NOT* a one-to-one correlation between parts-count reduction and reduction in *overall* cost. Parts count is simply not a sufficiently reliable surrogate metric for overall cost minimization.

Interface control is a vastly superior metric. According to *this* measure, parts integration can be beneficial if it does not create downstream interface problems, but is definitely counterproductive whenever it eliminates the possibility of sliding components into place, so that they fit with neither interference nor a need for shimming on assembly. There are no blanket rules to be applied to this issue but, in many cases for metallic structures, small size and complexity favour parts integration, particularly when the part can be produced by NC machining, while large size and simplicity favour built-up structure. In the case of advanced composite structures, the most powerful discriminator is the avoidance of structural weaknesses caused by the low interlaminar strengths of fibre-polymer composites; this same weakness should discourage designs with complex details, regardless of size. Perhaps surprisingly, it is usually quite simple to recognize where consolidating parts makes sense and where it doesn't. And, when the appropriate course is *not* obvious, one must infer that differences between the two cannot be substantial. In such a case, flipping a coin will achieve a 50-percent success rate far less expensively and far more quickly than by protracted formal evaluations. When taken to extremes, parts integration becomes uneconomic because of what is known as the fly-to-buy ratio. If 95 percent of the incoming ('bought') material is converted to chips, for example, the 'raw material' cost of what 'flies' has effectively been raised by a factor of 20.

Among the most convincing proofs that part-count-reduction is not always a wise path to follow are the numerous success stories where this option has either been shunned, or where a total redesign was necessary to recover from having fallen into the trap at an earlier date. The original design of a large composite tail cone on a large military transport aircraft had a co-cured stiffened skin, with innumerable discrete open ended hat stiffeners running longitudinally, with each notched right through to simplify the frame/stringer intersections. The shell of the tail cone was originally made in two extremely expensive halves, which were mechanically fastened together. The redesigned tail cone was made from a one-piece unstiffened skin with secondarily bonded pre-cured strings of continuous beaded stiffeners. The replacement design had already been validated in production for the tail cone of another aircraft, as described in Ref. 3. These new stiffeners were flattened at each frame station, but were structurally continuous with respect to transverse shear and longitudinal loads, eliminating the possibility of delaminations where the previous stiffener segments had been abruptly terminated adjacent to each frame, to simplify the construction of the frame. Many more details of this redesign, and its implementation, could be told. But,

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* Strictly, the target should be raised by a further $100 to allow for the extra pound of primary structure.

suffice it to say, here, that a roughly *six-fold increase in part count resulted in a three-fold reduction in cost of manufacture (including the cost of new tooling)!*

The author is unaware of *any* situation in composite secondary structures where such an outcome should *not* have been anticipated – and aware of very few such applications where the design and manufacturing concepts actually used enabled such benefits to be realized. Significantly, the only composite assemblies on Douglas commercial aircraft to match the price per pound of equivalent metallic structures, such as the outboard ailerons on the MD-11, were all made by secondarily bonding *simple* wrinkle-free details together. The cost savings accrued from replacing about 90 percent of the fasteners by simple adhesively bonded joints. This, in turn, permitted substantial weight savings by eliminating the need for local thickening of the components that would have been needed for seams of fasteners. And to prove that the composite tail-cone experiences were no fluke, similar co-cured control surfaces for another application cost twice as much per pound as did these secondarily bonded ailerons.

Apart from saving on the cost of manufacture, the use of secondary bonding enables the stiffener run-outs to be far more structurally sound than commonly occurs when the run-out details are compromised by a decision to co-cure skin and stiffeners together. Access for removing mandrels often prevents material from being included where it is most needed, resulting in weaker alternative load paths. It also forces discontinuities in such stiffeners, which have been a real problem with several highly loaded composite structures, as well as a major nuisance with many such secondary structures. What have been found over the years to be adequate load paths for secondary loads in isotropic metallic structures are often found to be inadequate for composite structures because the enhancement of fibre-dominated in-plane loads is accompanied by far greater reductions in transverse, matrix-dominated, strengths of composite laminates. In other cases, co-curing has resulted in such mark-off on the skins that the entire outer surfaces had to be hand glazed and sanded before painting. Is this not a second operation, equivalent to secondary bonding, which can produce skins of far higher quality that need no such finishing? On the other hand, *some* co-cured structures have been successful – because the applications permitted designs that did not suffer from distorted or missing load paths, and because the fabrication techniques needed for these specific components were simple, rather than complex.

This problem of inappropriately integrated stiffeners is not confined to composite structures. What is not commonly recognized is that stress concentrations at bolt holes in metallic structures are on the order of only 3, whereas those associated with improperly terminated integral stiffeners are often as high as 10. Designing large *lightweight* integrally stiffened panels that need to be joined to each other is no trivial undertaking. Built-up structures have inherently superior damage tolerance, because of the multiplicity of load paths and better crack-arrest capability. They also have more flexibility, and hence lower stress concentrations at stiffener run-outs, whenever they do not extend to the very ends of the panel, something which is usually avoided since it complicates the splices. This same flexibility makes it easier to align stiffeners across skin splices without any need for shimming or concerns about interference fits. Adhesively bonded stiffened panels gain all of the benefits in regard to crack arrest and low fatigue-crack growth-rates through laminated structures. However, experiences on the pressurized wide-body fuselage built and tested under the Primary Adhesively Bonded Structure Technology (PABST) program confirmed the unforgiving nature of any poor detailing at the frame/stringer intersections. Bonded internal gusset plates were needed to complete the hoop-wise load path and avoid the kinds of skin cracks developed at the mouse holes in some flat-panel tests. The problems, and their successful resolution, are documented in Ref. 8.

It is equally true that castings, when applied where their properties are suitable, can achieve very great cost reductions with respect to built-up metallic structures. And Ref. 4 includes typical examples where parts consolidation *is* appropriate, without contradicting any of the information contained here, because the *contexts* were different. The important message is that, no matter how many times parts-count reduction has been used successfully to reduce costs, there are so many instances when it had the opposite effect that a reminder is needed that it is only a *tool.* When misapplied, it defines too narrow a goal and becomes, instead, a counterproductive *constraint.*

THE VALUE, OR COST, OF QUALITY

The final issue to be addressed here is the ambiguous relation between cost and quality (or precision). Despite a perception that higher quality can command higher prices, and thereby justify higher costs, higher quality in the right places can actually *save* on cost – at least on *total* cost. Higher quality in production obviously results in reduced costs of inspection and rework, for example, unless the baseline quality is already near perfection. Every defect or discrepancy that is detected must be tagged, dispositioned, and possibly repaired or replaced. More liberal tolerances in manufacturing might reduce *their* costs by accepting work that would otherwise be scrapped, but this is *not* the best approach for the *entire* organization if the downstream costs exceed the cost of scrapping the parts, as is often the case.

The author once explained this to the managers of a large US adhesive bonding facility. The first response to a bond defect should be to find the cause to prevent its recurrence, not to ask Engineering to buy it off, as is. By examining the bonding tools where defects were found during the inspection process, in metal-bonded structures, and finding local areas slightly out of contour, simple adjustments or reworking were found to eliminate any further such discrepancies. Stiffeners that were not quite straight enough to fit properly against the skin could be reworked *before* bonding, once the supply of details at the bond shop had been increased from one set to two, by sending them back to the other factory where they were made, for straightening. With *no* spare details available, bonded assemblies had to be made with what was available, to meet schedule. This, too, had contributed to the MRB action. Because most such defects were structurally tolerable, no effort had previously been made to eliminate them. One outcome of this change in approach was that, by the time the author had completed his task of helping those building these parts, six large bonded wing-skin assemblies had been made in succession, without a single defect! The factory assessment showed that these were the *least* expensive panels they had ever bonded. Pre-bond fit checks were reduced, as was the need for additional adhesive to fill gaps between the parts. Post-bond inspection costs had been minimized and MRB action eliminated, for a trivial cost in simple reworking of the tools. In this case, and others, the minimum cost was achieved by *tightening* tolerances. Conversely, for panels that *did* contain defects, the best course of action was to repair only the largest of defects, because most such repairs do more harm than good, by breaking the environmental protection and thereby reducing the life of the part with no increase in its strength. This is a perfect example of how manufacturing, by acting alone, had been *reducing* its costs – by not fixing its own problems and creating additional work in *other* departments – but did not truly *minimize* its *own* costs until this particular task was tackled from a more global perspective.

Higher precision early in an assembly process can reap tremendous savings in final assembly, particularly with large structures. Indeed, it is simply not *possible* to automate the assembly of low-precision detail parts.

The cost of quality, its creation, and the measurement of compliance are among the most interactive of all costs and, therefore, in the greatest need of being assessed at a global, rather than incremental level.

HOPE FOR THE FUTURE

Specific technical examples in this paper have identified instances where what seem to the author to have been avoidable costs have been incurred, or opportunities to save cost missed. There are also some success stories, but many of these refer to solving a problem that need not have existed, had there been a better overall perspective during design. Conversely, the author could cite many success stories, from his own experiences and from observation, that were successful precisely *because* they were contrary to tradition. The PABST adhesively bonded fuselage demonstrator program, performed at Douglas Aircraft under contract to the USAF Flight Dynamics and Material Laboratories at Wright-Patterson AFB was the most successful R&D undertaking for all involved for decades before and decades since. It was run in isolation from the main organization, with a largely co-located small team in a single building. The same building housed the X-shop team that developed the YC-15 prototype transports – so efficiently that there was money left over to build and fly a second, larger, wing, and to install and fly a later engine, with better fuel efficiency, without over-running the *original* budget. Regrettably, this same isolation made it more difficult to transfer this technology and improved approach to program management back to the home groups for exploitation.

The World-renowned Lockheed Skunk Works operated the same way, except that they were empowered to take the development of new ideas right through to production. They have *many* outstanding products to their credit, including the F-80/T-33, F-104, U-2, SR-71 and the F-117A. A history of the accomplishments of this organization is recorded in Ref. 9. To quote from p. 26 of this book; "Robert E. Gross, former president of Lockheed Aircraft Corporation, gave his permission to Clarence L. (Kelly) Johnson in mid-1943 to pirate 27 engineers and 105 shop mechanics from other projects to form the original Skunk Works". It is significant that it was provided with a succession of new products to develop. It did not languish into disuse and have to be re-established each time.

The Lear Fan all-composite executive transport was developed, and flown, for a minuscule price by contemporary standards, because it was created by a small, enthusiastic team in the Nevada desert, just outside Reno. Very few of the engineers had prior experience in composite structures. However, the appeal of the project was so great that it acquired help from about half a dozen of the best experts in the country and, through their contacts, access to virtually the entire nation's expertise on the subject. Everyone wanted it to succeed. It ultimately failed for financial, rather than technical reasons, as explained in Ref. 10. But, on the way, an entire composite aircraft was designed, built, and successfully flown for about the same $20 million dollars as it took the very much larger Douglas Aircraft Company to design, test, to build 20, and to introduce in service 15, composite upper aft rudders for the DC-10, under a NASA Langley contract (see Ref. 11) a few years earlier. Yet, by 'big-company' standards, the composite rudder program was itself an outstanding success. The preliminary design of these rudders, one of which has more flying hours (some 80,000 during the past 20 years or so) than any other composite component on *any* aircraft, was completed by a small (3-man) 'second team' while the first team was pre-occupied with a much larger primary structure component.

These successful teams were all *lean* in today's usage of the word, but none that the author participated in was ever 'mean'. In every such case, there was a single, capable, leader who knew exactly what was happening throughout his entire organization – either as the result of spending hours each night reviewing design drawings and leaving comments and suggestions for the designer, for example, or by relying on a lower-level expert experienced in all of the disciplines to keep him informed. In every case, these programs were *led*, rather than *managed*. The opposite is true of those programs the author has seen fail to achieve their real, as distinct from paper, goals.

As noted earlier, such small teams tend to be self-forming. The tasks need to provide a technical challenge for the members of such teams, who must perceive a real need for the product and have faith in it. This is why it was so easy for the then new space program to attract innovative engineers from the aircraft industry in the 1960s, once the number of new aircraft produced per year started its steady decline. Such teams are very difficult for managements to create; they are *not* the residue of shrinking (down-sizing) a large organization. The ideal qualifications for membership often derive more from a person's hobbies than from his assigned work. What management needs to do to harness such assets is to nurture, rather than to stifle them – or, worse still, to drive them from the company by *not* developing new products to make such employees *want* to work there, or to inhibit them by the weight of a succession of bureaucracies and procedures developed *in lieu* of new products.

CONCLUDING REMARKS

Some might argue that the examples cited here of "missed opportunities to save on real costs" could be tied to the individuals involved, and that others might have done better. The author does not believe that this is the *major* factor. These anecdotes are symptoms of an organizational focus on *sub-tier goals* rather than on the best possible set of *overall objectives*. The primary message of this paper is that, without a better set of goals, anyone else would still have had to overcome the same kind of pressures to do the 'wrong' thing. There is a better, and quicker, payoff to be obtained by removing these pressures than in re-training all of the management, and their financial advisors. Deming told us how. All we need to do is to listen and understand.

One intent of this paper is to encourage those involved in this and other industries to make decisions based on *total* costs, and *total* times taken from concept beyond delivery of the final complete products into the period of maximum profitability, from selling spares. The same distinction needs to be drawn in regard to overall structural weight.

To paraphrase yet another famous quote, from Abraham Lincoln; "You can minimize some of the costs all of the time, or all of the costs some of the time. But you can't minimize all of the costs all of the time."

During the 30 years that the author has worked in the aerospace industry, he has observed two truisms that merit repeating. The first is that the least expensive way to complete a task is to do it right the first time, *no matter what it costs.* The second is that to complete a task in the shortest possible time, one should do it right the first time, *no matter how long it takes!*

The author would add a personal observation that the one activity he sees as being in greatest need of improvement in the aircraft industry is the ability to correct a mistake or to implement an improvement quickly, and inexpensively. This in no way belittles the importance of doing things right the first time; rather, it is intended to decrease the penalties associated with the inevitable impossibility of being right the first time, *every* time.

The paper has included several typical examples to help those at the technical level identify opportunities for cost savings, in design and production, and to broaden their perspective to appreciate how the actions of what they have customarily perceived as *independent* departments can both undermine and enhance their own. The point is that there needs to be better communication, and better co-operation. There should be no recurrence of the situation in which, for the leading-edge skin of a mass-balanced control surface, tungsten balance weights were installed to compensate for the weight removed by chemically milling the skins to save weight – for in excess of 20 years!

The paper has not dwelt exclusively on malpractices that need to be stopped. It also includes the author's observations, some of which he knows *are* shared by others, about the characteristics of the *successful* development of new products. These include small teams, ably led, working enthusiastically, and *supported* by their managements. It is noted that such teams are often self-forming, from the bottom up, rather than created from a tops-down organization. However, they *have* succeeded in the *same* global business climate that has inhibited the financial success of larger undertakings; they have a proven track record when other alternatives do not. Supporting a few such small teams, even if only one at a time until the entire company operates this way, could well be the *only* way for large bureaucracies to survive (albeit in diminished form). This is particularly true when managements have already convinced themselves that 'business-as-usual' is a recipe for eventual disaster. Sixty years ago, such teams represented *entire* organizations. Today, they would not survive in isolation; they need access to considerably more technical support than they can generate themselves in today's far more complicated world.

Specific examples have been cited here where minimizing some individual costs has been very detrimental to the overall success of various projects. Many more could have been identified. Contemporary economic policies often do *not* achieve what is claimed to be their goals. Fortunately, for anyone willing to heed the messages, a fully developed science has been available from the world of mathematics to explain the complex interactions between multiple variables in seeking optimum solutions. In a nutshell, they state incontrovertibly that attaining *globally* optimal results requires that *some* incremental costs cannot *simultaneously* be minimized. Minimizing all, or even many, of the incremental costs in isolation serves only to *constrain* the process of overall cost minimization, and to *PREVENT* the potential minimum cost from ever being approached. Some costs can be *reduced* in isolation, but very few can be *minimized.*

The attitude of asking "What can I contribute to minimizing the costs of the department to which I belong?" must be replaced by the idea of "What is it that I and the department to which I belong can contribute to minimize the costs (or maximize the accomplishments) of the *entire* organization?".

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