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DEVELOPMENT OF A METHOD FOR DETERMINING THE RELATIVE MANUFACTURING COMPLEXITY OF ADVANCED ENGINEERING MATERIALS

by

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A Dissertation submitted to the Faculty of Old Dominion University in Partial Fulfillment of the Requirement for the Degree of

DOCTOR OF PHILOSOPHY

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May 1997

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ABSTRACT

DEVELOPMENT OF A METHOD FOR DETERMINING THE RELATIVE MANUFACTURING COMPLEXITY OF ADVANCED ENGINEERING MATERIALS

SHARDUL Y. PANDYA, ABD.
Old Dominion University, 1997.
Director: Dr. Han P. Bao.

The immediate adaptation of newly developed materials—with unique and highly desirable properties—is hampered by several factors, including:

- high material cost and limited availability
- lack of information on them, including prior experience in their design and manufacture, immature manufacturing processes and general uncertainty in their behavior patterns
- unique handling issues, such as excessive manual labor, high process temperatures, toxicity, disposal problems, limited working lives, and low damage tolerance

Therefore, in spite of their significant benefits, potential users tend to shy away from the widespread use of new materials, instead preferring conventional and tested materials forms.

This dissertation is on a methodology developed to compare manufacturing complexity of new materials with that of conventional ones. It entails development of a 5 level multi-attribute hierarchy of 18 factors and several processes that influence the manufacturing risk of new materials. A Manufacturing Complexity Factor (MCF) and a Delta Complexity Factor (DCF) are developed to compare new materials with older, traditional ones. The Analytic Hierarchy Process is used to judiciously assign weights to all factors and sub-factors.

Materials are assigned "ranks" based on information available about their unique properties and requirements. From the rank and attribute priorities, values for MCF/DCF can be obtained. Since information available is often

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limited, the ranks assigned to materials are not highly accurate values. The Monte Carlo simulation technique is used to take away some of the uncertainty in the ranks of the newly developed materials and generate a more "robust" MCF/DCF value.

Sensitivity of the method to varying inputs is examined. An attempt is made to compare this practical methodology with two popular approaches, one used for analyzing the complexity of composite materials and another that develops manufacturing complexity factors for given input parameters. It is shown that the methodology in this dissertation generates results not possible by either of the other two methods.

Co-Directors of Advisory Committee: Derya A. Jacobs
Bllie M. Reed
Resit Unal
Sebastian Y. Bawab

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this work is dedicated to

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A sincere thank you to my parents and my grandfather for all the guidance throughout my formative years, and an apology for all the sleepless nights I must have given you back then. Finally, my heartfelt acknowledgment and a sincere thank you to Bela, whose personal sacrifices for my benefit can never be repaid.

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LIST OF ACRONYMS

Acronym	Meaning
A-bC	Activity Based Costing
LF	Lay-up Forming
A-bM	Activity Based Management
LOX	Liquid Oxygen
ACCEM	Advanced Composite Cost Estimating Manual
MATUR	Maturity
AHP	Analytic Hierarchic Process
MC	Material Cost
Al-Li	Aluminum Lithium
MCF	Manufacturing Complexity Factor
ANOVA	Analysis of Variance
MCPLXS	Manufacturing Complexity
ASEE	American Society of Engineering Educators
MFG	Manufacturability Issues
CER	Cost Estimating Relationship
MI	Machinability Index
CIM	Computer Integrated Manufacturing
NASA	National Aeronautics and Space Administration
CM	Compression Molding
ODU	Old Dominion University
CR	Consistency Ratio
PEEK	Poly-ether-ether-ketone
CS	Computer Science
PLTFM	Platform
CSSD	Composite Spacecraft Structures Design Guide
PRECI	Precision
DB	Database Extent

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Acronym	Meaning
PRICE	Parametric Review of Information for Cost Estimation
DCF	Delta Complexity Factor
PRICE H	PRICE Hardware Model
df	degrees of freedom
PRICE HL	PRICE Hardware Life Cycle Model
DM	Diaphragm Molding
PRICE M	PRICE Electronic & Microcircuit Module Model
DOD	Depart of Defense - US Government
PRICE S	PRICE Software Model
ENMA	Engineering Management
PUL	Pultrusion
FW	Filament Winding
rn	random number
GDSS	General Dynamics Space Systems
RTM	Resin Transfer Molding
GMA	Gas-Metal Arc Welding
s/s	Sheet and Stringer
Gr.-Ep	Graphite-Epoxy
ThF	Thermo Forming
HN	Handling Issues
VPPA	Variable Polarity Plasma Arc Welding
IM	Injection Molding
X-NFR	eXtended Normalized Factor Rating
LCCW	Low Cost Composite Weapons—Program Report

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APPENDICES

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CHAPTER I

INTRODUCTION

The demands on materials serving man in the space age are considerably more rigorous than on those in centuries' past. These demands have fueled research interest, corporate curiosity and private and government money into the study of composite and other material forms as possible substitutes for traditional steel and aluminum. Given the sophistication of research and development today, an almost endless combination of material forms can be created, with unique properties—often tailored to a specific application.

The aerospace industry—which has been using conventional aluminum alloys for its parts and structures—has traditionally taken a keen interest in new material forms—such as plastic-matrix composite materials, metal-matrix composite materials and other advanced metal alloys—because new materials can offer the unique properties that aerospace parts need at lower densities than that of conventional aluminum. Aircraft and spacecraft parts are highly weight-sensitive structures, and so aerospace designers are enthusiastic about the lighter alternative that the new materials present—specifically, strength-to-weight and stiffness-to-weight ratios lower than conventional aluminum. Weight savings can directly result in reduced launch and mission costs, reduced fuel consumption and increased payload capacity. It is estimated that every pound of weight reduced on a spacecraft can result in between $10,000 and $50,000 in cost savings [2, 29].

Moreover, it is possible to develop composite materials with properties specifically tailored to requirements, something not achievable in conventional aluminum. Therefore, composites have been used in spacecraft applications as an enabling technology—even when cost savings or weight reductions are not

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necessarily high [29]. Consequently, as one might expect, it has been recognized that composite materials are indispensable in aircraft and spacecraft applications [29, 44]. This has significantly contributed to the development of new composite materials, in the study of their properties, and in the development of their manufacturing processes [11].

Unfortunately, immediate adaptation of newly developed materials in aircraft and spacecraft structures—as in other commercial applications—is impeded by several factors. These include [1, 2, 7,9, 15, 17, 29, 44]:

- The new materials are expensive;
- There is a very limited number of suppliers;
- The newly developed materials are not always fully tested or proven in the field;
- Many of the fabricating processes are not fully developed;
- In many cases, the manufacturing equipment is inhibitively expensive;
- Processing and manufacturing of composites is often highly labor intensive;
- Low production volume deters automation, and therefore cost remains high;
- Some composite materials are potentially harmful to the environment, toxic to their human handlers, and are not recyclable;
- The unique environment of space—vacuum, and cycles of extremely high followed by extremely low temperature—is liable to degrade the integrity of a composite structure, thereby putting a space mission at risk;
- There is a serious lack of any manufacturing database easily accessible to the users of these materials and structural designers;
- Designers often use design and manufacturing practices that have been learnt while working with conventional aluminum designs.

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Composites present new challenges and requirements that are either not known or not realized;

- There is a great amount of uncertainty associated with new materials which tends to make potential users shy away from using them;
- Conventional accounting systems tack company overhead costs on to direct labor as a percentage or multiplier factor of direct labor hours. Since composites often require high labor to process assemble and inspect, this further augments to their per-part costs;

and

- Conventional costing methods require heavy reliance on the existence of process plans, with very specific material, process and labor rates. For parts fabricated using new materials, a process plan may not exist, or may be very rudimentary. Costing of such parts is very inaccurate or often incorrect.

Furthermore, not too long ago, a newly developed material with better strength-to-weight or stiffness-to-weight ratios might be considered for an application on the basis of its performance measures alone. However, today spacecraft development is under very close scrutiny in terms of cost expenditure. Therefore, as with everything else, the costs associated with a composite material are *"considered more important than a number of other selection metrics"* [17]. Today, even government agencies—such as DOD and NASA—and their contractors have to consider the cost implications of an enabling technology before exploiting the said technology.

Therefore, there is a need to develop a unified method to evaluate a new material for a given potential application. This need is addressed in this research proposal, in the form of a **RESEARCH QUESTION:**

Suppose a program manager or designer were exploring different materials for some proposed part or structure. Further suppose, that while some conventional material were

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suitable for the part, a newly developed material was also a possible candidate. Given the fact that there exists a tremendous uncertainty related to newly developed materials, can a unified method be developed for potential users that would enable them to select the most appropriate material from a given set of materials?

The concern voiced in the above question is not new. It has been known for some time now, that the uncertainty related to new composite materials needs to be addressed for the industry to exploit their remarkable properties. In Chapter II, some alternatives that have been espoused to answer the research question are presented. In Chapter III, it is explained why, in spite of considerable research on composite material uncertainty, there is a need for more work. The research question is then presented as a formal research hypothesis. It is proposed to test the hypothesis on composite as well as conventional materials; and on specific aerospace parts, as well as in a generic comparison.

In Chapter IV, one of the alternatives espoused to answer the primary research question is revisited. That alternative is developed into a formal research methodology. It is proposed to use the methodology to test the research hypotheses. A sample material comparison is also made in Chapter IV. In Chapter V, the methodology is used to make specific comparisons between challenger and defender materials. Comparisons are also made between the results of this effort and another published result. Thereby, the proposed methodology is validated, and hence the hypothesis is accepted. In Chapter VI, the sensitivity of the methodology to different input parameters is examined.

In Chapter VII, specific comparisons and differences are drawn out between the methodology developed in this research and two other approaches that could be used to address the research question. It is shown that both of

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the other methodologies are excellent at what they are intended to accomplish. However, their results are divergent, and not as encompassing as those of the methodology developed in this dissertation. Hence, this work is presented as the only all-encompassing approach to comparing the manufacturing complexity two materials. Finally, in Chapter VIII, some concluding remarks, including areas for future development, are presented.

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CHAPTER II

LITERATURE REVIEW

The following steps have been undertaken to study the general applicability of newly developed materials in the industry. There are several other works geared towards the manufacturability of specific materials. However, these being too narrow in scope, are not accounted for in the following review.

2.1. LCCW AND CSSD REPORTS

After extensive studies, two highly detailed reports concerning advanced composite materials have been published. These are the LCCW program report and the CSSD guide.

Towards the end of 1988, the McDonnell Douglas Missile Systems Company authored a report, sponsored by the US Air Force. It was called the "Low Cost Composite Weapons Program", or LCCW. The program objective was to develop a broad "technology base" on several composite materials and their manufacturing processes. Their report is a reference handbook on composite materials, their manufacturing processes, tooling, assembly and quality issues. This detailed, extensive and highly comprehensive report has been prepared in an effort to meet a "need to reduce cost of our (US) defense systems, while maintaining high performance". It contains lists of guidelines, in handbook format, on the specifics of several composite materials and their manufacturing processes [44].

Another similar report is the "Composite Spacecraft Structures Design (CSSD) Guide". It is prepared under the supervision of a team of industry, university and government personnel who have had "extensive practical experience" in the design of spacecraft structures. The list of corporate members of this team reads like a who's-who of organizations working with the space program. The document was developed because the existing documents

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on design of composite structures "do not adequately cover the issues of interest to spacecraft program managers and preliminary designers". Like the LCCW program report, this too is a highly extensive reference document to be used in the development of potential composite structures. It addresses all aspects of design, fabrication and service, with an emphasis on the space environment. It is designed to serve as a resource document, and provides references to more advanced design information [29].

Both the above reports are excellent resource materials for the intended reader. They both require box files about two inches thick to hold the extensive material they contain. They are both prepared by reputed professionals in the field, and are expected to be highly useful to fellow professionals designing structures composed from composite materials. They both provide extensive information on several composite materials in descriptive, tabular and graphical format. However, they do not present the reader with any structured basis for selecting between two composite materials for use on a specific structure.

2.2. PRICE H

The PRICE System's PRICE H module (Parametric Review of Information for Costing Evaluation - Hardware) is an extremely powerful and very popular costing program. It has been used in deriving cost estimates for several different applications in many industries for more than 30 years. Originally developed by RCA in the early 1960's, it is currently owned by the Lockheed-Martin Corporation. The PRICE models are also used in the aerospace industry for financial, cost analysis and cost estimating purposes, including the estimation of composite parts. PRICE H is a highly conventional and traditional costing approach, and the accuracy of its results is based on the accuracy of the input data. Needless to say, given the uncertainty of composites, inaccurate input data leads to inaccurate cost models [8].

The PRICE H module includes a "Manufacturing Complexity" generator. In theory, this could be used to quantify the manufacturing complexity of new

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and existing materials, and hence evaluate newly developed ones. However, the Manufacturing Complexity generator is limited in scope, and hence its ability to evaluate new—or existing—materials is also limited. This limitation, and hence the superiority of the methodology developed in this dissertation, are further discussed in Chapter VII.

2.3. The ACCEM model

A standard method of estimating fabrication time or cost for most parts is to use some form of a detailed process plan. Each process and sub-process step can be estimated and parameters summed to get an estimate of the part fabrication time or cost. An extension of this method was proposed for composite parts in the Advanced Composites Cost Estimating Manual (ACCEM) developed by Northrop Corp. for the US Air Force [Referenced by 7, 9, 10, 21, 30]. The ACCEM model involves estimating the time for each step in the process plan as accurately as possible. Using a log-log paper, the time is then plotted versus some prominent design parameter of the part—such as length or weight. From this plot, a "power-law" relationship is developed between the variables. This relationship, can be extended to other parts or composites.

However, accuracy of this empirical method depends heavily on the accuracy of the input data. Naturally, given the uncertainty of process knowledge, this method is not the best means of estimating manufacturing cost of newly developed composites. Furthermore, models developed in the ACCEM manual are cumbersome, and do not easily incorporate changes as processes evolve [30].

2.4. Scaling Laws by Gutowski

A major research effort aimed at overcoming the ACCEM's limitations comes from a group led by a Dr. Timothy G. Gutowski of the Laboratory for Manufacturing and Productivity, at the Massachusetts Institute of Technology. Their framework for estimating fabrication time and manufacturing cost of advanced composites extends the power-law relationship to "general scaling-

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laws". This process offers *"physical interpretation for the most important effects of part size and complexity"* [30]. Part costs are rank ordered for different designs within a certain process. Size, design and complexity scaling laws are developed to estimate fabrication time.

The scaling laws of Gutowski incorporate one important observation into the power law models of the ACCEM method. In the ACCEM method, time estimates are diligently made for all the individual steps in a manufacturing process. However, Gutowski et al. claim that Pareto's Law of "vital few, trivial many" applies to composite fabrication. Based on several observations, a pareto plot is developed [10, 30]. It clearly shows a distribution where a bulk of the fabrication time is taken up by a very small number of operation steps. This 80/20 distribution is exploited to simplify the time estimating procedure in the scaling laws model.

Instead of estimating each of the several process steps—often using unavailable or unreliable data and unknown or incomplete process steps—effort can be concentrated on a few dominating steps. These steps can be identified based on expert opinion or manufacturing preplans. The remaining steps can then be scaled over the dominating steps to obtain an estimate of the part fabrication time. To a first approximation, Gutowski says, this scaling can just be a multiplier. The system user is then free to concentrate on improving estimates of the few vital steps. Detailed modeling, experimentation or comparisons are suggested as the means of examining and improving on the few vital steps. As more process knowledge is gained and existing data is more reliable, the above method can be repeated.

Physical significance of the scaling is derived based on another observation of composite manufacturing data. Based on review of considerable data, Gutowski, et al. claim that manufacturing operations can be represented as dynamic systems with first order velocity response to a step input [30]. The manufacturing processes are then characterized by two physical constants, τ

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and v_0. τ is the dynamic time constant, with the unit of time; and v_0 is the steady state velocity, with dimension (λ/time); where λ is an extensive part measure (length, area, weight etc.). Power law equations developed for the first order velocity response using λ, τ and v_0 are directly correlated with the power law models of the ACCEM. The physical significance of τ and v_0 is used to facilitate the rough estimates of the vital few steps. The process parameter values of τ and v_0 can be found based on physical arguments and comparisons to similar class of problems [9, 10, 21, 30].

The mathematics involved in developing the scaling law models is not exactly elementary. For this reason, possibly, the application of the scaling laws by a novice is not straight forward. However, it is acknowledged that this is an important development in the cost and time assessment of composite manufacturing. This approach does incorporate the general uncertainty associated with composites, which is the goal of the present research program. For this reason, in Chapter VII, the Scaling Laws approach is compared to the methodology developed in this dissertation.

2.5. Techno-Economic Study by Foley

Foley [7] has studied different manufacturing processes, composite parts and design geometry's with an economic/geometric perspective. He acknowledges that several processes and techniques for manufacturing composite parts lead to confusion in selecting the "optimum" process. Selection of the actual process is dependent on several considerations, including cost, the design geometry of the part, and batch size. Foley establishes some general guidelines for selecting the optimal manufacturing process for processing composite materials, given a certain part geometry and manufacturing scenario. His work compares five manufacturing processes amongst four raw materials over three different part geometry's. The results are specific suggestions for selecting among the process/material/part geometry studied in his paper. General conclusions that can be inferred from the study

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are also presented. However, while Foley's study discusses specific processes, material types and design geometry's, this work does not extend to the general uncertainty related to new composite materials.

2.6. AHP AND A-bC BY KARBHARI

Dr. Vistap M. Karbhari of the Center for Composite Materials, Department of Civil Engineering, University of Delaware has published articles related to the cost aspect of composite materials. One of these discusses the use of Saaty's Analytic Hierarchy Process (AHP) in making a decision to use a composite material for an automotive part [17]. This paper is not on the economics of composite versus conventional materials, but more on a "go-no go" decision being reached using the AHP, and the advantages of the AHP versus other decision methods.

Two other papers by Karbhari and Jones [17, 18] exemplify an important cost concern when dealing with composites—the inadequacy of standard cost methods when dealing with composite materials. Standard costing methods treat company overheads as a multiplier to direct labor costs, thereby treating composites unfairly. Karbhari and Jones propose Activity-based Costing (A-bC) and Activity-based Management (A-bM) as methods of identifying and controlling manufacturing costs. Using A-bC and A-bM, they present a tool for understanding costs during the initial design phase, and controlling product cost during manufacturing. A-bC recommends the use of "cost pools" to assign the cost of different activities that contribute to final cost. This contributes to the analysis of activities for improvement opportunities, and elimination of waste or redundancy. It also helps in identification of activities that contribute to the success of the composite part.

2.7. MCF/DCF FACTORS BY BAO

And last, but not least, is Dr. Han Bao's work on manufacturing risks assessment related to composite materials for spacecraft structures [2]. Bao's work is two-fold. First, he has generated a manufacturing database of eight composite materials that are considered potential candidates for use in

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spacecraft structures. These eight materials are individually ranked to represent their risk and reliability. The ranking is based on six factors: raw-material costs, handling problems, and problems related to manufacturing processes, tooling, labor and quality assurance. Eight manufacturing processes are highlighted in the database. These are the ones most frequently used while manufacturing composite structures for spacecraft applications.

Second, in order to analytically evaluate the manufacturing complexity associated with composite materials in the database, Bao has developed a Manufacturing Complexity Factor, or MCF. As mentioned, the database establishes six factor-groups for addressing manufacturing complexity. Based on the information available on these six factor-groups, the MCF generates a rating among two or more materials vis-à-vis each other. The methodology is based on the individual manufacturing complexities of different materials. Theoretically, any number of materials can be compared with each other using the MCF.

The MCF calculations assume that one of the materials being compared is a baseline material—a defender. It is accepted that the user is familiar with the defender—with its properties, capabilities, problems and cost. The MCF calculations are intended to be performed when some new composite material—a challenger—presents itself. Suppose a newly developed composite material were available in the market that merited a closer look, but about which only a little was known. Then, by amassing all available information on the challenger material, its manufacturing complexity could be compared against that of the older defender material via the MCF.

Bao's work further introduces a Delta Cost Factor, or DCF. Based on MCF values, the DCF gives an approximate measure of how much more expensive—or inexpensive—the challenger is over the defender.

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2.8. CONCLUSION

In this chapter, seven different methodologies are discussed. Each of these has been espoused in order to evaluate newly developed materials for specific applications. However, as discussed, each has its own limitations, which hinder in it being called a truly unified methodology.

—

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CHAPTER III

RESEARCH HYPOTHESIS

The research presented in this thesis is essentially developmental in nature. It attempts to provide the structured basis for choosing between two materials—a newly developed challenger, and a well-known and tested defender. In Chapter 2, seven other methodologies were discussed, all of which could possibly be used to make the same selection. However, an underlying limitation in them all—Bao's methodology to a lesser extent—is the lack of a structured and uncomplicated basis. While Bao attempts to do this with his MCF and DCF values, all other work either develops a descriptive database for specific applications, or submits complicated, sometimes cumbersome cost and time models for fabricating composite structures.

The methodology developed in this dissertation builds upon the groundwork laid out by Dr. Bao with his MCF and DCF calculations. The direction of this research can be stated in terms of the following RESEARCH HYPOTHESIS:

> **Accounting for the high amount of uncertainty associated with newly developed materials, a unified methodology can be developed for selecting the most appropriate material from a given set of materials.**

As stated above, the hypothesis does not differentiate between composite and conventional material forms. It simply states that a methodology can be developed which would select "a" material from a "set of materials". Admittedly, it is not necessary to differentiate between composite and conventional materials in a unified methodology—it should handle both. However, it is important to note that this research will be carried out because of the complexity and uncertainty associated with newly developed composite materials. Had the issue been a comparison between regular, conventional

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materials—such as steel and aluminum—there would be no need to write a thesis. These materials have been used in their present form for several years, and their use is well defined and documented. Therefore, although it is not explicitly stated in the hypothesis, this research is limited to a comparison that includes newly developed materials—composite or otherwise—which have some uncertainty associated with them.

Secondly, the data used to test the methodology is drawn from aerospace applications. It is acknowledged that the methodology developed herein should be applicable to all parts and structures developed using new materials— indeed, that is the contention. However, this research is confined to materials used in designing spacecraft and aircraft parts. Other applications, such as parts of automobiles and toasters—although suitable—will not be evaluated during the current research program. They can and should be addressed during further development work.

Therefore, assuming that among a set of materials being evaluated:

- at least one of the materials is a new material with uncertain properties;

and

- they are being evaluated for an aerospace application

a unified methodology can be developed to select the most appropriate material from the given set. This is the hypothesis.

To ensure that the developed methodology is what it portends to be, it has to be tested. Possibly, the best means of testing the unified method would be to:

a) make a comparison such that it can be determined that for some part, material B is say X% more complex to fabricate than material A;

and

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b) follow-up the comparison by actually building that part using material B and determining whether the effort required to make that part was indeed X% more than when the same part was being manufactured with material A.

However, since physically manufacturing an aerospace part is beyond the scope of this dissertation, the developed unified method will be tested by asking it the following questions:

- If a unified methodology were developed, could any two or more materials be compared with each other?
- Can the methodology be readily applied to two disparate materials—composite and conventional?
- Are there any limitations or special considerations while comparing composites?

As stated, the hypothesis does not differentiate between generic material selection and selection for a specific part or structure. Therefore, the following question would also be posed:

- If a generic methodology is developed to compare two or more materials, will it be specific enough for a particular part or application?

In Chapter IV, an existing method is built-up into a unified methodology to address the hypothesis. This methodology is tested in Chapter V. Sensitivity issues are discussed in Chapter VI.

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CHAPTER IV

RESEARCH METHODOLOGY—THE 'X-NFR' METHOD

The work done in this dissertation is essentially developmental in nature. It builds on the groundwork laid out by Bao in his MCF and DCF calculations [2]. The following discussion details the proposed work. Section 4.1 is an overview of the general methodology, called the Normalized Factor Rating Method. Its specific application to evaluating composite materials—as adopted by Bao—is discussed in Section 4.2. The limitations and recommended modifications of that work are presented in Section 4.3. These modifications lead to the development of a new problem structure, which is discussed in Section 4.4 along with a sample result.

It is intended to show that the new problem structure would result in a methodology more robust than the one developed by Bao. The proposed methodology would be used to compare materials for a specific part, as well as to make a general comparison. These comparisons are described in Chapter V.

4.1. The Normalized Factor Rating (NFR) Method

NOTE: In order to develop the MCF/DCF calculations, the Normalized Factor Rating method uses a 2 level factor/sub-factor hierarchy. In the discussion here onwards, the words "factor" and "sub-factor" are used interchangeably with the words "attribute" and "sub-attribute" respectively.

The methodology developed for the MCF calculations is based on methodologies often used in cost, performance evaluation and payback period analysis [3, 13, 14, 32]. The "spirit" of the method can be traced back to a letter written by Benjamin Franklin in 1772 [3]. Applications that closely parallel the MCF computations of Bao can be found in a methodology for evaluating robots [13, 32], and an evaluation of CIM alternatives [3]. It has also been adopted in an evaluation of alternatives for developing teaching methods within a Systems Engineering perspective [35]. The specific developments described in this chapter have been discussed in Pandya & Bao [34]. The methodology, and its several variations have different names, including "multi-objective model",

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"evaluation method for robots", "weighted evaluation of alternatives", and "the weighted evaluation of alternatives with subjective and objective factors". Since the weights of alternatives in all these problems are ultimately normalized before evaluation, it can also be called the Normalized Factor Rating (NFR) method. It has the following advantages:

- The procedure allows subjective factors to come into play while making economic decisions. Depending on the user, the application and the situation, respective subjective factors can be given higher or lower importance in the final decision;
- The procedure provides a rating for different candidates being considered—such as composite materials. It is hence suitable for comparing several different alternatives. Moreover, alternatives can be compared against a baseline alternative for tradeoff considerations;
- The methodology is flexible enough to accommodate new data, new perceptions, new reliability measures, new developments and new thinking.
- Elements of the calculations performed are relevant to the objectives of the trade study—such as assessment of various advanced material applications to aircraft and spacecraft structures or the evaluation and selection of a robot.

4.2 The Bao Method of Normalized Factor Rating

In order to develop the MCF based on the NFR, Bao suggests six groups of factors that can affect manufacturing complexity of materials. Five of the six factors are further developed into several sub-factors. The six main factors and their respective sub-factors are described in several publications [2, 29, 44].

The six groups that represent Level 1 of the NFR hierarchy are:

- Material Cost
- Handling

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- Manufacturing Processes
- TOOLING required for the manufacturing processes
- LABOR required for the manufacturing processes
- QUALITY ASSURANCE required for the manufacturing processes

Five of the above factors—with the exception of material cost—are further broken down into several sub-factors, leading to a Level 2. The HANDLING sub-factors are:

- POT LIFE
- PROCESS TEMPERATURE
- DATABASE EXTENT
- MOISTURE RESISTANCE
- OUTGASSING
- SCRAP DISPOSAL
- SHELF LIFE
- CHEMICAL/SOLVENT RESISTANCE
- DAMAGE TOLERANCE
- TOXICITY
- VOID PRESENCE

The sub-factors for the MANUFACTURING PROCESSES factor are the eight processes included in Bao's database. These are:

- LAY-UP FORMING/AUTOCLAVE (LF)
- COMPRESSION MOLDING (CM)
- FILAMENT WINDING (FW)
- RESIN TRANSFER MOLDING (RTM)
- PULTRUSION (PUL)
- THERMOFORMING (THF)
- INJECTION MOLDING (IM)
- DIAPHRAGM MOLDING (DM)

The other three main factors—TOOLING, LABOR and QUALITY ASSURANCE—are quasi subjacent to the MANUFACTURING PROCESSES factor. For example, the PULTRUSION sub-factor for TOOLING is the tooling required for the Pultrusion process. Similarly, the PULTRUSION sub-factors for LABOR and QA are the manual labor and QA efforts required for the Pultrusion process.

The above breakup results in a two level factor and sub-factor hierarchy. The materials being compared are then evaluated by all the elements of the hierarchy. This is visually shown in Figure 4-1 on the following page.

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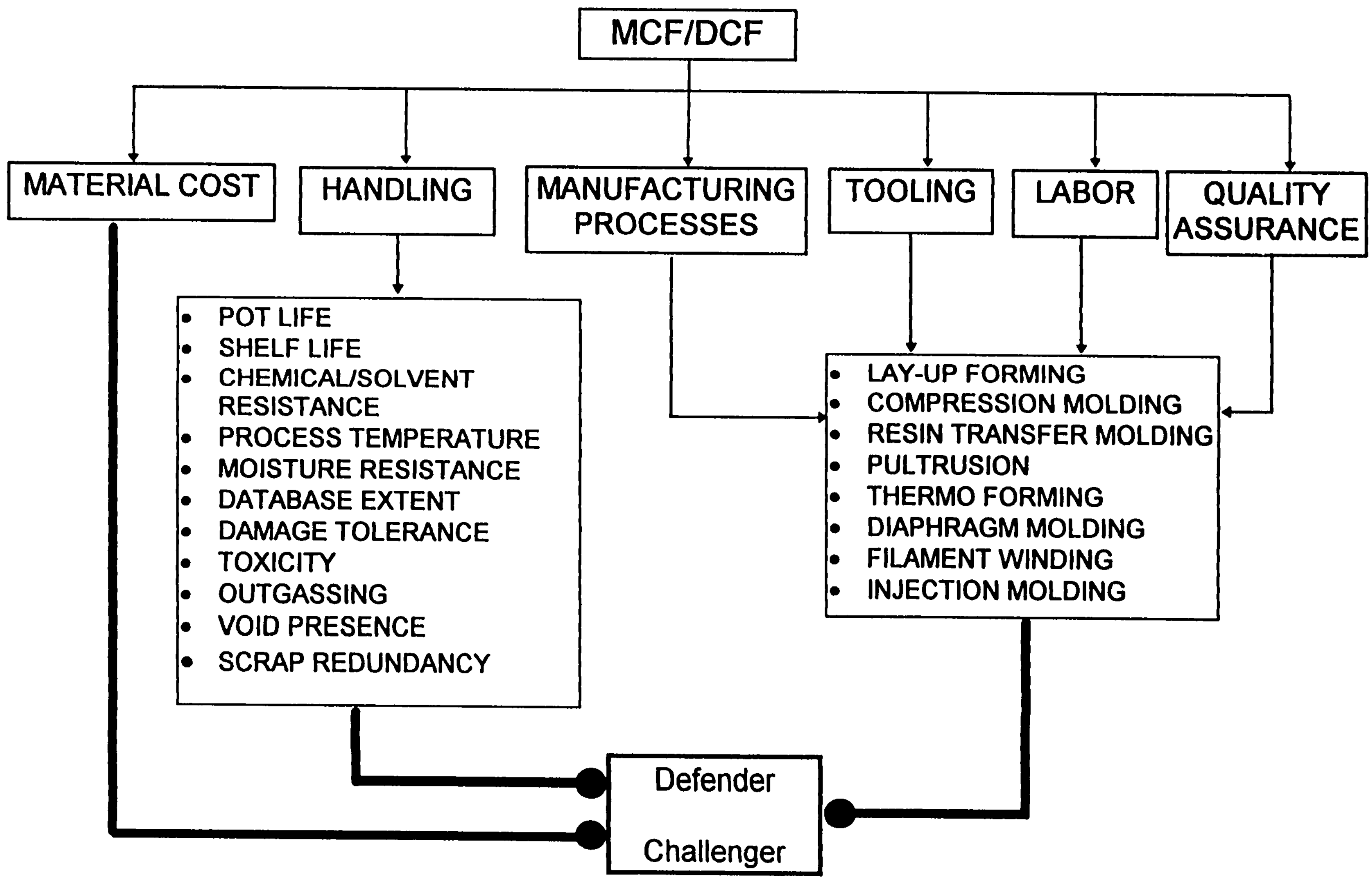

Figure 4-1 — The NFR Hierarchy of the Bao Method

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Manufacturing complexity (MCF) calculation equations in the Normalized Factor Rating method adopted by Dr. Bao—hereafter called the Bao method—are as follows:

$$MCF \equiv \sum_i w_i F_i \qquad .....4\text{-}1$$

Where i is the i^{th} factor. w_i is the factor weight, and F_i is a dimensionless value of factor i.

F_i is determined by the equation:

$$Fi \equiv \sum_j \frac{\text{severity}_{ij}}{\sum \text{severities}} * \frac{\text{ranking}_{ij}}{\sum \text{rankings}} \qquad .....4\text{-}2$$

Where j is the j^{th} sub-factor of factor i. severity_{ij} is the importance of sub-factor j among i sub-factors. ranking_{ij} is the rank of a candidate material when being compared to another material. By choice, severity_{ij} and ranking_{ij} are integers between 1 and 5.

These calculations are a "lower-the-better" characteristic, i.e. material with lower MCF values is less complex and therefore preferable to one with a higher MCF value.

Given the MCF's of two materials—MCF_A and MCF_B—the Delta Complexity Factor (DCF) provides a measure of the increase—or decrease—in manufacturing complexity that can be expected by going from material A to material B. The DCF is calculated as:

$$DCF_{(A\ over\ B)} = 1 + \left(\frac{MCF_B - MCF_A}{MCF_A} \right) \qquad .....4\text{-}3$$

The Bao method gives all six main factors an equal weight— w_i —of 1/6. The sub-factors are also weighted. In the Bao method, the sub-factor weightings are called "severity". They are on a scale of 1 through 5, 1 being the best. Based on experience, judgment and expert opinion, the system user would assign respective severity's to the sub-factors. Therefore, in the Bao method, the factor and sub-factor severity's are highly subjective.

Assignment of severity's for the HANDLING sub-factors is reasonably straight-forward. For example, if expert opinion is that PROCESS TEMPERATURE and TOXICITY are very important HANDLING sub-factors, they both could be

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assigned a severity of 1. If POT LIFE and SHELF LIFE are a little less important, they may get severity values of 2 each. If VOID PRESENCE and OUTGASSING are not really important, their severity values would be 5.

However, the assignment of sub-attribute severity's for the four manufacturing attributes is a little different. The eight processes—sub-attributes —are ranked in one of two ways, depending on how the MCF/DCF calculations are being performed.

1. The MCF/DCF calculations being performed for a general material comparison: In this case, all processes are ranked equally—a mid-way rank of 3 is assigned to all processes.
2. The MCF/DCF calculations being performed for a specific part or application:
   In this case, the processes are ranked in terms of the importance a process has in the manufacturing of the part using that material.

Upon assigning the main factor weights and the sub-factor severity's, candidate materials for comparison can be evaluated. Based on the information available on these materials, the system user would assign ranks for each of the factors/sub-factors for them. For example, if a material is very expensive, it may be ranked 4 or 5 for the MATERIAL COST factor. If it needs processing at very high temperatures, its rank for PROCESS TEMPERATURE sub-factor may also be 5. If that material is a little bit toxic, its TOXICITY rank may be 2. These values are "best guess" or point estimates. That is, if TOXICITY is 2, then that rank could actually have been a 1 or a 3, but 2 is most likely. Moreover, if actual numbers are available, they can be substituted for the rankings, thus getting better accuracy. That is, instead of the cost being a "5", a value of "$1500/lb." could be used, if available.

Ranking of the sub-attributes for the four Manufacturing attributes—PROCESS, TOOLING, LABOR and QA—is similar, accept for one small difference. For example, if a material is readily or easily processable by a process, it may

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get a rank of 1 or 2, while if it is extremely difficult to process, the rank may be 4 or 5. However, if a material has not yet been tried or tested by a process, then, in the Bao method, that material gets a rank of 0.

Upon assignment of weighs and ranks, the simple albeit extensive calculations of equations 4-1 and 4-2 would result in MCF values for the contending materials. A DCF value—the entity of interest—can be calculated once two MCF's are available, using equation 4-3. The DCF gives an approximate measure of how much more—or less—complex to manufacture one material is over the other. A specific application of the Bao method of Normalized Factor Rating is available in the public domain [2].

It is important to note that by themselves, the MCF values do not mean much. The DCF—the difference between the respective MCF values—is the entity of interest to a potential user.

4.3. Improvements to the Bao Method

The Bao method for evaluating contending materials is conceptually clear and easy to implement. It is based on a proven and accepted format for comparing multi-attribute alternatives. However, as the method now stands, it has certain limitations that could be improved upon. It is also possible to strengthen the MCF calculations by doing some re-structuring. So long as the fundamental calculations of NFR and the simplicity and clarity of the Bao Method are not violated, such changes to the method should enhance its utility.

In this section the changes intended to "improve" the Bao method are discussed. These changes result in considerable modifications to the Bao method of Normalized Factor Rating, and substantially change the original method. For obvious reasons, the new method is henceforth called the "X-NFR" Method, short for 'eXtended-Normalized Factor Rating'.

In Section 4.4, the X-NFR method is demonstrated by comparing two composites and generating sample MCF and DCF values. The following points are suggested as areas to change or improve in the Bao Method.

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4.3.1. LIMITED DATABASE The ranks given to materials being evaluated for MCF calculations are based on information available in Bao's database. This database contains information primarily drawn from two published sources—the LCCW guide and the CSSD guide. Admittedly, the database fills a void in terms of providing valuable information on newly developed composite materials. However, it is limited by the literature it covers. There are several other published sources which could be tapped for information. Strengthening the database would directly result in more "robust" MCF values. This is an area to be pursued during this dissertation. It is not a direct modification of the Bao method, but an avenue to enhance its integrity and utility. Theoretically, this is an unending process.

4.3.2. DATABASE EXTENT IS NOT A HANDLING SUB-FACTOR In the Bao Method, DATABASE EXTENT is treated as a sub-factor of the main factor, Handling. This is not very accurate, since Database Extent has nothing related with the physical "handling" of the material being considered. Database Extent is simply the extent of information available on that material.

This is a very important factor when analyzing composite materials, since several composites have been developed within the past few years, and not everything is known about them. The element of risk or uncertainty when dealing with such new materials is high. Similarly, composites and conventional materials that have been used for the past several years have all been thoroughly tested and analyzed. Thus, considerable information is available on them, and developers may prefer using them simply because they are comfortable with them.

The difference in "information availability" of prospective materials is an important attribute while selecting between such materials. This is especially so, when one of the materials being screened has very desirable features, but is otherwise new and untested.

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However, as contended, DATABASE EXTENT is not related with the physical handling of the material. Therefore, it should not be a HANDLING sub-attribute. On the other hand, it is important enough as an attribute when dealing with the uncertainty of newly developed materials, and should be considered in an analysis of the same.

Consequently, it is suggested that DATABASE EXTENT be removed from its stature as a HANDLING sub-attribute, and that it be elevated to major attribute in dealing with MCF/DCF calculations.

4.3.3. POT/SHELF LIFE Among the handling sub-factors, POT LIFE and SHELF LIFE are treated as two separate entities. While they are indeed two individual attributes, it is not strictly necessary to treat them as such. For the most part, they both represent the same property—working life of the composite material—under one of two situations.

Shelf Life relates to thermoplastic and thermoset resins as well as all other material forms. It is *"the length of time that a material, substance or product can be stored under specified environmental conditions and continue to meet all applicable specification requirements and/or remain suitable for its intended function"* [29].

On the other hand, Pot Life is applicable only to thermosets. Thermoset resins are plastic forms which, once reacted, will not soften or flow, even under heat or pressure. This irreversibility in their reaction allows them to be processed one time only. Therefore, once a reaction has been initiated, the length of time available for processing is critical. This time is known as its Pot Life. By definition, it is *"the length of time that a catalyzed thermosetting resin system retains a viscosity low enough to be used in processing"* [44].

Unlike thermosets, thermoplastic polymer resins can soften and flow under heat and pressure. This 'hardening-softening' process is reversible, which allows thermoplastics to be reprocessed. Therefore, their pot life is not as critical as that of thermosets. Thus, depending on whether the composite

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material being considered for evaluation is thermoplastic or thermoset, one or the other attribute will be overriding—Pot Life for thermosets, Shelf Life for thermoplastics and other materials forms.

For simplicity, hence, they need not be considered two separate handling sub-attributes. They could be clubbed together as one sub-attribute, POT/SHELF LIFE. However, considering the simplicity of calculations involved, it would be just as easy split the two—if necessary. That is, if some particular thermosetting resin had both a limited Pot life as well as a limited Shelf life, then they could be treated as two distinct HANDLING sub-attributes. But unless specifically necessary, it is suggested that they be used as one single sub-attribute: POT/SHELF LIFE.

4.3.4. MANUFACTURING ISSUES MANUFACTURING PROCESSES is a major attribute in the Bao method, with eight processes as its sub-attributes. Other manufacturing issues specific to composite materials —Tooling, Labor and Quality Assurance— are also major attributes in the hierarchy. Their sub-attributes are the same as the MANUFACTURING PROCESSES sub-attributes.

It is hence proposed that instead of having these four as independent major attributes, they be "lumped" together as sub-attributes under a MANUFACTURABILITY attribute. This would add another level to the hierarchy, but additional calculations are not overly complex. The simplistic nature of the Bao method is also not violated. Consider figure 4-2.

As shown in figure 4-2, since PROCESSES, TOOLING, LABOR and QUALITY ASSURANCE are all manufacturability issues, a MANUFACTURABILITY attribute can be weighted against the other major attributes.

Additionally, this discussion draws on a combination of two events—an assumption in the Bao Method, and, as its outcome, a drawback of the NFR calculations. The result is an inadequacy in the MANUFACTURABILITY attribute introduced above. The inadequacy is brought about in some cases, as explained below.

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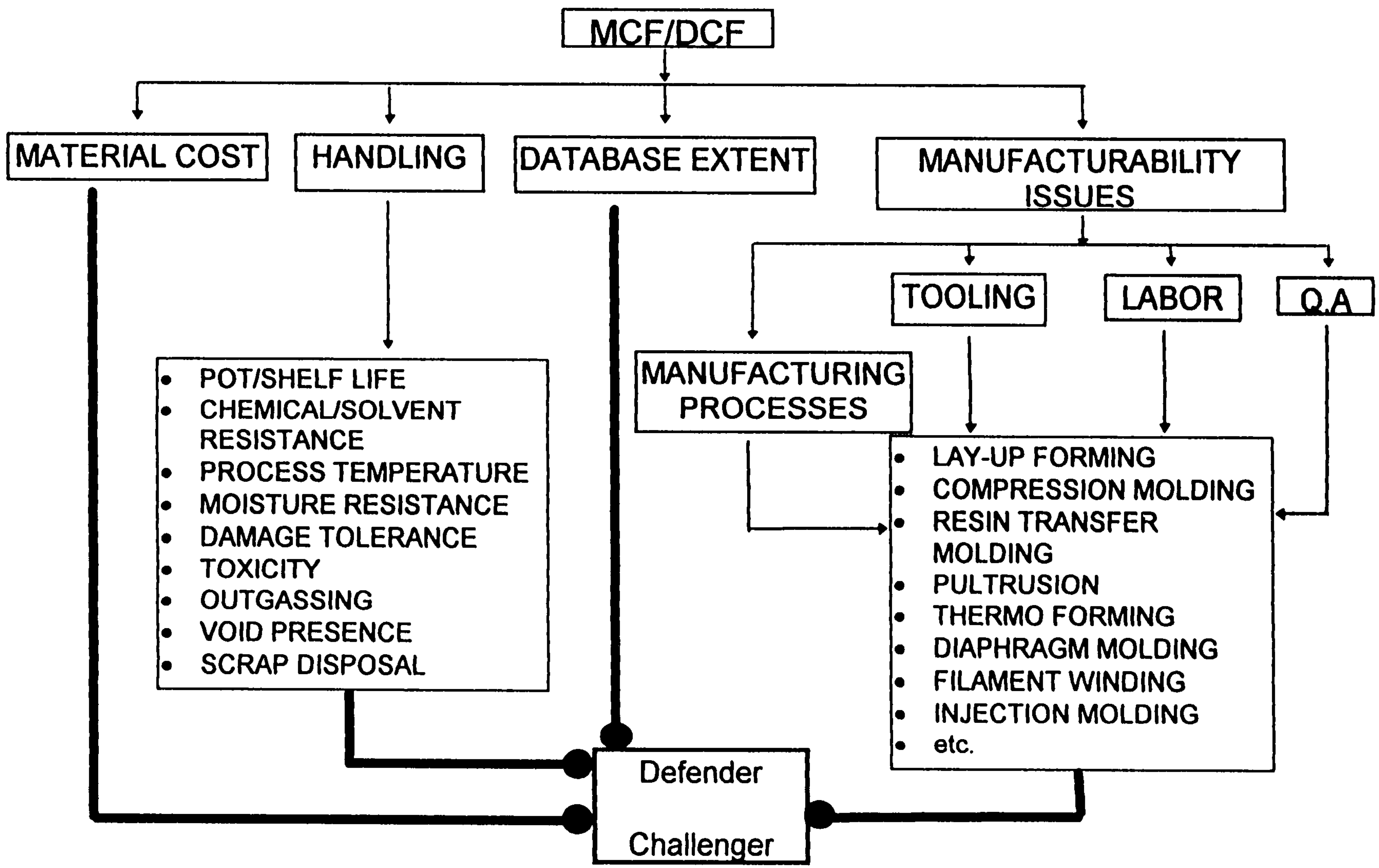

Figure 4-2 — Hierarchy with DATABASE EXTENT and MANUFACTURABILITY Attributes Added

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Consider a hypothetical situation, where some candidate material was being ranked by the MANUFACTURING PROCESSES sub-factor. Suppose that material was processable by processes X and Y, while it had not yet been tried or tested on process Z. Then, the rank for X and Y would be between 1 and 5. However, according to the Bao Method, the rank for Z would be 0. Similarly, that material would be ranked for TOOLING, LABOR and QA sub-factors with respect to X and Y, but it would be ranked 0 for process Z.

Therefore, when two materials are being compared, and only one of them can be processed by Z, there is a discrepancy. Since the MCF calculations are comparative, the Manufacturability sub-factors would fairly evaluate only those processes compatible to all the materials being evaluated. That is, process Z would be left out. To illustrate, consider three candidate materials being evaluated over five processes in Table 4-1.

Table 4-1 — Materials Processable by Processes

Processes	Candidate Materials		
	mtl. A	mtl. B	mtl. C
Pultrusion	processable	un-tried/tested	processable
Filament Winding	processable	processable	un-tried/tested
RTM	processable	processable	processable
Injection Molding	un-tried/tested	un-tried/tested	processable
CM	un-tried/tested	un-tried/tested	processable

In the above example, material C is processable by 4 different processes, A by three and B by two. However, only one process—Resin Transfer Molding —is common to all three materials. Thus, only RTM would get a rank between 1 and 5 for all three materials. This is typical in the NFR rating method, since the calculations compare one candidate over others. Hence, only that attribute common to all three would be considered in the calculations.

However, this would be unfair to a material—such as material C above—which can be processed by more processes than its peers. To counter this

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"unfairness" the following three changes are proposed to the Bao method of NFR.

4.3.4.1. REPLACE THE "0" RANK BY A "5" The Bao method assigns a rank of 0 to a material that is untried or untested on a process. While comparing two materials, if one of the two has a rank of 0, then the other is at a disadvantage. This is because, according to equation 4-2:

$$Fi = \sum_{j} \frac{severity_{ij}}{\sum severities} * \frac{ranking_{ij}}{\sum rankings} \quad .....4\text{-}2$$

a $rank_{ij}$ of 0 would make the F_i value 0. Considering that these are "lower-the-better" characteristics, a $rank_{ij}$ of 0 would render that material more desirable than the other contender, irrespective of the contender's rank.

To avoid this situation, the Bao method recommends that the process not applicable to all materials be removed from contention. Thus, materials would be compared on only those processes applicable to all materials being considered. In table 4-1, therefore, only RTM would be used in the MCF/DCF calculations.

This would be unfair to materials A and C. It is hence recommended that the default rank of 0 be changed to a default rank of 5. That is, make the assumption that if processing of a material is un-tried or un-tested by a certain process, it is the same as that material being extremely difficult to process by that process. This would render all processes useable in the MCF/DCF calculations.

The argument for making this assumption is that if a process is as yet un-tired or un-tested, then that is so because industrial experience has led process developers to expect potential difficulties in trying that process on that material. Otherwise, given the advantage of using composites in industry, it is very likely that a material that shows any promise of being processed by a certain process would have been tried out and the results included in journals and handbooks.

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In addition to changing the rank from default 0 to default 5, it is suggested that two new factors be added to the NFR hierarchy.

4.3.4.2. VERSATILITY FACTOR This factor is recommended to indicate how "versatile" a candidate material is in terms of its processability. For the eight—or more—manufacturing processes selected for MCF/DCF calculations, the manufacturability factor indicates how processable a material is by these processes. By changing the 0 ranking to a 5, all processes are now considered in these evaluations, including, those un-tried and un-tested.

However, a dimension of a material's versatility is lacking in the calculations. The VERSATILITY factor is introduced to add a simple "sheer number" measure—a measure of how many different processes can be used to process a composite material. In this factor, issues such as how much more compatible one process is to another, or how much more cheaper or expensive one is to another are considered irrelevant. Such a factor would be very useful in early material evaluations, when specifics of the part to be designed are not yet clear. At that time, the designer may wish to closely study a material processable by several different processes. By changing the VERSATILITY factor weight appropriately, more or less importance can be given to this factor.

For this situation, the material-process rank is simply a "1" or "0"; 1 if the material is processable by that process and 0 otherwise. The processes themselves are not ranked with respect to each other. The formula adopted for the VERSATILITY factor was first proposed in 1972 as the Brown-Gibson model [3] and a generalized version of it appeared as part of a procedure for evaluating robots [13]. For a material *m*, its VERSATILITY FACTOR (F_m) value is:

$$F_m \equiv \frac{1}{VF_m * s} \qquad \text{.....4-4}$$

where $s \equiv \sum_{m=1}^{M} \frac{1}{VF_m}$ and VF_m is the versatility of material m. 4-5

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For example, of the three candidate materials considered in Table 4-1, material A can be processed by three, B by two and C by four of the eight processes. Thus, $VF_A = 3$, $VF_B = 2$ and $VF_C = 4$. Then,

$$s = 1/3 + 1/2 + 1/4 = 1.083$$

and

$$F_A = 1/(3*1.083) = 0.308$$

$$F_B = 1/(2*1.083) = 0.462$$

$$F_C = 1/(4*1.083) = \underline{0.231}$$

$$1.00$$

4.3.4.3. EQUIPMENT OUTLAY This factor is introduced to address two issues that the VERSATILITY FACTOR considers irrelevant—cost of the process and compatibility of the material with the process.

Very often, the equipment required to process composites is considerably expensive. This cost is ignored in both the MANUFACTURABILITY and VERSATILITY factors. For instance, in the example in Table 4-1, it was seen that material C was processable by four processes and material B by two. However, it is possible that both of B's processes are relatively common or inexpensive, while one or more of C's processes is either new, or inhibitively expensive. Then, while C has a lower Versatility weight, B's inexpensive processes should also be acknowledged. It is intended to drawn out this difference via the EQUIPMENT OUTLAY factor.

In order to incorporate the EQUIPMENT OUTLAY factor into the NFR hierarchy, all the processes involved in the study must be individually assigned severity's on a scale of 1 to 5—1 if the process is well tested or inexpensive, and 5 if it is very new or expensive. This information will have to come from published literature.

Then, just as with the Manufacturability sub-factors, the materials for contention have to be ranked against the processes. The rankings can be the

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same for both the attributes. The calculations would also be the same as before.

4.3.4.4. LOCATION IN THE HIERARCHY A final note on the addition of VERSATILITY and EQUIPMENT OUTLAY factors is their location in the NFR hierarchy. Both these factors are manufacturing concerns and both are more suited as sub-attributes rather than major attributes. Moreover, a major attribute proposed earlier—see figure 4-2—called "MANUFACTURABILITY" is also a manufacturing concern. It is therefore proposed to lump these three factors together under a single major attribute related to manufacturing, and call it "MANUFACTURING ISSUES".

The resulting final hierarchy is shown on the following page in figure 4-3. As shown in figure 4-3, the NFR hierarchy would have four main attributes—MATERIAL COST, HANDLING ISSUES, DATABASE EXTENT and MANUFACTURING ISSUES. MANUFACTURING ISSUES would have three sub-attributes, VERSATILITY, MANUFACTURABILITY and EQUIPMENT OUTLAY. And MANUFACTURABILITY would have four sub-sub-attributes PROCESSES, TOOLING, LABOR and QA.

4.3.5. ATTRIBUTE AND SUB-ATTRIBUTE WEIGHTS In the Bao method, the six major attributes are all given an equal weight, of 1/6. Moreover, the sub-attributes are subjectively ranked, based mostly on expert judgment or opinion. There is a need to structure these rankings. It is proposed to use the Analytic Hierarchy Process to rank the attributes and sub-attributes in the Bao method.

There are several means of assigning severity's to multi-attribute decision problems. The simplest is a judgmental assignment, as used in the Bao method. Attributes could also be ranked in order of decreasing preference. The method of paired comparisons is one such ordering method. This pairwise comparison method could be elaborated by quantifying the relative importance of each attribute. Many numerical formula methods also exist for assigning weights to attributes, including: Uniform or Equal Weights Formula; the Rank

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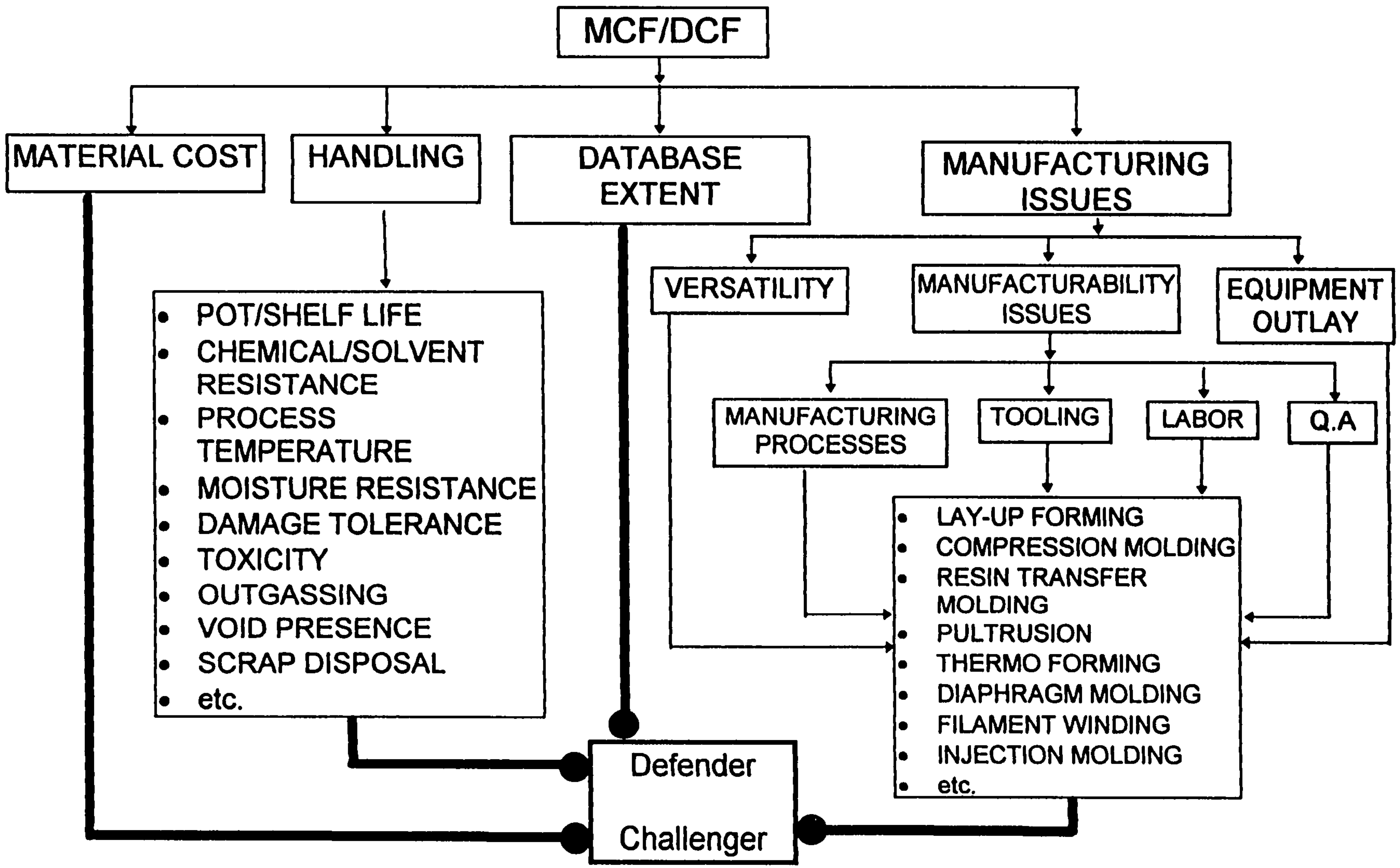

Figure 4-3 — The eXtended NFR Hierarchy

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Sum of Weights Formula; and the Rank Reciprocal Weights Formula. Some of the more detailed, quantitative methodologies include use of the multi-attribute utility models; the analytic hierarchy process; goal programming; expert system technology; and the use of fuzzy logic techniques [3, 14, 17, 39].

The various methods listed above for assigning weights to multi-attribute decision problems are well studied and documented, and so are not elaborated upon herein. Among them, Analytical Hierarchy Process (AHP) is uniquely suited to the Bao method because of its hierarchical structure. The AHP works within a functional hierarchy, with a top level, called the focus, consisting of only one element, an overall objective. Subsequent levels may have more elements —between 5 and 9—which are compared with one another against a criterion in the next higher level [39]. The Bao method is very similar, with the MCF/DCF calculations as the focus. The main factors are to be compared with one another against the MCF. Similarly, the eight handling sub-attributes are to be compared with each other against the handling attribute.

Typical AHP approach involves decomposing a problem into high level attributes and their respective sub-attributes. Then, a pairwise comparison is made amongst all attributes on a given level against the related element on the next higher level. A matrix of comparisons is constructed for each level in the hierarchy. Working through matrix calculations developed by Saaty, a priority can be developed for attributes at each level of the hierarchy. As a result, elements at each level are assigned normalized weights. A consistency ratio (CR) is used to check the consistency of the weights assigned to the attributes. The alternatives to be compared are evaluated against all elements at the lowest level of the problem hierarchy. Finally, the weights for each alternative are evaluated against the focus to get a difference between them.

The AHP methodology is well developed, clearly documented, and widely used in several different situations [3, 4, 17, 33, 38, 39]. Once again, for

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brevity, the actual technique for assigning weights via matrix calculations will not be explained herein.

It should be noted, though, that this research merely adopts a part of the AHP process. Hierarchical calculations of the AHP method are used to assign factor weights to the attributes and sub-attributes in the NFR method. However, unlike the traditional AHP literature, the calculations are not carried through to make the final selection between contending materials. Instead, after the factors have been assigned weights as appropriate, the calculations developed in the Bao method are used to generate MCF/DCF values.

4.3.6. EXTRAPOLATING POINT ESTIMATES It was mentioned in the last section that ranks assigned to the materials are point estimates. For example, if a material is a fair bit toxic, it may be assigned a rank of 4 and a slightly damage tolerant material may be assigned a rank of 2. Considering the uncertainty associated with composite materials, these "best guess" values may be the only available means of analyzing composites. In this section, an improvement to these best guess values is proposed using a simulation method.

A material assigned a "4" for Toxicity implies that it is a fair bit toxic. That is, some probability does exists that the rank could have been a 3, or a 5, but 4 is most likely. However, the probability that the rank is 2 or 1 is almost zero.

Similarly, suppose that the rank assigned for some other attribute is a 1. A probability exists that the rank could be a 2, or even a 3, but it is most likely a 1. Moreover, the probability that that rank be a 4 or a 5 is almost nil.

Somehow, if the above probabilities were accounted for in the MCF calculations, the resulting MCF values would be more "robust" than the point values presently used. Therefore, as an attempt at quantifying these uncertainties, the following rule is suggested:

If x_i is the rank assigned to a material, then the rule for assigning probabilities is:

For I = 1, 2, 3, 4 or 5, P (rank=x_i) = 0.50

For I = 2, 3 or 4, P (rank=x_{i-1}) = P (rank=x_{i+1}) = 0.25

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For I = 1, $P(rank=x_{i+1}) = 0.30$ and $P(rank=x_{i+2}) = 0.20$

For I = 5, $P(rank=x_{i-1}) = 0.30$ and $P(rank=x_{i-2}) = 0.20$ 4-6

For example, if the assigned rank is a 4, then P(rank=4) = 0.5, and P(rank=3) = P(rank=5) = 0.25. Similarly, if the assigned rank is a 5, then P(rank=5) = 0.5, P(rank=4) = 0.3 and P(rank=3) = 0.2.

In general, it is assumed that the probability of the rank being more than one digit away on either side—if the assigned rank is a 2, 3, or 4—and more than two digits away—if the assigned rank is a 1 or 5—is zero. It is also assumed that the rankings are discrete integers, and not decimal values.

While probability assignments by the above rule are likely for most attribute rankings, they could be inappropriate in particular situations. For example, in some cases, the ranks may be assigned with a little bit more precision than "highly toxic" or "slightly damage tolerant." Suppose the material cost is "about 100 dollars per pound". Then, the probabilities could be assigned accordingly, say by assigning a 90% probability to the cost being exactly $100/lb., and a 5% probability of the material costing more or less than $100/lb.

Another situation where the general rule of equation 4-3 will change stems from an assumption proposed in an earlier section. It was proposed that if a process is un-tried or un-tested on a material, it be assumed than this is the same as that material being extremely difficult to process by that process. In such a situation, it was suggested that a default rank of 5 be given to the concerned material.

If this is the case—a process has not yet been tried or tested on a material—and the rank given is a 5, then it is not reasonable to assume that the probability of the rank being 5 is 0.5. The rank of 5 in this case is different from a regular rank of 5, where 5 was assigned knowing fully well that the material is indeed difficult to process by that process.

Thus, the proposed rule of assigning probabilities need not apply to this particular case. Then, it needs to be decided, which—if any—rule will apply

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when a rank of 5 is forced on an un-tired process. One could decide to leave the point estimate of 5 as is, i.e. assume that the probability of it being 5 is 100%. Or, one could assume that it is equally likely that the rank will be any one number between 1 and 5—a probability of 0.20 each. Or, the rank could be either 1 or 5, with equal probabilities of 0.50 each. Or, assume it could be a 1, 3 or 5, all with probabilities of 0.333 each. Given the uncertainty of the situation, any, all, or none of the above alternatives could be acceptable.

In order to make a decision in this situation, the following is proposed. The rank of 5 for the un-tried process was initially given based on the assumption that an un-tired process equals a difficult process. Given this assumption, it can be further argued that if a 5 is incorrectly assigned, its true rank assignment is much more likely to be near 5 than near 1. That is, if 5 is incorrect, its correct rank is more likely to be 4 or 3 than 1 or 2.

The above assumption is based on the following argument. The rank of 5 was given for an un-tried or un-tested process. One reason that a process is un-tried or un-tested on a newly developed composite material could be that that process is indeed difficult. Given the research and manufacturing interest in composite materials, it seems reasonable to assume that processing of any newly developed composite would have been attempted on all those processes that lend themselves to the new material. Therefore, if a process is un-tried or un-tested on a material, this is more so because the industry—with their knowledge and hands-on experience—have an inkling of that process not working for that material. Otherwise, it probably would have been tried out.

Resultingly, if a rank has to be forced on a process in such a case, 5 is more likely than 1. Similarly, if a probability is to be assigned to the 5, then it is reasonable to assume that the true rankings be clustered closely around 5 rather than lower down the scale. Given this reasoning, the following rule is proposed for assigning probabilities when the material is un-tried or un-tested on a process.

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For a material un-tried/tested by a process, its rank x_i is assigned by the following rule:

For i = 5, $P(x_i) = 0.85$, $P(x_{i-1}) = 0.10$ and $P(x_{i-2}) = 0.05$ 4-7

Having set the ranks up in this fashion, it is easy to simulate the values using a random number generator—a procedure routinely applied, and commonly known as the Monte Carlo simulation technique. This technique, also known as the method of statistical trials, evolved during World War II, when solutions to problems in the development of the atomic bomb were attempted using the Monte Carlo simulation [22]. It uses random numbers for solving deterministic, static problems, and is not suitable for dynamic systems. This technique is used to improve on the "best guess" point estimates originally used in the Bao method. To better explain the simulation method, the probability distribution for two sample rank values is shown in figure 4-4 [3].

Using any random number table, or a suitable software, random numbers between 0 and 1 can be generated. These correspond to the ordinate scale in figure 4-4. For each random number, a horizontal line can be drawn until it meets the probability distribution curve. Then a vertical line dropped to the abscissa determines the corresponding outcome. The dashed line in figure 4-4 illustrates the generation of a sample rank outcome for a number between 0.25 and 0.50 [3].

This method can be repeated several hundred or thousand times, and rank values generated for each alternative material being analyzed. For each iteration, new MCF/DCF values can be calculated. The resulting mean and variance of numerous MCF/DCF values will be more accurate than a single point estimate currently obtained by the Bao Method.

4.3.7 Comparison with other Methods The Bao method is but one effort undertaken to assess the uncertainty associated with the use of composite materials. It is based on a proven technique, the Normalized Factor

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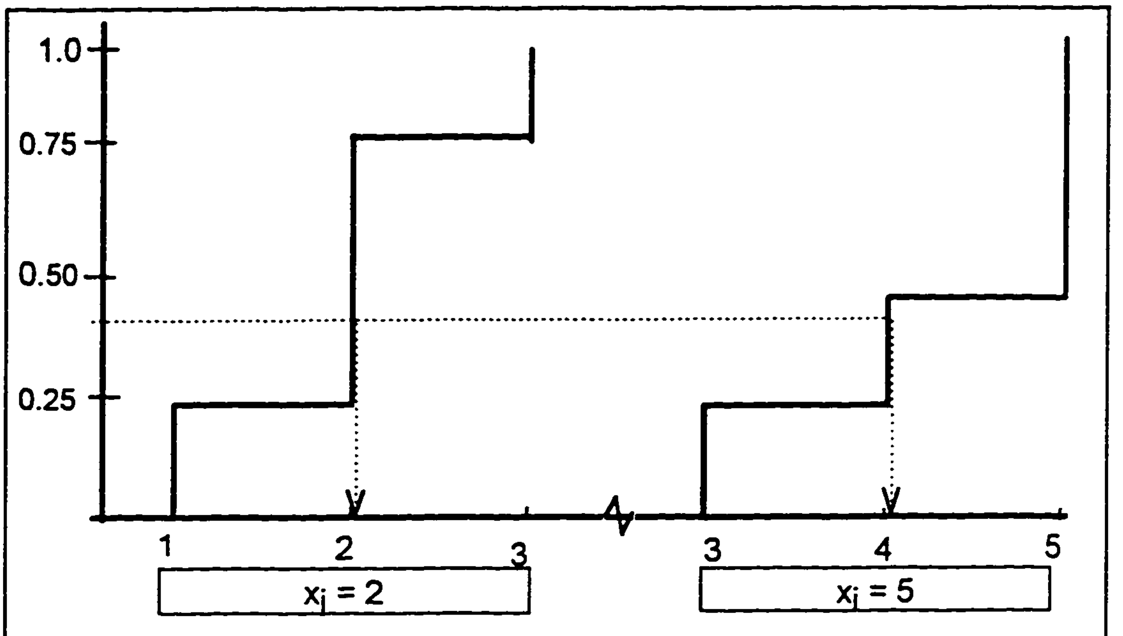

Figure 4-4 — The Random Number Generation Process

Rating method. Moreover, the Bao method was demonstrated in an existing situation, the selection between conventional Aluminum and a lighter material, Aluminum-Lithium [2]. The results of the method were comparable with actual industry experience, thus establishing the validity of the Bao method.

However, prior work on this method has not included any comparison with the two other prominent methods of analyzing manufacturing complexity of composite materials—the Scaling Law models, developed by Gutowski's team from MIT, and the Manufacturing Complexity Generator in PRICE H. It is important to show an association—if any—between the X-NFR and either of these two methods. This effort would enhance the validity of the methodology developed by Han Bao.

This final point—like the first one—is not a modification of the Bao method, but draws out a need for further work. The comparison between the two methods is elaborated upon in Chapter VII.

4.4. The 'X-NFR' Method

Incorporating the discussions above results in a Normalized Factor Rating Methodology that is considerably different from the original method used

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by Bao [2]. The new method is hereafter called the eXtended-Normalized Factor Rating, or 'X-NFR' method.

MCF calculations are performed under the new hierarchy shown in figure 4-3. Weights for each of the four major attributes, and the various sub-attributes —with the exception of the processes—are derived from the AHP. Weights for the processes are not included in the AHP. Instead, they are assigned ranks as intended in the original Bao Method.

The MS Excel™ spreadsheet software is used for the actual AHP calculations. In the spreadsheet, the user must compare the attributes with each other and give ranks for each comparison. The matrix calculations needed to convert numerical preferences into normalized weights were adapted from Canada and Sullivan [3], and are not explained herein. A Consistency Ratio (CR) is included with each AHP structure to verify the values of that structure.

The Consistency Ratio (CR) was developed by Saaty to validate the consistency of the assigned weights at every level. A high CR value indicates high inconsistency in the rankings. It is necessary to check for consistency, because, while comparing between alternatives in the AHP, human nature may lead the users away from a truly consistent judgment. For example, while comparing attributes A, B and C, suppose attribute A were considered more important than attribute B, which was considered more important than attribute C (i.e. A>B>C). Then, while comparing attribute C with attribute A, the user must remember that C should be considered less important than A, and not vise versa. It is easy to get carried away during the comparison of several attributes, and loose consistency in judgment. Giving C an equal or higher weight than A in the above situation would be considered an inconsistency. Since absolute consistency may be realistically impossible to achieve, Saaty suggests that a CR less than 0.10 (10% inconsistency) is acceptable for pragmatic purposes.

The AHP structure for all the attributes and sub-attributes in a typical scenario is shown in Appendix A. Any user of the X-NFR method wishing to

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change priorities assigned to the attributes and sub-attributes can easily do so within the MS Excel™ spreadsheet. A brief explanation for using the spreadsheet is included in it, and printed in Appendix A. Appendix A has three pages, for comparisons of all the attributes and sub-attributes in figure 4-3. For example, the first page is a comparison of the four main attributes. That is, MATERIAL COST, HANDLING, DATABASE EXTENT and MANUFACTURING ISSUES are weighted against each other with respect to their contribution to minimal manufacturing complexity. The principal diagonal is a "1", because each attribute is as important as itself. For consistency and convenience in matrix calculations, the user is required to compare rows with columns and enter values in the cells above the principal diagonal.

So, a "0.25" in the MATERIAL COST — HANDLING ISSUES cell is actually a "1/4", which implies that handling issues are between weakly and strongly preferred over material cost. Similarly, a "3" in the MATERIAL COST — DATABASE EXTENT cell implies that Material Cost is weakly more important than Database Extent. Based on the matrix calculations developed by Saaty, the user's preferences are converted into normalized "priority weights". The priority weights are used in the X-NFR calculations.

The value in the CR box is a consistency check for the user. That value should be less than 0.1 for the preferences to be acceptable. Currently, that value is 0.06, meaning that the user is consistent in the ranking of attributes. However, if for example, the 0.25 for the MATERIAL COST — HANDLING ISSUES cell were changed to a "7" then the CR value would change to "0.65", meaning an inconsistency in the rankings had occurred.

As a sample of the actual X-NFR calculations, a straight comparison between two composite materials, Gr-Epoxy and PEEK is shown in Appendix B. This too is an Excel print-out. Ranks of the two materials are adopted from the Bao Database. Appendix B is a 'straight' comparison, i.e. without the Monte-Carlo simulation.

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The attribute and sub-attribute weights in Appendix B are the respective priority weights from Appendix A. However, individual processes are not ranked via the AHP. They are all given straight ranks on a scale of 1-5, and normalized. Since appendix B is a generic case—i.e. the comparison is not for a particular part or structure—all processes in the "Manufacturability Issues" sub-factor are given equal ranks. However, they are given appropriate ranks in the "EQUIPMENT OUTLAY" sub-factors depending on the expense/complexity of the manufacturing processes.

The first two rows in Appendix B are the MCF and DCF values. The MCF for Gr-EPOXY is 0.406 and that for PEEK is 0.594. That is, PEEK is 46% more complex to manufacture than Gr-EPOXY, as seen by the DCF value (1.4629). The remaining rows in Appendix B are the various attributes, and sub-attributes of the NFR hierarchy, going down four levels. A break-up for the four main attributes as got from Appendix B is shown in Table 4-2.

Table 4-2 — Break-up for four main attributes

Attribute	Attribute-Weight	Defender Gr-EPOXY	Challenger PEEK
Material Cost	0.106	0.0177	0.0883
Handling	0.376	0.1800	0.1961
Database Extent	0.078	0.0195	0.0584
Manufacturing Issues	0.440	0.1908	0.2495
Manufacturing Complexity Factor		0.406	0.594

The graph in Figure 4-5 allows the break-up to be compared visually. As can be seen both in table 4-2 and figure 4-5, the challenger (PEEK) is more complex than the defender (Gr-Epoxy) with respect to all four main attributes.

4.5 CONCLUSION

In this chapter, a unified methodology is developed for comparing two materials. It is intended that someone wishing to evaluate different materials and employ one for some intended application would be able to use this

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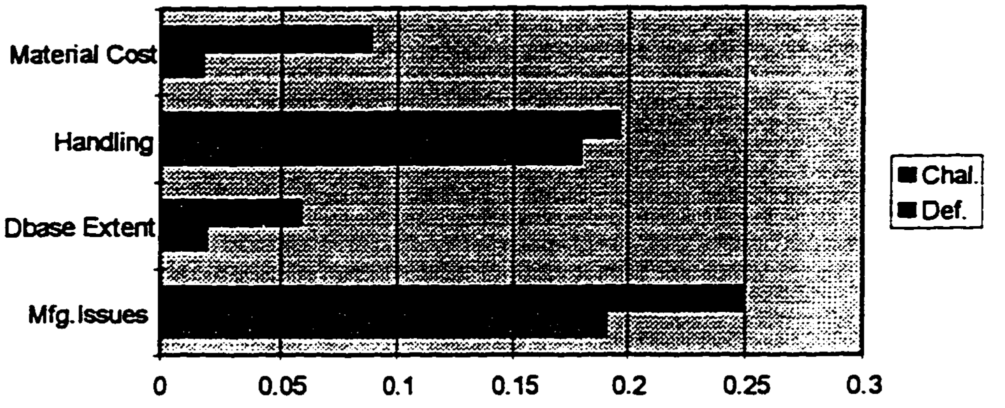

Figure 4-5 – Defender/Chalenger Comparision for Attributes

methodology in reaching a decision. The methodology is called the X-NFR method—an abbreviation of "The eXtended Normalized Factor Rating Method". It is developed from a rudimentary procedure advanced and demonstrated by Prof. Han Bao of Old Dominion University. The X-NFR methodology builds upon Bao's method by:

- expanding the original hierarchy and adding more elements for evaluation;
- making changes in the way materials not processable by certain processes are handled;
- adding one new calculation to evaluate a conflicting element (VERSATILITY);
- Systematizing weight assignments by incorporating the AHP;

and

- Relying on the Monte Carlo simulation technique to decrease the ambiguity associated with the uncertainty of new materials.

No part of the X-NFR method is fundamentally new, untried or untested. The equations, the Analytic Hierarchy Process and the Monte Carlo simulation technique have all been individually developed and used by researchers in the past. However, this application stands out in that the three approaches are used in tandem. The result is a unified methodology for comparing materials under a high level of uncertainty. In Chapter V, the X-NFR methodology is used

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to make comparisons between different materials. By making comparisons between the X-NFR results and those published by actual users of two of the materials, the X-NFR method is validated. The sensitivity of the X-NFR to different inputs is discussed in Chapter VI.

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CHAPTER V

X-NFR RESULTS

In this chapter, results of six X-NFR comparisons are presented. Section 5.1 introduces two specific X-NFR based comparisons, and their importance to this dissertation. Section 5.2 is a discussion on another paper where the same two comparisons are presented. A similarity between the X-NFR results and those published in the other paper would make a basis for the validity of the X-NFR results. The two X-NFR comparisons are then presented in Sections 5.3 and 5.4 respectively. Other X-NFR comparisons are presented in Section 5.5. The conclusions are in Section 5.6.

5.1 Comparison Between Al and Al-Li

The bulk of this chapter is dedicated to comparisons between a conventional Aluminum alloy (Al 2024) and an Aluminum-Lithium alloy (Al-Li 2090) for two specific aerospace structures: a Sheet & Stringer (s/s) payload adapter for an Atlas commercial launch vehicle; and a Liquid-OXygen (LOX) cryogenic tank for a Delta launch vehicle. The results of these two comparisons are particularly important to the X-NFR method for two reasons:

(a) the fabrication of both these structures using an Aluminum-Lithium alloy instead of the conventional Aluminum alloy has been specifically addressed in two publications (20, 42). The papers also discuss—as appropriate—comparative behavior of Aluminum-Lithium as opposed to the conventional Aluminum that was used to fabricate the two parts prior to using Aluminum-Lithium. Therefore, these two papers form a basis for the ranks assigned to the two materials in the X-NFR method.

And more importantly,

(b) the expected increase in complexity incurred by substituting Aluminum-Lithium over Aluminum for these very two structures is available in another related paper, by Kaminski, Willner, Kerr and Taketani [16]. This paper by Kaminski et al. is a general discussion on the use of Aluminum-

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Lithium alloys in space applications, including: comparisons of some properties of different alloys of Aluminum and Aluminum-Lithium; a cost comparison of the two alloys over four different metrics; and a description of some aerospace industry programs replacing conventional Aluminum with Aluminum-Lithium alloys.

The X-NFR results specifically address the relative increase in processing complexity that manufacturers would experience when substituting an Aluminum-Lithium alloy for the conventional Aluminum alloy in the manufacture of the two structures in question—the s/s adapter and the LOX tank. Therefore, the results generated by comparing the two alloys via the X-NFR can be measured-up against the results published by Kaminski, et al. Hence, the Kaminski paper could serve as a basis for validity of the results of the X-NFR method. This basis becomes particularly important considering that specific manufacturing complexity numbers between two materials/composites are available <u>only</u> from the Kaminski, et al. paper. Other publications, when discussing composites and special alloys discuss alloy benefits in general, and are more attentive to weight <u>savings</u> rather than in increased cost or complexity. Consider for example, three papers selected at random:

- A detailed paper describing the extrusion, weldability and other characteristics of Aluminum-Lithium alloys in space-shuttle structures, says "*...... Lockheed and NASA ...... determined that direct substitution of aluminum-lithium for conventional aluminum alloys could cut aircraft weight by 7.8% to 10.6%*" [26].
- Or, an article discussing substitution of an aluminum helicopter blade for a s-glass/Epoxy helicopter blade, says: the "*epoxy blade ...... decreases the amount of fuel consumed by 5% and cost justifies the conversion from aluminum on a life-cycle basis*" [27].
- Similarly, another paper on the use of newly developed alloys in aerospace applications says: "*Using aluminum-lithium alloys to replace conventional*

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high-strength alloys in existing aircraft could save 8-10% of the aluminum structural weight" [23].

The almost universal interest in weight savings—as exemplified in the three random examples above—is understandable knowing that weight savings drive aerospace designers to substitute the conventional metals and alloys with composites and Aluminum-Lithium alloys. Since weight savings are a desirable feature, people are probably eager to publish such numbers. However, increased manufacturing complexity—usually an inevitable result of experimenting with new alloys and composites—is an undesirable feature. Possibly, this is why authors are not eager to publish figures related to increased complexity. With the result that there is an apparent lack of any explicit cost or complexity factor available in the public domain. Therefore, the validity established by two comparisons—the s/s adapter and the LOX tank—must serve as a sufficient condition for the acceptance of numbers generated by the X-NFR method. One can only hope that in the future other researchers will publish results similar to those published by this study and that the comparisons will be corroborative.

5.2. KAMINSKI, ET AL.'S RESULTS V/S THE X-NFR RESULTS

Kaminski et al. have considered four factors in their cost comparisons. Table 5-1 below—as published in the Kaminski, et al. paper—has values for the s/s adapter and the LOX tank respectively for these four factors.

Table 5.1 — Cost v/s Conventional Alloys.

Structure	Buy-to-fly	Location factor	Material	Processing	Total
sheet & stringer payload adapter	1.5x	1x	4x	1.2x	7.2x
LOX tank	5x	5x	4x	1.5x	150x

(As published in Kaminski, et al.[16])

These values represent *"typical cost scenarios"* that the authors have published, presumably based on general experience with conventional aluminum alloys and aluminum-lithium alloys, as well as experience in fabricating aerospace structures using them.

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Directly comparing results of the X-NFR method with those published by Kaminski et al. is not accurate. Their values—7.2x and 150x—are based on four main factors—buy-to-fly ratio, location factor, material and processing—and no sub-factors. Moreover, these four factors are all given an equal importance, and their respective values are simply multiplied to come up with the final outcome. This is not an entirely accurate scenario, since the stand alone importance of individual factors would not always be equal in the final outcome. The results would be more realistic if the factors were weighted against each other.

Secondly, the material cost factor—4x—is apparently an upper-bound value. In the paper, the authors say: *"The cost of Aluminum-lithium is 3 to 4 times conventional alloys."* If so, would 3.5x not be a more appropriate value to use than 4x?

Third, the interpretation of "Location Factor" in their cost scenario is confusing. From the brief explanation in the Kaminski, et al. paper, Location Factor can be understood as follows. Since aluminum-lithium is a lighter metal, the weight saved by replacing aluminum can allow designers to increase the weight of the spacecraft's payload. From their explanations, it is clear that the physical location of the structure fabricated using aluminum-lithium has a direct impact on the increased payload weight. For example, if a structure in the payload module was built out of aluminum-lithium—as is in the case of the s/s payload adapter—1 kilogram weight saved on the structure directly results in an increase in 1 kilogram of the payload. Hence the 1x value for Location Factor in the table above. Similarly, *"..... it would take between four to ten kilograms saved in the first stage"* to realize a 1 kilogram increase at the payload. Hence, one might interpret, the 5x value for location factor in the LOX tank row.

If the above explanation is indeed the intended significance of "Location Factor," then it is not clear why it would act as a direct cost multiplier. In one case, one pound of material replaced results in one pound of increased payload, and that does not contribute to the cost. In another case, up to five

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pounds of material has to be replaced to yield one pound of increased payload, and so the cost of replacement increases 5 times! Now suppose an existing aluminum payload is replaced with an aluminum-lithium payload. Say an experiment weighing 1lb. contained 100 aluminum balls. Now, by using aluminum-lithium, suppose 100 balls weigh about 0.7 lb. Therefore, a 1 lb. payload can now carry 140 balls instead of the original 100. If this results in an improved experiment, is the location factor less than 1x ? Would the cost of an aluminum-lithium payload actually go down because of an improved experiment? Such nuances of the Location Factor are not clear from descriptions in the Kaminski, et al. paper.

So, buy-to-fly ratios, material costs and processing costs are legitimate concerns for an increase in cost using aluminum-lithium. Location factor—as a cost measure—is slightly ambiguous. Therefore, the 7.2x and 150x figures in the Kaminski, et al. paper are deceptive.

Finally, the 1.2x and 1.5x values in the Processing column of the above table are not clearly developed in the paper. The only explanation available is "*Manufacturers should only experience a slight increase in production costs by using Aluminum-Lithium alloys. This occurs as a result of reduced scrap value, increased handling costs and increased tool wear.*" Obviously the numbers are based on first hand experience, and therefore cannot be doubted. Moreover, the cost table is by no means the primary focus of the Kaminski, et al. paper. However, a reader interested in the manufacturability and cost aspects of Aluminum-Lithium would be interested in knowing more about the basis of the 1.2x and 1.5x processing values, which are not elaborated in that paper.

On the other hand, results of the X-NFR method give an overall increase in manufacturing complexity of a challenger—an aluminum-lithium alloy—over a defender—a conventional aluminum alloy—based on several factors and sub-factors. Calculations for the X-NFR method are a fair bit more involved than those in the Kaminski, et al. paper, involving factor weightings and value normalization's. The basic construction of the X-NFR—a four level factor and

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sub-factor hierarchy—is considerably more complex and structured than the basis of Kaminski's 7.2x and 150x values. Two factors—buy-to-fly ratio, and location factor—included in Kaminski, et al. are not considered in the X-NFR method. On the other hand, several other factors are considered in the X-NFR method, and only some of which are implicit within Kaminski, et al.'s values.

Therefore, the total values—7.2x or 150x—of the Kaminski, et al. paper cannot be directly compared with the overall complexity result obtained by the X-NFR method. Nevertheless, in isolation, the Processing factor in the Kaminski et al. paper could be compared with the X-NFR results. This is so, because the factors and sub-factors in the X-NFR hierarchy are all oriented towards the processing—manufacturing—of the structure in question. However, a direct comparison between Kaminski et al's Processing factor and the X-NFR results would be somewhat incorrect.

In the Kaminski et al. paper, the cost of the material is considered as an independent entity at the same level as processing. This is not so in the X-NFR hierarchy, where material cost is a part of the hierarchy and therefore included in calculating the overall manufacturing complexity of the alloy or composite. So, if the overall manufacturing complexity of the alloy or composite in X-NFR is compared with the process factor in Kaminski, et al., then a more accurate figure that could be drawn from Kaminski, et al. is possibly:

(4x for material cost) * (1.2x for processing) = 4.8x for the s/s adapter,

and (4x for material cost) * (1.5x for processing) = 6.0x for the LOX tank.

Or, the above two values could somehow be weighted against each other, as in the X-NFR. Or, the X-NFR values could be considered without the Material Cost factor. Or, considering that "Manufacturing Issues" is a factor and "Manufacturing Process" is a sub-factor of the X-NFR hierarchy, either of those values could be directly compared with the 1.2x or 1.5x in Kaminski, et al. Excepting that, in which case, the handling issues or database extent would not be accounted for in the X-NFR, while Kaminski, et al have probably accounted for them in their Process factor.

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Before establishing which of the above several scenarios is the most appropriate, attention is diverted on the X-NFR results. The next two sections develop ranks used in the X-NFR hierarchy and give the results of comparing the two alloys—aluminum and aluminum-lithium—for the s/s adapter and the LOX tank respectively. Comparison with Kaminski et al.'s results are also presented simultaneously.

5.3. THE SKIN & STRINGER PAYLOAD ADAPTER FOR AN ATLAS COMMERCIAL LAUNCH VEHICLE [16, 20]

General Dynamics Space Systems (GDSS) in San Diego, CA., have been evaluating aluminum-lithium alloys for several years. Alcoa's 2090 Al-LI alloy was specifically studied to assess the feasibility of substituting it for conventional aluminum alloys on the various skin/stringer structures of the Atlas and Centaur launch vehicles. A project was undertaken to take advantage of a lighter structure fabricated using the less dense aluminum-lithium by direct substitution of the materials, with no change in design. Effort was concentrated on verifying *"that the numerous manufacturing operations associated with fabrication of the aerospace structure could be satisfactorily accomplished with aluminum-lithium"* [20]. The operations that the two alloys (2090 AL-LI and 2024 AL) were subjected to were: sheet forming, heat treating, chemical milling, machining, fastening, inspecting, cleaning and finishing. That effort demonstrated that aluminum-lithium could replace aluminum with a high degree of confidence.

Based on information available in several different sources [including 2, 16 and 20] respective ranks were entered in the X-NFR hierarchy (Figure 4-3). These ranks are individually detailed next:

a) <u>Material Cost</u> ranks assigned were 1 and 4 for aluminum and aluminum-lithium respectively. However, the formula used in the Monte Carlo simulation was slightly different from the one developed in equation 4-5. For a rank of "4", the original distribution suggested in equation 4-5 was: if the random number (rn) was less than 0.25, the rank assigned would be a "3", rn

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over 0.25 and less than 0.75 would imply a rank of "4", and m over 0.75, a rank of "5". These distributions were not used because of several different cost scenarios available for aluminum and aluminum-lithium. For example, while Kaminski et al. say that aluminum-lithium is approximately 3-4 times more expensive than conventional aluminum, the value in the cost comparison table of their paper is 4x, not 3.5x. [16]. In another publication, *"aluminum-lithium alloys are expected to be modestly more expensive than contemporary aircraft alloys"* [6]. In an article in Modern Metals and Alloys [26] the cost of aluminum-lithium alloys is *"up to three times that of conventional alloys."* Finally, as one might expect, the actual cost of procured material will vary depending on the quantity, lead times, material specifications and contracts and negotiations on orders [29].

Given such uncertainty in the information available, running the Monte Carlo simulation is desirable on these numbers—as it is in almost all other numbers used in this analysis. Hence, the simulation formula for this situation was appropriately spread out to: m less than 0.15, the rank would be a "2", m over 0.15 but less than 0.45, the rank would be a "3", m over 0.45 but less than 0.85, a "4', and m over 0.85, a "5".

b) Handling factors considered in the study were: Ductility, Shear & Bending Strength, Extra Handling required for aluminum-lithium, Ingot quality, and Scrap disposal. These have been discussed in different papers [including 23 and 24]. DUCTILITY studies compared Al-Li 2090-T8 with Al 7075-T6, and it was shown that the ductility of 2090-T8 is a little lower than that of 7075-T6. Since specific comparison studies were not made using the Al 2024 plate—which was the control alloy in the s/s adapter study—general properties of aluminum alloys had to be referred to so that the behavior of 70XX and 20XX aluminum alloys could be compared. Ductility of 7075-T6 is higher than that of 2024-T4 [15]. Therefore, for the ductility sub-factor in the X-NFR analysis, Al 2024 was given a rank of 2 and Al-Li 2090 a rank of 3.

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The Monte Carlo simulation has to be relied upon to make such comparisons between 2024 and 2090 stronger.

c) Shear & bending strengths of 2090 are comparable to those of 7075 [24]. However, 2090 is better than 2024 with the bend axis parallel to the rolling direction [20]. This information was accounted for and exploited while fabricating the s/s adapter. So, 2090 got a rank of 2 while 2024 had a rank of 3.

d) In general, aluminum-lithium requires some extra handling. For example, unlike the bending of 2024, 2090 had to be bent with the bend axis parallel to the rolling direction while fabricating the s/s adapter. Furthermore, 2090 alloys *"containing copper and/or magnesium require stretching prior to aging to obtain optimum strength and fracture toughness combinations."* [24]. Hence the ranks assigned were 1 to 3 for aluminum and aluminum-lithium respectively.

e) Maintaining good ingot quality is an essential requirement for aluminum-lithium alloys. For example, Lithium is a reactive metal, with an affinity for O_2 and N_2. So, close tolerances need to be maintained during the casting process to avoid introduction of impurities into the ingot, which would adversely affect its processability [6]. Also, superior ingot quality will directly result in improved compositional consistency, minimized strength and toughness variations and a reduction in scrap rate of the aluminum-lithium alloys [23, 24]. Since aluminum has not been similarly chastised, the ranks assigned were 1 and 3 respectively.

f) Scrap is a major factor while machining aluminum-lithium alloys because of the reactive nature of Lithium. For example, scrap containing Lithium in excess of 1.5% by weight, if melted, can violently explode in contact with water. Hence, aluminum-lithium scrap requires segregation to prevent contamination of non-lithium aluminum alloys. *"Scrap segregation will become increasingly important as the Al-Li alloys come into widespread use"*

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[6]. Therefore, the ranks assigned for the scrap sub-factor are 1 and 4 for aluminum and aluminum-lithium respectively.

g) Database Extent is the extent of general manufacturing information available on a material. Research on aluminum-lithium alloys has been conducted since the 1950's and aerospace manufacturers—such as General Dynamics Space Systems, Lockheed Martin and McDonnell Douglas Space Systems Company—are confident enough to undertake projects replacing conventional aluminum for aluminum-lithium alloys. In fact, replacing the s/s adapter was undertaken because of a *"firm database"* available on aluminum-lithium. Moreover, *"Al-Li alloys have evolved to a level of maturity where well-defined databases on properties, manufacturability and prefacing are available"* [36]. However, in the s/s adapter study, mechanical and physical property tests were carried out because of *"gaps in the GDSS Al-Li database."* Such conflicting reports led to the ranks assigned to aluminum and aluminum-lithium being 1 and 2 respectively.

h) All the Versatility sub-factors were given ranks of 1 for both materials because Kerr, et al. say that all manufacturing operations could be satisfactorily accomplished with aluminum-lithium with a high degree of confidence.

i) The weight for the Equipment Outlay sub-factor was 0—it was not considered in the analysis. This is because the s/s adapter study required a "direct substitution" of aluminum for aluminum-lithium, and was undertaken to confirm whether the manufacturing processes used in fabricating conventional aluminum alloys were also useable on aluminum-lithium alloys. Since no new equipment were to be considered, Equipment Outlay could not be a factor in this study.

j) Manufacturability Issues sub-factor has four sub-sub-factors, viz. Process, Tooling, Labor and QA. The sub-factors for these four are the processes required in the fabrication of the part or structure in question. In the case of the s/s payload adapter, the process steps were: sheet forming, machining,

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heat treating, chemical milling, fastening, cleaning/finishing and inspection.

Stretch formed 2090 Al-Li plates met the mechanical property design requirements of the s/s adapters. Metallographic examination of the parts further conformed their high quality. However, process specifications had to be altered to require a 1.5 to 3% permanent set during stress relieving operation. Therefore, for the stretch forming process, aluminum-lithium was given a rank of 2, and aluminum a 1. Since stretch forming requires press brakes, tooling and labor involvement is generally high. Moreover, the aluminum-lithium alloy had the extra permanent set required. So the tooling and labor values assigned were 2 for aluminum and 3 for aluminum-lithium. Finally, QA values for stretch forming were 2 for both metals, because both underwent the same quality tests.

k) Machining of aluminum alloys is a "B" on a scale of A-D by Kalpakjian [15]. Moreover, in the s/s adapter study, both metals performed equally well with relation to machining. Thus, for machining, process, labor and QA factors were given ranks of 2 for both metals. For tooling, however, aluminum-lithium needed a milling machine to give a superior finish. For that reason, and the fact that aluminum-lithium got a machining/tooling rank of 4 in the Bao database [2], the aluminum-lithium value was a 4, while aluminum retained its value of 2.

l) Heat Treatment response of aluminum-lithium was comparable with that of aluminum. However, Sutherland [41] reports that tight process control is required in the production of aluminum-lithium alloys. Sutherland's comments, values in Bao's report [2], a brief description of the heat treatment process and its results in Kerr, et al., [20] and a description of the heat treatment behavior of conventional aluminum alloys by Kalpakjian [15] led to values of 1-2, 1-1, 3-3 and 3-4 being assigned to aluminum and aluminum-lithium for the four factors, Process, Tooling, Labor and QA respectively. The reasoning for aluminum values is that the process itself is

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not complex, but the equipment is sophisticated and needs monitoring and quality evaluations.

m) Chemical Milling of the 2090 alloy gave excellent results. Once again, ranks were assigned based on the data in Kalpakjian, Bao's ASEE report and Kerr, et al. As before, the reasoning for aluminum values is similar to that for the heat treatment values. Chemical milling, especially for an aerospace application, requires close tolerances; it is a labor intensive process because the surface has to be carefully prepared; and close monitoring is required during the milling process. Therefore, the ranks assigned were 1-1, 3-3, 3-3 and 3-3 for aluminum and aluminum-lithium for the four factors of Process, Tooling, Labor and QA respectively.

n) Fastening tests on both Al-Li 2090 and Al 2024 sheets proved that standard riveting and installation procedures were equally acceptable for both sheets. With the same reasoning as for chemical milling, the assigned ranks were 1-1, 2-2, 3-3 and 2-2 respectively.

o) Cleaning and Finishing was the final step in the s/s adapter evaluation study. This step evaluated the various surface finish treatments on Al-Li 2090 alloy and the control Al 2024 alloy. The results indicated that while the two alloys fared equally well on all tests, 2090 was superior to 2024 in corrosion resistance properties. Therefore, while Process, Tooling and QA sub-factors were ranked equally, chemical cleaning and finishing is a Labor intensive process, and so that sub-factor was ranked appropriately higher. The ranks assigned were 1-1, 1-1, 4-4 and 1-1 for aluminum and aluminum-lithium respectively.

p) Inspection is included as a separate process step in spite of a QA sub-factor for each of the other manufacturing steps. This is because, in the s/s adapter study—as in the manufacture of almost all other aerospace parts—there would be at least two separate QA steps. First, each individual operation or manufacturing process step would undergo a QA evaluation. Then, the entire part would undergo a terminal inspection prior to use.

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Likewise, in the Kerr et al. paper, the description of each manufacturing step includes a quality evaluation of that step, AND inspection is listed as a separate manufacturing step in the paper. Terminal inspection was carried out on the 2090 Al-Li alloy to verify whether standard inspection methods—in this case, visible and fluorescent die penetrant methods—were applicable to 2090 Al-Li, and that no adverse reactions occurred between the die and the material. The results were favorable. The ranks assigned to the four sub-factors were 1-1, 2-2, 2-2 and 2-2 for aluminum and aluminum-lithium for factors Process, Tooling, Labor and QA respectively.

Having thus entered values in the X-NFR hierarchy and set-up the probabilities, a 3000 iteration Monte Carlo simulation run was carried out. The AHP derived weights for the factors and sub-factors, and ranks generated on the last iteration along with the initial ranks are all shown in Appendix C.1. The mean values for the overall DCF and the various factors and sub-factors for the skin/stringer payload adapter for an Atlas Commercial Launch Vehicle are shown in Table 5-2 (more statistics on these results are also printed in Appendix C-1).

Table 5-2 — Values for skin & stringer payload adapter

	MCF		DCF
	Al	Al-Li	
Overall Mean	0.4220	0.5780	1.3695
Material Cost	0.0277	0.0783	2.8308
Handling	0.1538	0.2221	1.4435
Database Extent	0.0300	0.0478	1.5937
Manufact. Issues	0.2105	0.2298	1.0915
Versatility	0.0898	0.0898	1.0
Equip. Outlay	0.0	0.0	n/a
Mfg.ability	0.3884	0.4322	1.1126
Process	0.2480	0.2732	1.1341
Tooling	0.0604	0.0710	1.1751
Labor	0.1274	0.1358	1.0658
QA	0.0448	0.0469	1.0457

As can be seen, according to the X-NFR results, aluminum-lithium would be about 37% more complex to manufacture than conventional aluminum. Compared to Kaminski, et al's results, this 1.37 value of DCF is much higher

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than their 1.2x. However, as discussed earlier, considering that the 1.37 factor includes material cost, perhaps a more accurate value gleaned from Kaminski, et al. should be:

(4x for material cost) * (1.2x for processing) = 4.8

In which case, the 1.37 complexity is way too low!

Except that, of itself, the 4.8x figure is inaccurate considering that material cost and processing are given equal weights in the Kaminski, et al. paper. Supposing the weights used in the X-NFR method were also applied to the two Kaminski et al. values, the comparison might be more accurate. Based on the AHP outcome, Material Cost factor was given a weight of 0.106 in the X-NFR derivation. The weight of 0.894 (1 - 0.106) was distributed among the three other sub-factors, Handling, Database Extent and Manufacturing Issues. So, incorporating the two sub-factor weights, Kaminski, et al.'s values would be:

$$4 * 0.106 + 1.2 * 0.894 = 1.496$$

This value is considerably closer to the 1.37

But, material cost is still a matter of contention. According to written descriptions in the Kaminski, et al. paper, cost of aluminum-lithium is between *"3 to 4 times conventional alloys"*. So, assuming that Kaminski, et al. had used a value of 3.5x instead of 4x in their table—as discussed in the text of their paper —the comparable total for material cost and process would be:

$$3.5 * 0.106 + 1.2 * 0.894 = 1.444$$

a value still closer to the 1.37

Finally, taking the above argument a step further, let us consider the published divergent information on the cost of aluminum-lithium. Paragraph (a) earlier in this section is a discussion on the divergent information on Material Cost, and the resulting ranks and respective probabilities that were assigned to the contending materials for the MATERIAL COST factor. Suppose that, in submission to divergent cost data, the material cost value in Kaminski, et al.'s cost table were subjected to the Monte Carlo simulation of the X-NFR method. Now, the delta value for the Material Cost factor in Table 5-2 is 2.831 This

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value is obtained as a result of generating three thousand random numbers using a distribution explained in paragraph (a) earlier in this section. Using 2.831x instead of 4x or 3.5x in Kaminski et al.'s cost values, the comparable total for material cost and process would be:

$$2.831 * 0.106 + 1.2 * 0.894 = 1.373$$

This result measures up to the value generated by X-NFR.

Although the above exercise is not of any practical significance or value, it demonstrates the importance of Material Cost in the comparison of results published by Kaminski, et al. and those obtained by the X-NFR method. In order to investigate whether Material Cost did indeed pose a major significance in the comparative results, it was decided to re-work the AHP based weight distributions, re-work the X-NFR calculations and re-do the Monte Carlo simulation. This time, in the AHP, the Material Cost factor was given a weight of 0, and only three main factors were considered in the analysis. Appendix C-2 shows the new weights and ranks. The mean values for the overall DCF for the skin/stringer payload adapter when material cost is not considered are given in Table 5-3 (more statistics on these results are also printed in Appendix C-2).

Table 5-3 — Values for skin & stringer payload adapter when Material Cost is NOT considered

	MCF		DCF
	Al 2024	Al-Li 2090	
Overall Mean	0.4532	0.5470	1.2070
Material Cost	0.0	0.0	n/a
Handling	0.1169	0.1659	1.4194
Database Extent	0.0287	0.0450	1.5673
Manufact. Issues	0.3075	0.3360	1.0926

Thus, discounting material cost, the overall complexity of Al-Li is about 20% more than that of conventional Al, a figure validated by Kaminski, et al. [16].

5.4. Machined, Integrally Stiffened Liquid-OXygen (LOX) Tank

This section is based on a fabrication project undertaken by the McDonnell Douglas Space Systems Co. [16, 42]. The project was taken up to meet future aerospace requirements of increased payload capacity at reduced

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unit cost per payload. This project demonstrated the use of a lighter aluminum-lithium alloy (2090-T81) for a "proof of concept" eight-foot diameter, ten-foot long, cylindrical cryogenic tank that could replace existing Delta cryogenic tanks made of aluminum alloy 2024-T6. The aluminum-lithium tank was fabricated using design, tooling, and numerical control (NC) tapes used in fabrication of the original 2024 aluminum tanks.

The basic steps in fabrication of the tank were [42]:

- isogrid machining of three plates
- press brake forming of the plates to achieve a cylindrical shape
- lengthwise welding of the three plates
- final cleaning and inspection.

The basis for assigning the ranks to aluminum and aluminum-lithium for this comparison, the AHP based weights, and the assigned ranks are detailed in the X-NFR table in Appendix C-3. The mean values for the overall DCF and the various factors and sub-factors for the LOX tank comparison between 2024 Al and 2090 Al-Li are shown in Table 5-4 (statistics of the results are also available in Appendix C-3).

Table 5-4 — Values for LOX tank

	MCF		DCF
	Al 2024	Al-Li 2090	
Overall Mean	0.4016	0.5983	1.4897
Material Cost	0.0313	0.0747	2.3834
Handling	0.1547	0.2212	1.4298
Database Extent	0.0304	0.0474	1.5633
Manufact. Issues	0.1853	0.2550	1.3766
Versatility	0.0480	0.0480	1.0
Equip. Outlay	0.0989	0.1521	1.5388
Mfg.ability	0.2740	0.3792	1.3840
Process	0.2029	0.3110	1.5329
Tooling	0.0632	0.0682	1.0794
Labor	0.1142	0.1490	1.3042
QA	0.0392	0.0525	1.3370

The value for the "processing" cost of the LOX structure published by Kaminski, et al. is 1.5x (Table 5-1). In the LOX comparison above, quiet unlike the s/s adapter comparison, the overall DCF value—1.490—is very close to the

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published 1.5x value. Bypassing the rigmarole of weighting Kaminski. et al.'s figures, suffice it to say that via the X-NFR calculations, the LOX complexity comes out to be marginally lower than that predicted by Kaminski, et al.

However, the 1.490 value includes material cost, which is not present in Kaminski, et al.'s 1.5x value. Hence, to get an accurate and comparable X-NFR value, the LOX comparison was also re-run with no Material Cost factor. Table 5-5 shows the mean values for the DCF and three main factors for the LOX tank comparison when Material Cost is not considered (once again, the weights, ranks and statistics are available, in Appendix C-4).

Table 5-5 — Values for LOX tank, when Material Cost is NOT considered

	MCF		DCF
	Al 2014	Al-Li 2090	
Overall Mean	0.4108	0.5853	1.4108
Material Cost	0.0	0.0	n/a
Handling	0.1157	0.1671	1.4441
Database Extent	0.0285	0.0453	1.5866
Manufact. Issues	0.2706	0.3729	1.3781

When considering the process related factors and sub-factors only, the delta complexity between an aluminum-lithium alloy and a conventional aluminum alloy for a cryogenic LOX tank is 1.41. That is, the LOX tank is approximately 41% more complex to fabricate using the aluminum-lithium alloy. On the other hand, Kaminski, et al. have published a comparable value of 50%.

To explain this discrepancy, it was decided to re-evaluate the ranks assigned to the two alloys in the X-NFR hierarchy. The ranks for the manufacturing steps are based on the Taketani and Boman paper, which is basically a detailed description of the efforts to fabricate a cryogenic welded cylinder from Al-Li alloy 2090-T81. This effort entailed three major processing steps, machining, brake forming and welding. The new structure was fabricated using the same drawings and designs of the original structure, including numerical control tapes, to take advantage of the data available on the initial design. Descriptions of the development effort, and the ranks assigned, follow:

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- Machining was done using the numerically control tapes that were originally developed for the aluminum alloy tanks. The tapes included use of specialized interactive graphic systems, information on automated cutter routines, feeds and speeds and a module for automated machine set-up instructions. Machining was done on a specialized three-axis mill, and took approximately two hours per panel. Upon completion, the first panel was manually inspected to prove the tapes, while the rest were subjected to an ultrasonic tester. Therefore, although the machining effort was fairly involved, the aluminum-lithium alloy did not require any extra effort. Hence, for the machining sub-factor, the ranks assigned were 3-3, 3-3, 3-3 and 2-2 for aluminum and aluminum-lithium for Process, Tooling, Labor and QA respectively.
- Brake Forming of the machined panels was done on a *"brake press using 'open-air' forming (no dies were used)."* However, the process itself was considerably more complex. Numerous cracks formed on both sides of two panels, shimming had to be reduced to avoid cracks, the panels suffered from an anticlastic curvature (an hour-glass shape), special braces had to be installed where the ribs cracked, and, the panels had to be closely inspected to ensure that existing cracks were removed and no additional cracks were present. That is, the Process, Labor and QA efforts in brake forming of the aluminum-lithium panels were considerably more complex while Tooling was about the same. On the basis of such explanations, the ranks assigned for Press Brake for aluminum and aluminum-lithium were 2-5, 4-4, 3-5 and 3-5 for the four respective sub-factors.
- The welding program included two welding processes, the variable polarity plasma arc (VPPA) welding process and the gas-metal arc (GMA) welding process. Formation of the final LOX tank included experimentation required to develop welding procedures, including fixtures. Ranks assigned to the welding Process sub-factor were 1-3 for aluminum and aluminum-lithium respectively, because of the procedure development. For Tooling, the VPPA

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welding system required an extra fixture to remove the back-purge, hence the ranks assigned were 3-4. Labor and QA were both assigned ranks of 2-4 each, because a few trials were needed to establish procedures, cracks were initially observed and minor discrepancies were observed in the first few welds. By the same token, simulation distributions for Tooling and QA sub-factors for aluminum-lithium were assigned as: values less than 0.10 - "2", values grater than 0.10 but less than 0.50 - "3" and values above 0.50 - "4".

- Cleaning and inspection, as a process, is not explicitly discussed in the Taketani and Bowman paper. However, it is mentioned as a process, and so ranks were assigned based on "common sense" interpretations drawn from the two papers. The ranks assigned were 1-1, 1-1, 2-2 and 1-1 for the four sub-factors respectively.

If the above interpretations of the complexity of fabricating an aluminum-lithium structure are correct, then an aluminum-lithium alloy is indeed more complex to manufacture than a conventional aluminum alloy. The question is, by how much?

The Taketani and Bowman paper does not quantify the extra effort. The X-NFR method attempts to do so by assigning ranks to the four process steps and performing simple calculations. If the reasoning in the four bullet paragraphs above is correct, then the ranks assigned to the four process steps are also correct. Thus, it stands to reason, that the manufacturing complexity of aluminum-lithium is indeed about 41% higher than that of conventional aluminum.

Why then would Kaminski, et al. assign a complexity of 1.5x? It should be noted that the objective of the Kaminski, et al. paper is not the cost comparison table. That paper is a general report on the use of aluminum-lithium alloys in space applications. The cost comparison table is one of four tables in that paper, all of which emphasize divergent issues. The values in their cost table are probably based on experience and judgment, not on any

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quantified analysis. For example, according to the cost comparison table, the location factor for the LOX tank is 5x (Table 5-1). In the same paper, there is a section discussing the LOX tank development effort by McDonnell Douglas Space Systems Company. In that section, the location factor is addressed as: *"a full scale Delta vehicle would provide a savings of over 60 kgs., which in this stage translates into an additional 14 kgs. of payload."* Simple math could quantify the ratio of 60 kg. in weight savings to 14 kg. in increased payload as a location factor of 4.29x, not 5x. Therefore, it can be argued that 5x is a simple and convenient rounding off of an actual 4.29x calculated Location Factor value, just as 4x may be a convenient rounding off of an actual 3.5x Material Cost value. In which case, is it not possible that 1.5x is also a rounding off of an actual 1.41x value?

Thus, it is argued that the 1.41 value determined by the X-NFR method is also acceptable, although it cannot be precisely validated by the 1.5X value published by Kaminski, et al.

5.5. Some Other Comparisons

As discussed in Chapter III, the feasibility of the X-NFR method was to be demonstrated by making the following three material comparisons:

1. Comparing a composite material with another composite material.
2. Comparing a composite material with a conventional material.
3. Comparing a conventional material with another conventional material.

and, two other "type" comparisons:

a. making comparisons for a specific part or structure.
b. making generic comparisons between two material forms.

The comparisons in sections 5.3 and 5.4 above satisfy the material comparison number 3, since a conventional material—aluminum—was compared with another conventional—albeit newly developed—material, aluminum-lithium. Similarly, they satisfied the part comparison requirement (a), since they were for specific parts, the skin & stringer payload adapter, and the liquid oxygen tank

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respectively. The validity of the results were also discussed in sections 5.3 and 5.4 respectively. Sensitivity of the results to different inputs are discussed in Chapter VI.

This section discusses some of the other comparisons made via the X-NFR method. Specifically, these were:

1. A comparison between two composites for a specific part—Carbon-Epoxy and Poly-ether-ether-ketone (PEEK) compared for the skin of an aircraft spoiler;
2. A generic comparison between two composite materials—a thermoset, Carbon-Epoxy and a thermoplastic, PEEK ;
3. A comparison between a composite material—Carbon-Epoxy—and a conventional material—aluminum-lithium—for a specific part, the end-rib of an aircraft spoiler;

and

4. A generic comparison between two conventional materials—aluminum and aluminum-lithium.

Table 5-6 on the following page shows a synopsis of the results of each of the above four comparisons. Statistics on the results, as well as the X-NFR spread-sheets—with factor and sub-factor weights, and basis of the ranks assigned to the factors and sub-factors in the four comparisons—can be found in appendices C-5, C-6, C-7 and C-8 respectively.

Table 5-6 — Overall Mean Values of Some Comparisons

		MCF		DCF
		Defender	Challenger	
1	Comparison between Carbon-Epoxy and PEEK for the skin of an aircraft spoiler	0.397	0.603	1.521
2	Generic comparison between Carbon-Epoxy and PEEK	0.445	0.555	1.247
3	Comparison between Carbon-Epoxy and aluminum-lithium for the end-rib of an aircraft spoiler.	0.512	0.323	0.625
4	Generic comparison between conventional Al and Al-Li	0.388	0.611	1.574

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As seen in Table 5-6, for the general comparisons, the two challengers—PEEK and Aluminum-Lithium—are both more complex to manufacture than their respective defenders, Carbon-Epoxy and conventional aluminum. Details for the specific parts—the skin of an aircraft spoiler and the end-rib of the spoiler—are available in Stoecklin [40]. This paper was the basis for the ranks assigned to the materials. In a general comparison, PEEK comes out to be about 25% more complex than C-Epoxy. But when specific production steps for an aircraft Spoiler are considered—Layup forming followed by Autoclave; Drilling and Deburring; and Ultrasonic inspection—the complexity associated with using PEEK doubles, to almost 52%.

For these processes, specifically Layup forming / Autoclave and Drilling / Deburring, the problems associated with PEEK are considerably more than those with C-Epoxy. PEEK requires high process temperatures, which increase the curing effort required for autoclave. Moreover, machined lay-up forming of PEEK is not very efficient, so hand lay-up is required. Accordingly, labor and QA efforts would be higher when working with PEEK compared to working with Carbon-Epoxy. Finally, drilling of PEEK and other thermo-plastic stocks requires machining at both ends [29], which would increase the drilling effort, with correspondingly extra de-burring required. Tooling and QA effort is accordingly high for the machining of PEEK. In contrast, Carbon-Epoxy is the preferred composite for outer skins of various aircraft parts, and accordingly its ranks are low. Specific ranks for the two materials for the Spoiler comparison, along with the results of that comparison are in Appendix C-5.

PEEK was chosen for the above comparison because it is a good alternative material for aircraft parts such as the dispenser tube, shell or nose—parts which are similar in shape and form to an aircraft spoiler. But, PEEK is more conducive to being manufactured by other processes—ply stacking, diaphragm forming and pultrusion—which were not considered in the spoiler skin comparison above.

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When making the general comparison between the two composites, the equation changes considerably. In the general comparison, nine different processes are considered. These include processes conducive to both thermoplastics and thermosets. Therefore, the imbalance is less, and hence the complexity is about 0.25. Specific ranks for the generic comparison are available in Appendix C-6.

Similarly, comparing Carbon-Epoxy with aluminum-lithium for the end-rib of the spoiler, the complexity of the challenger—aluminum-lithium—is considerably less than that of the defender—Carbon-Epoxy. This is understandable considering that:

a) the challenging material is not nearly as expensive,
b) Handling issues are a bigger concern for Carbon-Epoxy,
c) Carbon-Epoxy requires fewer processing steps, but they are all complicated and require sophisticated/expensive equipment,
d) Aluminum-lithium requires more steps to fabricate the end-rib, but they are all common place and the equipment is standard,
e) Carbon-Epoxy takes longer to fabricate the part—5.2 hours/part is available from the Stoecklin paper [40].
f) Aluminum-lithium should take far less time—about 1.5 hours/part. This number is "developed" based on questioning a professional who is experienced with fabricating aluminum, and extrapolating that number to include the nuances of aluminum-lithium.

Thus, as one might expect, aluminum-lithium is less complex to fabricate than Carbon-Epoxy. The X-NFR method helps quantify this difference—about 37% less complex. Specific ranks that led to this number are available in appendix C-7.

Finally, in a general comparison, aluminum-lithium is about 57% more complex to manufacture than conventional aluminum. Specific ranks assigned to the two materials are available in Appendix C-8. This comparison includes 10 different processes that can be used while working with aluminum.

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Aluminum-lithium can be processed by all of those presses. But in almost every case, the rank assigned to aluminum-lithium is higher than that assigned to conventional aluminum. This significantly contributes to the complexity of aluminum-lithium.

Unfortunately, although the detailed steps involved in development of a spoiler skin and its end-rib are available in the Stoecklin paper, and the behavioral characteristics of Epoxy based composites, PEEK, conventional aluminum, and aluminum-lithium are also available in several publications, specific numbers detailing with the complexity of going from one material to another are not. Therefore, there is no basis for comparing numbers from the X-NFR results with any other numbers—because no other numbers are available!

5.6. CONCLUSION

In this chapter, the results of six specific X-NFR comparisons are presented. Also discussed is an evaluation of two materials in another publication (16). In that publication, the authors have presented specific numbers—presumably based on experience—quantifying the increase in complexity when going from one material to the other. The same comparisons are carried out via the X-NFR method. It is shown that the two sets of numbers can be considered complimentary, although they are not exactly equal. The differences between the two sets are discussed and justified in Sections 5.3 and 5.4 respectively.

Four other comparisons are discussed in Section 5.5. Since results from similar comparisons are not available in any other publications, the results from Section 5.5 cannot be individually validated. Therefore, comparisons with Kaminski, et al.'s results have to be relied upon to justify the validity of the X-NFR methodology.

Together, these six comparisons include combinations of composite as well as conventional material comparisons and generic comparisons as well as

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comparisons for specific parts or structures. It can therefore be said that the new unified methodology—the X-NFR—can be used for all of the following:

- Comparing any two materials with each other. Although more than two materials have not been specifically compared, the simple structure can easily incorporate the additional material without any change in the X-NFR methodology. Thus, the X-NFR methodology can be used to compare two or more materials with each other to evaluate their relative manufacturing complexities.
- The methodology can be readily applied to disparate materials—composites and conventional;

and

- The methodology can be used to compare materials for specific parts and structures as well as used for generic material comparisons.

Of the three question posed to the methodology in Chapter III, one—as yet unanswered—is: Are there any limitations or special considerations when comparing composites?

The answer is: Yes and No. No, there are no limitations / special considerations strictly for composites. However, there are special considerations for each individual comparison. Each comparison is different, and has to be treated accordingly. For example, HANDLING issues will vary between comparisons, and will have to change from one comparison to another. Similarly, an entire attribute may not be considered in some comparisons, as EQUIPMENT OUTLAY was not considered for the s/s adapter. Correspondingly, the AHP based attribute and sub-attribute weights would have to be re-evaluated from one comparison to the next. Likewise, probabilities assigned to ranks for the Monte Carlo simulation would have to change depending on the information available on the material's attributes.

Nevertheless, such nuances are to be expected, given the diversity of different materials being compared, and the differences between the different parts and structures being evaluated.

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Therefore, the X-NFR is presented as the unified methodology for selecting the most appropriate material from a given set of materials. THE HYPOTHESIS IS HENCE ACCEPTED.

Having established a methodology, presented results and validated them, the next step is to examine the sensitivity of the methodology to different inputs. The input parameters that varied were associated with the Monte Carlo simulation, the ranks assigned to the contending materials, and the AHP based weights assigned to the factors and sub-factors of the hierarchy. These three are independently addressed in the next chapter.

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CHAPTER VI

SENSITIVITY OF THE X-NFR RESULTS

The X-NFR results are dependent on three input parameters. These are:

1. the Monte Carlo simulation,
2. the ranks assigned to the two—or more—materials,

and

3. the weights derived by the AHP for the factors and sub-factors.

6.1 THE MONTE CARLO SIMULATION

Monte Carlo simulation and the required random number generation are a definite contributor to the final results of the X-NFR method. However, this study—finding the relative manufacturing complexities of advanced materials via the X-NFR method—is not geared towards a sophisticated statistical analysis, research in Monte Carlo simulations, or on random number generation. Neither is the result of the X-NFR method highly affected by a number accurate to the fourth, fifth or sixth decimal place. A number—good to two or three decimal places—that would indicate approximately how much more effort is required to fabricate a part using material B as opposed to some conventional material A, is a sufficient X-NFR result. The difference between the X-NFR result being 1.298 or 1.293 is insignificant. In either case, 1.30 would be acceptable. Therefore, in importance, the other two factors—the weights assigned to the various factors and sub-factors, and the ranks entered for the two materials for those factors and sub-factors—probably overshadow the Monte Carlo simulation.

Nonetheless, the simulation is a significant contributor to the results, and warrants a closer look. Two issues had to be addressed.

- The number of iterations required for the Monte Carlo simulation

and

- The type of random number generator used

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6.1.1 The number of Iterations. There are several publications and book chapters that discuss the Monte Carlo simulation, and address the number of trials required. However, it is almost universally known that no magic number is suitable, and the investigator has to make a judgment depending on the problem at hand. Procedures for determining a sample size that may give a specified precision in a Monte Carlo simulation include the regenerative method [12] , Analysis for Terminating Simulations [22] and Convergence Monitoring [3, 37].

In this study, it was decided to adopt the "traditional approach"—Convergence Monitoring. Basically, this requires running the simulation for several iterations and monitoring the statistic of interest. As discussed in Canada and Sullivan, this is would simply require one to: *"keep a cumulative average on the answer(s) of interest for increasing numbers of trials and judge the number of trials at which those answer(s) have become stable enough to be within the accuracy required"* [3].

It has to be expected that although the average will stabilize after sufficient iterations, it will not be a constant. It will continue to vary with increasing number of iterations. Therefore, the typical approach is to run the simulation for a while without collecting data, *"until it is believed that the simulated system has essentially reached a steady-state condition"* [12]. As one might expect, estimating the time that the simulation needs to stabilize is difficult. One approach, followed by the @RISK simulation package, does convergence monitoring on-line. @RISK has three sets of statistics which are steadily monitored at regular intervals. When changes in the monitored statistics are less than a threshold value, the simulation can terminate.

This was attempted in the X-NFR method, but failed. The statistics of interest were to be the Mean and Standard Deviation of "n" iterations. Although the programming was simple to conceive on paper, the software platform selected—the in-built Visual Basic based Macro module in MS Excel v 5.0—was unable to perform the simple mean and standard deviation calculations for a

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different range of numbers every time. The Macro required a range as specified in Excel, such as:

=Average{ (Row 1 : Column 1) to (Row 100 : Column 1) }

It would not accept any pre-programmed range—such as

=Average { (Row 1 : Column 1) to (Row N : Column 1) }

where N changes every time the function is called.

This simple problem could be very easily overcome in almost any other programming language. However, the simplistic but highly repetitive nature of the calculations makes Excel—or any other spreadsheet—an ideal tool for the X-NFR. Therefore, it was decided to stay with Excel and the built-in Visual Basic based Macro module, and abandon the @RISK style of continual convergence monitoring. Perhaps, further developments in the X-NFR approach can include substituting the @RISK software for the Visual Basic macro currently used to execute the Monte Carlo simulation.

Another alternative—as suggested by Canada and Sullivan—was attempted. For three different comparisons, the Monte Carlo simulation macro was run for ten thousand iterations each, and the results compared. The statistic of interest—the Mean—was plotted for multiples of every 500 iterations. These plots—figures 6.1 to 6.3—were used to decide what "magical" number to choose to terminate all simulations.

As can be seen from the three plots, none of the simulations seem to have unmistakably stabilized over 10,000 iterations. The text-book picture of a wavy line around some mean value as the number of iterations increase does not clearly appear in any of the three plots. However, the overall variability is of the order of about 0.001 units for each of the three plots. Furthermore, in the three plots, the difference between the 10,000th mean value and the 3,000th mean value is -0.0003, 0.0006 and -0.0005 units respectively. That is, the simulation terminating at 3000 iterations or 10,000 iterations would change the final result only at the 10^{-4}th place.

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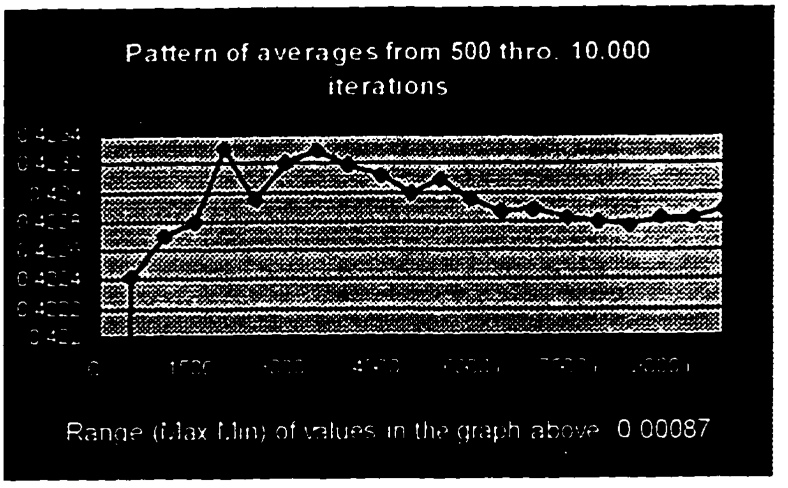

Figure 6.1 — A 10,000 iteration comparison for the s/s adapter

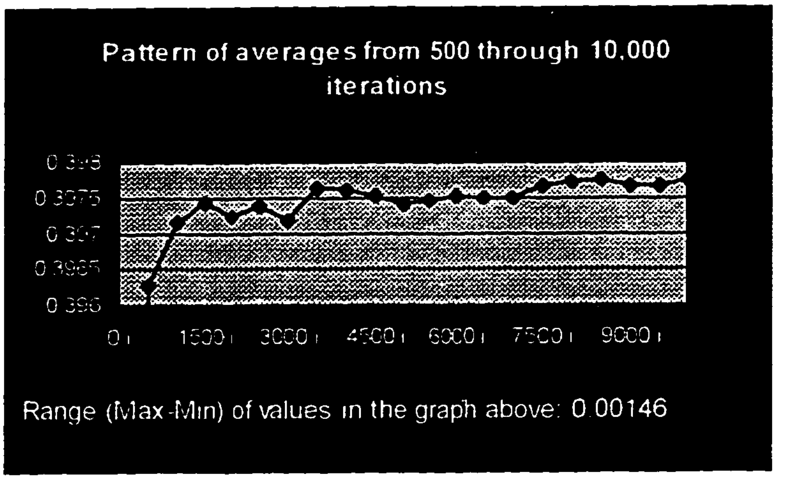

Figure 6.2 — A 10,000 iteration comparison for the LOX tank

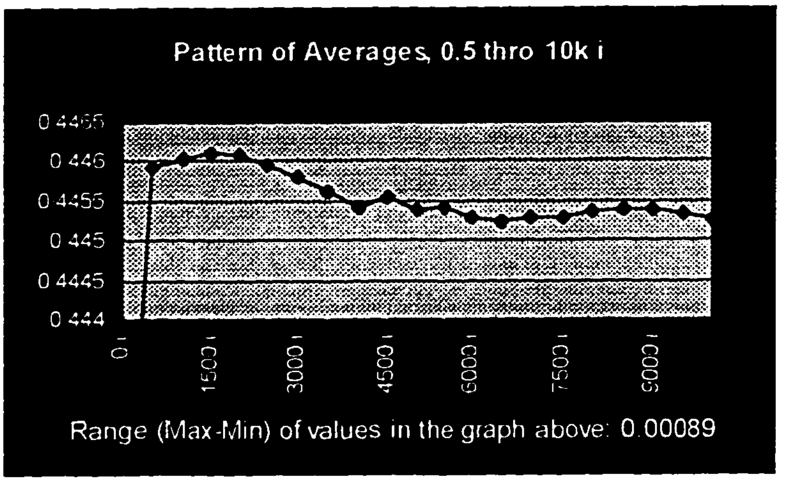

Figure 6.3 — A 10,000 iteration general comparison between two composites

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Considering that the final result of the X-NFR needs to be accurate up to two or three decimal places only, it was decided to run the simulation for three thousand iterations. Perhaps exploring the finer points of the Monte Carlo simulation within the X-NFR framework can be a topic of future investigation.

Finally, it has to be noted that discussions on arriving at the magical 3000 number are held after discussing some results of the X-NFR. However, the search for the number of iterations was conducted before the simulations that generated the final results were carried out. In other words, the work discussed above was carried out first. After arriving at the "3000 iterations is sufficient" result, the subsequent work on comparing X-NFR results with Kaminski, et al.'s results was done.

6.1.2 THE RANDOM NUMBER GENERATOR As discussed earlier, MS Excel was the primary tool for the X-NFR calculations. Hence, the random number generator within Excel was the obvious choice. Within Excel, there are several distributions that could be used to generate the results. However, the =RAND() command was the most ideal tool, since that command: *"returns an evenly distributed random number greater than or equal to 0 and less than 1. A new random number is returned every time the worksheet is calculated"* (MS Excel Users Guide [28]). This suits the X-NFR calculations supremely, where at a time, approximately 100 random numbers are to be generated, the collaboration of these numbers results in one DCF value, and the process is repeated 3000 times.

Accordingly, several attempts were made to learn more about the =RAND() command, such as:

- how does it calculate its random number?
- is it truly random? is it pseudo-random?

and

- is there any possibility of the sequence of numbers repeating itself?

Aside from the two line description above, no other explanation for the command was available. Efforts for searching for the nuances of the =RAND()

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command included thoroughly reviewing MS Excel user guides and the on-line help, consulting colleagues, querying faculty both in ENMA and the CS department at ODU, and posting the question to a simulation "user group" on the internet. However, a definite answer was not forthcoming. Therefore, the statement *"A new random number is returned every time the worksheet is calculated."* has to be heavily relied upon in the results of the X-NFR calculations.

Nonetheless, a legitimate question that would be posed is: "How do you know if the numbers are truly random?" It is very likely that the EXCEL software developers have accounted for that question in developing the =RAND() function. Indeed, since the only available statement describing the =RAND() command is that *"a new random number is returned,"* one can assume that each number generated is truly random. However, if asked the question: How do you know?, the answer is: "I do not"!

The proper use of random numbers requires the deployment of a seed which would generate a string of numbers. Then a new, albeit randomly generated seed would be used if the simulation were repeated, so that the sequence of random numbers is truly different from the first string. What if EXCEL uses the same seed every time the spreadsheet is invoked, so that each simulation ran with the same set of numbers?

To investigate this scenario, a simple experiment was executed. 100 =RAND() commands were used to generate 100 random numbers. In a typical X-NFR set-up, the number of individual ranks assigned to the two contending materials would be anything from as few as 15 per material, to as many as 65 per material. Therefore, at a time, 30 to 130 random numbers would have to be invoked. Generally, between 40 to 60 ranks per material—80 to 120 random numbers—is common. Therefore, 100 has been used as a "typical" number when discussing the general use of random numbers in the X-NFR.

In this experiment, statistics—mean, median, mode, standard deviation, minimum and maximum—for 100 random numbers were calculated, and

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compared with similar statistics for thirty different spreadsheet invocations. 30 is a sufficiently large number for a good approximation of the Central Limit Theorem. Therefore, the hypothesis that the =RAND() command does return a truly random number every time could be accepted if the mean of 30 samples closely approximates the mean of the population, which is known to be 0.5. On the other hand, if a pattern can be found among them, doubts could be raised regarding the accuracy of Excel's random number generator.

The 30 invocations included moving from one file to another, and exiting and returning to EXCEL, as would be required in a typical X-NFR based simulation. The only difference would be that in a typical simulation, such invocations would be repeated 3,000 times. The experiment was repeated on the two different PC's that were used in the simulation runs. The resulting statistics, rounded to the third and fourth decimal place, are shown in Table 6-1.

As can be seen, none of the statistics are exactly repeated. Each mean and median value is around 0.5, with a standard deviation of about 0.28. Considering that the =RAND() command generates a unique number between 0 and 1, a mean of 0.5 is acceptable. Each set of 100 numbers had no mode— i.e. the numbers

Table 6-1 — Statistics from 100 '=RAND()' Commands Executed 30 Times

	Mean	Median	Mode	Std. Dev.	Min.	Max.
1	0.542	0.542	#N/A	0.284	0.0235	0.9895
2	0.478	0.426	#N/A	0.303	0.0047	0.9993
3	0.543	0.591	#N/A	0.284	0.0165	0.9953
4	0.472	0.431	#N/A	0.288	0.0110	0.9905
5	0.530	0.538	#N/A	0.274	0.0057	0.9690
6	0.468	0.452	#N/A	0.289	0.0109	0.9994
7	0.498	0.531	#N/A	0.267	0.0170	0.9920
8	0.473	0.434	#N/A	0.297	0.0142	0.9863
9	0.483	0.460	#N/A	0.316	0.0032	0.9997
10	0.458	0.423	#N/A	0.273	0.0081	0.9804
11	0.489	0.473	#N/A	0.264	0.0114	0.9827
12	0.510	0.576	#N/A	0.285	0.0045	0.9948
13	0.514	0.504	#N/A	0.281	0.0142	0.9940
14	0.522	0.569	#N/A	0.301	0.0001	0.9989
15	0.511	0.492	#N/A	0.285	0.0018	0.9964

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Table 6-1 — Continued

	Mean	Median	Mode	Std. Dev.	Min.	Max.
16	0.486	0.446	#N/A	0.298	0.0011	0.9901
17	0.526	0.573	#N/A	0.286	0.0042	0.9695
18	0.459	0.470	#N/A	0.292	0.0043	0.9990
19	0.535	0.558	#N/A	0.284	0.0095	0.9987
20	0.537	0.566	#N/A	0.301	0.0200	0.9996
21	0.512	0.479	#N/A	0.292	0.0040	0.9876
22	0.548	0.570	#N/A	0.282	0.0105	0.9788
23	0.493	0.521	#N/A	0.296	0.0177	0.9962
24	0.485	0.468	#N/A	0.303	0.0044	0.9987
25	0.491	0.491	#N/A	0.293	0.0104	0.9773
26	0.496	0.530	#N/A	0.282	0.0077	0.9972
27	0.487	0.476	#N/A	0.303	0.0204	0.9814
28	0.534	0.536	#N/A	0.271	0.0339	0.9989
29	0.500	0.462	#N/A	0.287	0.0063	0.9966
30	0.523	0.515	#N/A	0.273	0.0069	0.9984

As can be seen, none of the statistics are exactly repeated. Each mean and median value is around 0.5, with a standard deviation of about 0.28. Considering that the =RAND() command generates a unique number between 0 and 1, a mean of 0.5 is acceptable. Each set of 100 numbers had no mode—i.e. the numbers were not repeated. All the minimum and maximum values are at the extremes of 0 and 1 respectively. In addition, figure 6.4 is a plot of the thirty mean values, which are distributed around the expected mean value of 0.50. That is, 100 =RAND() commands executed 30 different times do not indicate any repetitive pattern. Therefore, it is accepted that the =RAND() command within MS Excel does indeed produce random numbers, and so its use in the X-NFR calculations is justified.

6.2 The Ranks

The ranks assigned to the various factors and sub-factors are what differentiate one comparison from another. For a comparable Monte Carlo simulation and identical attribute and sub-attribute weights, the ranks would differentiate conventional aluminum from carbon-Epoxy or aluminum-lithium, and the s/s adapter from a LOX tank or an aircraft spoiler. As shown by results

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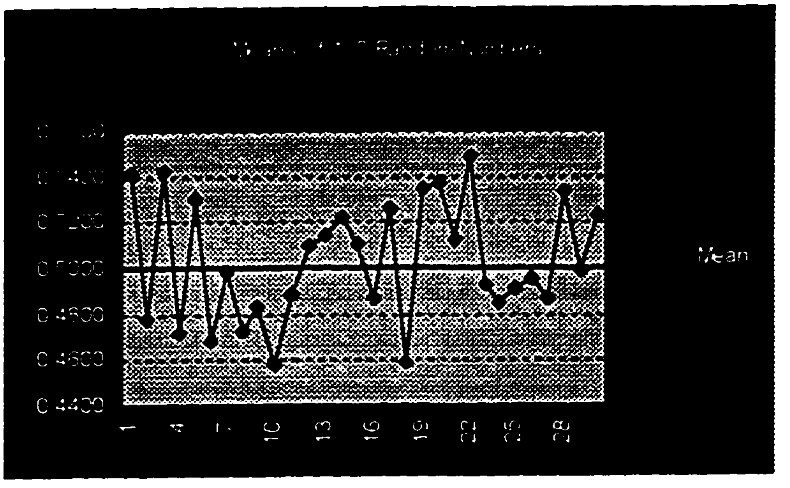

Figure 6.4 — Means of 30 samples of 100 =RAND() Commands

of the two comparisons in Chapter V (Sections 5.3 and 5.4), drastically different ranks have a major impact on the X-NFR results.

The question is how much would the results change if the ranks had been altered "slightly." That is, what would happen if the processing and QA factors for say Press Brake Forming were both changed from 5 to 4 for the LOX comparison?

The answer is: probably not much.

The word "probably" has to be used because an actual simulation was not performed, and so an absolute statement cannot been made. However, little changes in a few values should not affect the result drastically. Once again, major changes will change the scenario completely, but then it is expected that such major changes will be incorporated only when a totally different part or material is introduced. But it is very likely that the minor changes will not matter, because of the several different constituents of the five level factor—sub-factor hierarchy. There could be from as few as 30 to as many as 150 different individual ranks in a typical X-NFR comparison. Because of this sheer number, a few incorrect ranks buried down in the third or fourth tier of the hierarchy will not impact the overall result at the third or fourth significant digit. Beyond that, if an answer is incorrect at a higher significant digit, the overall delta complexity is not greatly altered.

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Nevertheless, the system user should be diligent in assigning ranks and appropriate probabilities to the Monte Carlo simulation, and must not take this task lightly.

If the rank in question is at the first level of the hierarchy itself—such as Material Cost or Database Extent—the effect of an incorrect rank will be significantly enhanced. This effect will be further egged by the weight assigned to the factor, so that an incorrect value for Material Cost—which has a higher weight—will have a higher impact on the final result than that for Database Extent. In such cases it would behoove the user to verify the ranks assigned and distributions chosen to run the Monte Carlo simulation.

In this, as in all other situations, the final effect will be further augmented by the Monte Carlo simulation. One of the reasons for executing the simulation is to abate the effect of possibly incorrect rank values, such as using a 5 where a 4 may have been more appropriate. Therefore, it can be safe to say —without actually changing ranks, simulating, and observing the result—that minor variations in ranks will not have major impacts on the final X-NFR results.

6.3 The AHP Based Weights

As one might expect, the weights assigned to the various factors and sub-factors would have a direct impact on the X-NFR results. By the nature of the calculations, different weights will and must give different results. In fact, one of the reasons that the AHP was chosen for weight assignment was that the weights could be easily and meaningfully changed. In order to investigate the sensitivity of the X-NFR results to the different weights, it was decided to vary attribute weights and re-work calculations in different situations.

6.3.1 Changing Main-Factor Weights The main factor weights were varied and the results of the X-NFR observed. Three different weight scenarios that were chosen for the main factor weights are given in Table 6-2. The basis for the weight scenarios is discussed following table 6-2.

In this analysis, only main factor weights were changed, while the sub-factor weights were left untouched. Original Weights were the ones selected

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Table 6-2 — Main Factor Weights for Three Scenarios

Scenario's	Attribute Weights			
	Material Cost	Handling	Database Ext.	Mfg. Issues
Original Weights	0.106	0.3759	0.0778	0.4402
New Weights	0.205	0.533	0.0448	0.271
Equal Weights	0.250	0.250	0.250	0.250

based on intuition and the expected inclinations of large aerospace contractors —such as the McDonnell Douglas Space Systems Company and the General Dynamics Corporation. One might expect that they have a material database available in-house, and therefore the database extent factor may not have a high priority for them. Material Cost may not be a very high priority either, considering that these companies are multi-million dollar corporations. On the other hand, investigating new materials and the development of a new aerospace part or structure is to their advantage. So, the handling of the new materials, and manufacturing issues may have relatively higher priorities to these contractors. Based on such thinking, the Manufacturing Issues factor was given the highest importance, closely followed by the Handling factor. Database Extent was considered to be the least important factor. As can be seen, the Original Weights reflect this thinking. In the AHP table, the consistency ratio had to be maintained at less than 0.1—it is 0.06, as shown in Appendix A. The results in Sections 5.3 and 5.4, which compare with the published results of Kaminski, et al., are based on using Original Weights in the X-NFR calculations.

The other two weight scenario's were also derived using the AHP. In the scenario called New Weights, Handling was given the highest importance, Material Cost and Manufacturing Issues were given equal albeit a little bit lower importance, and Database Extent was the scapegoat. In this case, it was assumed that an organization was experimenting with a new material, and how the material Handles is most important to it. Database available on the material is the least important, and the other two issues fall in between. The consistency ratio in this case is 0.0778. In the third scenario, all four factors were given

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Equal Weights, 0.25 each. The consistency ratio is an obvious 0.0—perfect consistency.

Table 6-3 gives the overall results of the iterations for both the s/s adapter and the LOX tank comparisons using the three weight scenario's.

Table 6-3 — Comparison for same rank, different factor-weights

Scenario	MCF		DCF
Overall Mean values for the S/S ADAPTER			
	Al	Al-Li	
Old Weights	0.422	0.578	1.370
New Weights	0.391	0.609	1.540
Equal Weights	0.385	0.615	1.595
Overall Mean values for the LOX TANK			
	Al	Al-Li	
Old Weights	0.402	0.598	1.490
New Weights	0.388	0.612	1.577
Equal Weights	0.379	0.621	1.641

These results are based on the original X-NFR hierarchy, and include Material Cost as one of the main factors. The results are obviously different for each different weight scenario. For a company that values:

- the Handling and Manufacturing of new materials highly,

and

- Material Cost is valued lower than the other two factors,

a S/S ASSEMBLY is about 37% more complex to fabricate using Al-Li. However, for some other company that values:

- the Handling of new materials very highly,

and

- Material Cost is valued equally highly as the Manufacturing of new materials, but both are not as highly valued as Handling,

the same S/S ASSEMBLY is about 54% more complex to fabricate using the new material. Obviously, how priorities are assigned to the factors is a definite contributor to the X-NFR result.

6.3.2. WEIGHTS WITHOUT MATERIAL COSTS Since it was established that the Material Cost factor influences the result and has to be discarded

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before any comparisons can be made with the Kaminski, et al. results, one simulation run was carried out on the s/s adapter, comparing "old" and "new" weights—without material costs. The old weights were based on giving a high importance to Manufacturing Issues, followed by Handling, and almost none to Database Extent. For the new weights, Database Extent was again ignored, while Manufacturing Issues and Handling were given equal importance. In both cases, Material Cost had a weight of 0.

Table 6-4 lists the "old" and "new" weights along with the respective results for the two runs. Note that the results using the "old" weights are the ones in Table 5-3.

Table 6-4 — Old and New Weights without Material Cost, along with appropriate results for the s/s adapter comparison

	Material Cost	Handling	Database Ext.	Mfg. Issues
Old Weights	0.0	0.2828	0.0738	0.6434
New Weights	0.0	0.4737	0.0526	0.4737

	MCF		DCF
	Al	Al-Li	
Overall Mean using Old Weights	0.4532	0.5470	1.2070
Overall Mean using New Weights	0.4409	0.5592	1.2685

As can be seen in Table 6-4, the DCF went up from 1.20 to almost 1.27 when Handling and Manufacturing Issues are considered equally important. An obvious conclusion is that the user's perception of the importance of the different attributes and sub-attributes will have a major influence on the final outcome. Since the original weights give a result close to that published by Kaminski, et al., it can be surmised that their priorities—although not explicit—must have been very close to the "old weight" priorities used in the X-NFR.

Furthermore, perhaps the priorities slightly changed while transgressing from the s/s adapter to the LOX tank. This is a likely assumption considering that fabrication of the two structures was undertaken by divisions of two different organizations, General Dynamics and McDonnell Douglas respectively.

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This might explain the difference between the X-NFR results and those published in Kaminski, et al. for the two comparisons.

6.3.3. Changing Sub-Attribute Weights A third comparison was carried out with a different focus. The above two comparisons have considered different main-factor weights, while leaving the sub-factor weights unchanged. Intuitively, one might expect that different main-factor weights will result in different results, and the numbers above support such expectations. However, it was necessary to verify whether constant main factor weights and modified sub-factor weights also result in ubiquitously different MCF values. In other words, suppose that the contribution of Handling and Manufacturability Issues factors to the overall complexity is unchanged. Then, it had to be investigated whether the overall result was affected by changing the distribution of the sub-factors that make up these two main factors. Once again, "gut feeling" would say that the results will differ, but the scenario had to be investigated.

Ergo, the s/s adapter comparison was run again. This time, the original main factor weights were maintained, but all the Handling and Manufacturability Issues sub-factor weights were re-evaluated. The old and new weights are as shown in Table 6-5, along with the results of the two comparisons.

As can be seen—and expected, disparate weights assignments have significant impact on the final outcome of the X-NFR results. With a cursory look, one might erroneously conclude that the original corroboration of Kaminski, et al.'s results with the X-NFR values for the s/s adapter is co-incidental! To say the least, such a deduction would be glaringly inaccurate. As with the main factors, the weight assignments for the original sub-factors were also made after considerable thought and contemplation. Not only was the AHP used, but the relative rankings between the sub-factors were very judiciously selected—based on the stand-alone importance of the sub-factors as well as their importance to the fabrication of aerospace structures. Literature

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Table 6-5 — Two Weight Scenarios and Comparison Results

	Old Weights		New Weights
Material Cost		0.1060	
Handling		0.3759	
Ductility	0.4355		0.2105
S/B Strength	0.2857		0.1578
Extra Handl.	0.1943		0.2632
Ingot Quality	0.0442		0.2632
Scrap	0.0442		0.1053
Database Extent		0.0778	
Manufact. Issues		0.4402	
Versatility	0.1797		0.1200
Equip. Outlay	0.0		0.0
Mfg.ability	0.8203		0.8800
Process	0.5140		0.5804
Tooling	0.1314		0.0686
Labor	0.2632		0.1301
QA	0.0917		0.2208
	MCF		DCF
Overall Complexity	Al	Al-Li	
Old Weights	0.4220	0.5780	1.3695
New Weights	0.3971	0.6027	1.5178

search, along with consultations with the local domain expert—Han Bao of Old Dominion University—went into the AHP as inputs.

For instance some thoughts that went into the relative rankings for the Handling sub-attributes were as follows. Ductility is the prime attribute for the s/s adapter because it is a stress critical structure [16]. This is closely followed by Shear and Bend Strength of the material, and the Extra Handling involved in working with the new material. Ingot Quality of both the materials is assumed to be at par, considering that suppliers of aluminum-lithium are also reputable manufacturers (Alcoa and Reynolds metals), and so it should not be a major concern. A major aerospace manufacturer working on an experimental development would not be excessively concerned with Scrap either. Hence these two issues would have relatively low importance. Accordingly, Ductility has the highest weight—0.44; followed by S/B Strength —0.29; Extra Handling — 0.19; and Ingot Quality and Scrap have equal weights at the bottom of the ladder—0.04 each.

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Similarly, with the MANUFACTURING ISSUES sub-factors—VERSATILITY and MANUFACTURABILITY—the general agreement was as follows. While MANUFACTURABILITY is considerably more important than VERSATILITY, VERSATILITY is not exactly insignificant. Considering that these are experimental prototypes, the ability of aluminum-lithium to be fabricated by all the processes that are applicable to aluminum would have a major bearing on its final acceptance as an alternative material. Therefore, VERSATILITY should be given some importance—in the original AHP assignment, "some" translated into 0.179 or about 18%.

Finally, the MANUFACTURABILITY sub-sub-factors—PROCESS, TOOLING, LABOR and QA. The thinking was that PROCESS as a factor must be considerably significant. Of the remaining three, QA can be subversant, taking into account inspection as an intrinsic part of each process step. TOOLING is important, but considering that the same process steps are considered, the effort required to work on new tooling would be less than that if entirely new processes were to be developed. Therefore, PROCESS has the highest importance—0.51; followed by LABOR—0.26; TOOLING—0.13 and finally QA—0.09.

On the other hand, no such thinking went into the "New Weight" assignments. The weights were distributed solely with the intention of coming up with an alternative set of weights for comparison purposes. The only requirement was that in every case, the Consistency Ratio must be less than 0.1.

Therefore, it has to be accepted that different weights will change the X-NFR results considerably. However, a judicious assignment of the weights is exceedingly important, and correct weight assignments should produce meaningful results.

6.3.4. MEASURED CHANGES IN ATTRIBUTE WEIGHTS Expecting different weights to produce different results, the next logical question would be: how much of a change in weights is necessary before the change in X-NFR results is

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significant? This question would best be answered by exploring the subtleties in the AHP. An experimental design could be set-up to systematically vary individual attribute and sub-attribute weights at two—or more—levels, measure X-NFR results, and identify relationships between changing attribute weights and the final outputs. Ordinarily, there are four attributes at the first level, one of which would have five sub-attributes and the other three. Two of the sub-attributes have four sub-sub-attributes. At two levels, a full-factorial design, considering all possible interactions, would require: $2^4 * 2^5 * 2^3 * 2^4 * 2^4$ or 1,048,576 experiments! Obviously a succinct experimental set-up would be required. What's more, the set-up would be further complicated by the fact that simply varying one element will not suffice, since the Consistency Ratio of the attribute set has to be maintained 0.1 or less.

Pursuing this avenue of the sensitivity of the X-NFR and its interactions with the AHP is beyond the scope of this dissertation. Mostly, because addressing the issue discussed in the paragraph above involves working with the nuances of the AHP, and thereby digresses from the primary objective of the X-NFR.

However, it has to be acknowledged that this is an important consideration for the X-NFR results, for the reason that the attribute and sub-attribute weights have a huge impact on the X-NFR outcome. Sensitivity analysis involves making measured changes in input and observing changes in output. Since this is not explicitly addressed in the three sensitivity cases above (sections 6.3.1, 6.3.2 and 6.3.3 respectively), further simulations were carried out by making measured changes in AHP weights and observing the X-NFR results—without regard to the Consistency Ratio.

To do so, the main attribute weights were systematically varied by 5 and 10%. For the s/s adapter, Table 6-6 lists the DCF values of 12 different X-NFR simulation runs. The weights of the three main factors—Material Cost (MC), Handling (HN) and Manufacturing Issues (MFG)—are increased and decreased by 5% and 10% respectively from the base case values used in the original

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simulation. In each case, the other three attributes are proportionately adjusted without regard to the Consistency Ratio, so that the sum of the four attributes always equals 1.0. Database Extent is ignored in this comparison, since its contribution is almost insignificant in the base case. In Table 6-6, DCF values from the 12 cases are compared with the result obtained from using the Original Weights (Orig. Wt.) in terms of a percentage change from the original DCF value.

Table 6-6—Three Main Attributes up and down by 5% and 10% from the Base Case for Al v/s Al-Li comparison, s/s Adapter

	Mat. Cost	Handling	Dbase. Ext.	Mfg. Issues.	DCF	Δ
Orig. Wt.	0.106	0.376	0.078	0.440	1.3695	100 %
MC up 5 %	0.111	0.374	0.076	0.438	1.3705	100.07%
HN up 5	0.100	0.395	0.072	0.434	1.3597	99.28
MFG up 5	0.099	0.369	0.070	0.462	1.3516	98.69
MC dn 5%	0.101	0.378	0.080	0.442	1.3574	99.11%
HN dn 5	0.112	0.357	0.084	0.446	1.3646	99.64
MFG dn 5	0.113	0.383	0.085	0.418	1.3767	100.53
MC up 10%	0.117	0.372	0.074	0.437	1.3739	100.32%
HN up 10	0.093	0.413	0.065	0.428	1.3527	98.77
MFG up 10	0.091	0.361	0.063	0.484	1.3307	97.16
MC dn 10%	0.095	0.379	0.081	0.444	1.3527	98.77%
HN dn 10	0.119	0.338	0.090	0.453	1.3688	99.95
MFG dn 10	0.121	0.391	0.092	0.396	1.3905	101.53

From Table 6-6, it is seen that as the weight of Material Cost factor is increased, the DCF increases, and vise versa. Conversely, as the weight of Manufacturing Issues factor increases, DCF decreases, and vise versa. However, the DCF decreases irrespective of whether the contribution of Handling is increased or decreased. Overall, it is seen that by varying the inputs by as much as 10%, the outputs change between 0.32% and 2.84% only. A 20% change in inputs—from -10% to +10%—results in the DCF increasing by 1.57% for Material Cost (MC), DCF decreasing by 1.18% for Handling (HN), and by 4.3% for the Manufacturing Issues (MFG) factor.

It is to be expected that varying MFG weights will result in higher DCF swings than varying MC weights, considering that MFG has the highest weight in the Base Case (0.44 for MFG, v/s 0.37 for HN or 0.106 for MC). However, by

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the same token, MFG and HN should both have higher swings than MC. This is not seen in the result, where both HN and MC vary the DCF by about 1-2% only, and MFG varies it by about 4%.

Furthermore, no specific pattern can be drawn from the changing inputs and the resulting outputs. There is no visible relation between increasing or decreasing weights and changing DCF values. For example, by increasing the MC weight by 5%, DCF increases by 0.07%, but on increasing the MC weight by 10%, DCF increases by 0.32%—an increase in DCF of 4.5 times. However, decreasing the MC weight by 5% decreases DCF by 0.89%, and decreasing MC weight by 10% decreases DCF by 1.23%—a decrease in DCF of 1.38 times! Several such comparisons were attempted across the board, but the results are inconsistent.

However, a regression on the X-NFR results—with 15 different main-attribute weights as inputs and the respective 15 DCF's as outputs—has an adjusted R^2 of 0.9986, indicating a strong relationship between the changing main factor weights and the resulting DCF values. The resulting regression equation is:

$$DCF = (-159.224) + (MC*161.735) + (HN*160.659) + (DB*160.595) + (MFG*160.284)$$

This equation was subjected to an arbitrarily selected weight distribution—where weight of the Database Extent factor was increased by 8%. In this situation, the resulting weights are:

Material Cost	Handling	Dbase Extent	Manufacturing Issues
0.1039	0.3738	0.0840	0.4381

The DCF calculated from the regression equation is compared with another 3000 iteration X-NFR simulation, using the weights above. The results are:

Scenario	DCF from Regression Equation	DCF from the X-NFR simulation run
Dbase Extent up 8%	1.3612	1.3699

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Therefore, one might conclude that after running several iterations, a regression equation can be used to analyze different main-factor weight distribution scenarios.

To assess whether such behavior is true in another case as well, 12 more simulations were carried out, this time using different materials for comparison. Table 6-7 is similar to table 6-6, in that it also lists the DCF values of 12 different X-NFR simulation runs, this time varying main attribute weights for a comparison between two composite materials, Carbon-Epoxy and PEEK. They are also compared with the base case—generic comparison of Carbon-Epoxy and PEEK (section 5.5, Table 5-6).

Table 6-7—Three Main Attributes up and down by 5% and 10% from the Base Case for a C-Epoxy v/s PEEK general comparison.

	Mat Cost	Handling	Dbase Ext.	Mfg. Issues	DCF	Δ
Base	0.106	0.376	0.078	0.440	1.247	100%
MC up 5%	0.111	0.374	0.076	0.438	1.2498	100.23%
HN up 5	0.100	0.395	0.072	0.434	1.2284	98.51
MFG up 5	0.099	0.369	0.070	0.462	1.2294	98.59
MC dn 5%	0.101	0.378	0.080	0.442	1.2435	99.72%
HN dn 5	0.112	0.357	0.084	0.446	1.2621	101.21
MFG dn 5	0.113	0.383	0.085	0.418	1.2610	101.13
MC up10%	0.117	0.372	0.074	0.437	1.2524	100.44%
HN up 10	0.093	0.413	0.065	0.428	1.2148	97.42
MFG up 10	0.091	0.361	0.063	0.484	1.2155	97.48
MC dn10%	0.095	0.379	0.081	0.444	1.2386	99.33%
HN dn 10	0.119	0.338	0.090	0.453	1.2771	102.41
MFG dn 10	0.121	0.391	0.092	0.396	1.2804	102.68

As with Table 6-6, the results observed in Table 6-7 are again not definitively conclusive. As before, when the weight of MC factor increases, the DCF increases, and vise versa. Similarly, DCF decreases as the weight of MFG increases and vise versa. However, unlike the earlier comparison, DCF changes in opposition to contributions of HN. That is, DCF decreases as the HN increases in weight, and DCF increases as HN decreases.

Overall, as before, it is seen that by varying the inputs by as much as 10%, the outputs change by between 0.22% and 2.66% only. A 20% change in inputs results the DCF increasing by 1.11% for MC, which is probably

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comparable to the earlier case. However, a 20% change in HN decreases DCF by 4.85%, and a 20% change in MFG decreases the DCF by 5.07% . Thus, both HN and MFG have a wider influence on the DCF value than MC, a behavior not seen in the first case.

Also unlike the earlier comparison, there seems to be a slightly discernible pattern when observing changes between specific inputs and outputs. In every case, as the attribute changes from 5% to 10%, the resulting change in DCF values is more structured. For example, as Handling weight decreases by 5%, the DCF increases by 1.2%; but when Handling weight decreases by 10%, DCF increases by 2.4%, or DCF increases by exactly 2 times. In the other five cases, the DCF changes from between 1.7 times to 2.4 times. This contrasts with the first comparison, where DCF changes were between 0.13 to 4.6 times.

Once again, a regression on the X-NFR results—this time, with 13 different main-attribute weights as inputs and the respective 13 DCF's as outputs—has an adjusted R^2 of 0.9971, again indicating a strong relationship between the changing main factor weights and the resulting DCF values. The resulting regression equation is:

$$DCF = -0.710471 + (MC*2.812602) + (HN*1.69966) + (DB*3.029612) + (MFG*1.78083)$$

This equation was subjected to two different main-attribute weight scenario's, one where Database Extent is increased by 8%, and the other, the New Weights (Table 6-2, Section 6.3.1), and the DCF's calculated. To make a comparison, the same weight distributions were run through two 3000 iteration X-NFR simulations. The results compare as follows:

Scenario's	DCF from Regression Equation	DCF from the X-NFR simulation run
Dbase Extent up 8%	1.2520	1.2538
New Weights	1.2942	1.2994

After running several iterations, a regression equation can be used to analyze different main-factor weight distribution scenarios. It is evident that the

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DCF values obtained by the regression equation are slightly lower than those obtained by the actual simulation.

Why a difference in the behavior of outputs with respect to inputs between the two comparisons—Tables 6-6 and 6-7—is not clear. Neither is it immediately clear why should the DCF increase when Material Cost attribute increases in weight, while DCF decrease when Manufacturing Issues attribute increases in weight, and vise versa. Also, why should the DCF behave differently when Handling Issues are increased and decreased for the two comparisons is not clear either. In all of the X-NFR comparisons above, there are two independent factors, one within the system users control—the AHP weights, and one not within the system users control—the Monte Carlo simulation. Perhaps, the Monte Carlo simulation adding its own twist to the results is a plausible explanation. Hence, 12 more comparisons were carried out, repeating the S/S ADAPTER experiments without the Monte Carlo simulation. That is, the main factor weights were changed, but the ranks were not subjected to random number simulations. The results are shown in Table 6-8.

Table 6-8—Three Main Attributes up and down by 5% and 10% from the Base Case for the S/S ADAPTER comparison without simulation.

	Mat Cost	Handling	Dbase Ext.	Mfg. Issues	DCF	Δ
Base	0.106	0.376	0.078	0.440	1.504	100%
MC up 5%	0.111	0.374	0.076	0.438	1.511	100.44%
HN up 5	0.100	0.395	0.072	0.434	1.498	99.62
MFG up 5	0.099	0.369	0.070	0.462	1.481	98.49
MC dn 5%	0.101	0.378	0.080	0.442	1.498	99.57%
HN dn 5	0.112	0.357	0.084	0.446	1.510	100.39
MFG dn 5	0.113	0.383	0.085	0.418	1.527	101.54
MC up 5%	0.117	0.372	0.074	0.437	1.517	100.87%
HN up 10	0.093	0.413	0.065	0.428	1.492	99.23
MFG up 10	0.091	0.361	0.063	0.484	1.459	97.01
MC dn10%	0.095	0.379	0.081	0.444	1.491	99.14%
HN dn 10	0.119	0.338	0.090	0.453	1.516	100.77
MFG dn 10	0.121	0.391	0.092	0.396	1.551	103.11

Analogies can be found between the results of Table 6-8 above and those of Table 6-7, and to a slight extent, Table 6-6. As in the case of C-Epoxy v/s PEEK comparison of Table 6-7, the DCF value changes in tandem with

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MC—as MC increases, DCF increases, and vise versa; and, DCF values change in opposition to HN and MFG—as the attribute weights increase, DCF decreases, and vise versa. Also, as the attribute changes between 5% and 10% in either direction, the change in DCF is almost exactly equal to 2—between 1.97 and 2.02—in every case. A 10% change in attribute weight results in the DCF changing between 0.38% and 3.11%. With a 20% change in attribute weight, the DCF changes by 1.74% for MC, 1.58% for HN and 5.93% for MFG. Fluctuations such as these are seen in the s/s ADAPTER comparison in Table 6-6.

In conclusion, one might say that the X-NFR results are sensitive to changes in the AHP based input. A 20% change in input can generate outputs that are variant by as much as 6%. The DCF changes in tandem with the changing weights of the Material Cost factor. However, its changes are in opposition to the Manufacturing Issues factor. The direction of DCF's changes are inconsistent when considering the Handling Issues factor—in one case, the DCF goes down irrespective of whether Handling weights increase or decrease; in another case, the DCF goes down when Handling weights go up, and DCF goes up when Handling weights go down. In all cases, the rate of DCF's change is not obviously related to the change in main factor weights. That is, in one case, as a main factor weight goes up by 5%, the DCF goes up by 0.07%, while in another case, as the same factor weight goes up by 5%, the DCF goes up by 0.22%. However, a regression analysis results in a high adjusted R^2 value for both the Al v/s Al-Li comparison for the s/s adapter and the general C-Epoxy v/s PEEK comparison.

6.4. Variance Analysis Between Different Runs.

To verify whether the difference between runs with different weights is significant, an Analysis of Variance (ANOVA) test was carried out. The ANOVA results for the 3000[1] MCF values for aluminum generated by two Monte Carlo

[1] It has been said all along that the simulation is run 3000 times. However, in actuality, the simulation stopped after 3001 iterations.

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Simulations—one with old weights and the other with new weights—are given in Table 6-9.

Table 6-9 — Single Factor ANOVA for Comparison for the s/s Adapter, No Material Cost factor, two groups: Old and New Weights.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Old Weights	3001	1359.973	0.45312	0.00048
New Weights	3001	1323.051	0.44087	0.00087

ANOVA

Source of Variation	*SS*	*df*	*MS*	*f*	*P-value*	*f crit*
Between Groups	0.22713	1	0.22713	338.65	1.29E-73	3.843
Within Groups	4.0241	6000	0.00067			
Total	4.2512	6002				

Comparing the *f* and $f_{critical}$ values in Table 6-9, the $f_{(0.05,\ 1,\ 6000)}$ critical value of 3.84 is considerably smaller than the *f* value of 339. Hence, it is safe to say that $\mu_1 \neq \mu_2$, and that two simulation runs with different weights will yield different results.

Similarly, variance analysis was carried out on some of the several other simulation runs. Specifically, nine ANOVA results were generated, comprising combinations of: (a) same rank values and different AHP weights; (b) different rank values and same AHP weights; and (c) same rank values and same AHP weights. Table 6-10 shows the *f*, $f_{critical}$ and *P* values for some of the different ANOVA results (complete ANOVA results are included in Appendix D, including the Tuckey's procedure—the *T* Method [5]—to determine if any μ_i's were not different from one another, when more than two μ's were compared).

As expected, the ANOVA table conforms that the simulation is sensitive to changing ranks and weights. In cases 1 and 2, the 3000 overall MCF values generated for aluminum for each of the three weight scenarios were compared

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against each other—for the s/s adapter and the LOX tank respectively. These two

Table 6-10 — *f*, *f critical* and *P values* for some ANOVA results.

	Comparison	*f value*	$f_{critical}$	*P value*
1	Al values of s/s adapter across three weight scenarios	964	2.997	0
2	Al values of LOX tank across three weight scenarios	441	2.997	1.73 E-183
3	Al values of LOX tank v/s the s/s adapter, for the same set of—Original—weights	1041	3.843	1.14 E-210
4	Al values of LOX tank v/s the s/s adapter, for the same set of—Equal—weights	46	3.843	1.56 E-11
5	Al values of s/s adapter when only sub-factor weights were changed	1708	3.843	0
6	Mfg.ability. factor comparison when its sub-factor weights were changed	7699	3.843	0
7	Mfg. Process sub-factor ranks for LOX tank across three weight scenarios	0.0008	2.997	0.9992
8	Mfg. Process sub-factor ranks for s/s adapter across three weight scenarios	0.8050	2.997	0.4471
9	LOX tank v/s the s/s adapter, for the same set of—Original—weights for the 10000k run	10548	2.996	0

cases show that if the ranks of two X-NFR simulations are held constant, but weights changed, the results are significantly different from each other. In cases 3 and 4, the weights were held constant, Original and Equal respectively, while the MCF values for s/s adapter ranks were compared with MCF values for the LOX tank ranks. Once again, it is evident that the results are not identical. Cases 5 and 6 are for the s/s adapter comparison of same main attribute weights and different sub-attribute weights. Case 5 is the result of a variance analysis for the overall MCF values of aluminum. Case 6 is the results of an analysis of the Manufacturability Issues sub-factor. In this scenario, both sets of values had the same main factor weights while the sub-factor weights were altered. In each of the six cases above, $f_{critical}$ is lower than the calculated *f* value, suggesting that the means are significantly different from each other.

Conversely, two cases—7 and 8—are comparisons when both the rank and weight remained the same. The Manufacturability Process sub-factor was

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chosen for the LOX tank and s/s adapter respectively, when the main factor weights were changed from Original to New to Equal. In both cases, $f_{critical}$ is grater than the calculated f value. That is, the two simulation runs are identical. This means that when both ranks and weights are held constant, one simulation run is as good as any other, and one should not expect to see different results.

Finally case 9 is a repeat of case 3, this time with 10,000 iterations. As before, when the weights are held constant and ranks changed, the results are significantly different from one another.

6.5 CONCLUSION

In conclusion, the X-NFR results are sensitive to all the different inputs—the attribute and sub-attribute weights, parameters for the Monte Carlo simulation, and the ranks assigned to the attributes and sub-attributes. The AHP based weights must be judiciously assigned to reach meaningful results, because they reflect the thinking and priorities of the system user. All else being equal, different weights will generate appropriately different X-NFR results for the same comparison. It was also shown, that a 20% variation in the weights will alter the results by about 6%. If several X-NFR results are available for the same set of ranks and probabilities, a regression equation can be generated, and could be substituted for making further weight-based comparisons.

The Monte Carlo simulation is a standard simulation technique, used in numerous different and divergent applications. The precautions required, drawbacks of, and benefits derived from the Monte Carlo simulation technique—which are well defined and documented—are applicable in its use in the X-NFR also. Although marginally incorrect rank assignments will not drastically alter the X-NFR results, it would behoove the system user to individually consider each rank to maintain system integrity.

From an analysis of variance (ANOVA) of the results, it was seen that changing ranks or weights—either jointly or individually—generate significantly

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different X-NFR results. Only when both ranks and weights are held the same, the results are also the same, and one simulation result is as good as the other.

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CHAPTER VII

COMPARISONS

The X-NFR method, with its four level hierarchy, inclusion of the AHP for establishing weights, and use of Monte-Carlo Simulation for robust estimates, is presented as a "unified methodology" for selecting the most appropriate material from a given set of materials. As was discussed in Chapter II, although seemingly other approaches also exist that could be used to reach similar decisions, none are as encompassing or comprehensive as the X-NFR. It was further discussed therein, that two approaches are particularly popular when dealing with the uncertainties of newly developed materials.

In this chapter, these two approaches—Scaling Laws and the Manufacturing Complexity Generator of PRICE H—are examined in detail. The differences between each of these approaches and the X-NFR methodology are also drawn out. It is submitted at the end of each discussion, that the X-NFR method is significantly different from either of the two methods, and the results of using the X-NFR *can not* be realized by either of the other two methods.

7.1 Scaling Laws.[1]

Dr. Timothy G. Gutowski of the Laboratory for Manufacturing and Productivity at the Massachusetts Institute of Technology has been leading a group of researchers to work on estimating time and cost of fabricating parts using composites. Their work is generally known as the Scaling Laws. It furthers the ACCEM model (section 2.3) for estimating the time for each step in a process plan.

An important application of the Scaling Laws is the doctoral dissertation of one of Dr. Gutowski's students, a Dr. Ein Neoh. His thesis, which is a manifestation of the Scaling Laws model, is essentially geared towards:

[1] This section is drawn primarily from Neoh, Ein Teck, *"Adaptive Framework for Estimating Fabrication Time"* Ph.D. Thesis in Mechanical Engineering, the Massachusetts Institute of Technology, August 1995.

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"estimating the time required for a given individual process step in a series of steps required to fabricate a part."

There is an observation in the Scaling Laws model—based upon several examples and analysis of ACCEM data—that the times for completing the individual process steps required to fabricate a part follow the 80/20 rule. That is, among the several process steps, a "vital few" steps take the highest amount of time to complete, while the "trivial many" steps take relatively small amount of time. This observation is exploited to estimate the time required to fabricate an entire part. This is done by:

1. Estimating—as accurately as possible—the time required to complete the single most time-consuming (dominating) process step. This is done via an equation derived for t_d, the time consumed by the dominating step.
2. Hypothesizing that the total time required is simply a multiplier "m" of the dominating step, i.e.

$$t_{total} = m * t_{most\ dominating\ step} \qquad \text{......7.1}$$

3. And, deriving "m" as a function of the time for the second most dominating step, and the time for remaining steps, i.e.

$$m = 1 + \frac{t_{2nd\ most\ dominating\ step}}{t_{most\ dominating\ step}} + \frac{\sum t_{average\ for\ other\ step}}{t_{most\ dominating\ step}} \qquad \text{...7.2}$$

Times for the second and successive process steps are approximated by drawing corollaries from other similar activities, in fields as far away as building construction. The specific input parameters for m are dependent on the process itself, and are expected to vary from one process to another. t_d, the estimated time for the most dominant step for fabricating a complex shaped part, is derived as a generic equation:

$$t_d = N_L \tau + \frac{V'}{whv_0} + \frac{V''}{whv_c} \qquad \text{......7.3}$$

where:

t_d is the time for the most dominating step

N_L is the total number of composite strips in the entire part, $= n*N$,

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where n is the number of strips in a layer—ply;
and N is the number of individual layers—plies.

τ is the dynamic system time constant.
To include compound curvatures, τ can be expressed as a function of the time constant for a linear surface τ_0, plus an average of j enclosed angles, $\overline{\theta_j}$, and the time per radian for the angles b_j, over the number of types of enclosed angles N_e, such that:

$$\tau = \tau_0 + \sum_{j=1}^{N_e} b_j \overline{\theta_j} \qquad \text{......7.4}$$

V is the part volume.
It is broken down into volume that is flat or simply curved, V' and volume that represents compound curvatures, V", such that:
V = V'+V"

w is the width of the tape of composite material

h the thickness of each layer, which is the thickness of a tape

v_0 is the steady-state velocity in the flat or simply curved region

and

v_c is the reduced steady-state velocity in the region of compound curvature

7.1.1 An Application

In order to demonstrate the applicability of these derived equations, Neoh has shown two scenarios. The total part fabrication time is developed for two different fabrication methods, hand lay-up and Automatic Tow Placement (ATP). The most dominating step for these two methods is hand lay-up time and machine run time, respectively. Therefore, based on the equations above, a t_d value is developed for these two individual steps. For demonstration purposes, the specific parts selected do not have compound curvatures. Hence, the complexity associated with equations 7.3 and 7.4 is moderately diminished.

For both these cases, an equation for "m" is derived based on the time taken for the second most dominating step and an average of the several remaining steps. The second most dominating step for hand lay-up is de-bulking. For ATP, it is tool cleaning. The two m values as derived by Neoh are:

$$m = 1 + \frac{wv_0}{n_{de-bulk} v_{de-bulk}} + \frac{wv_0 n_a}{\overline{v_a} N} \quad \text{for hand lay-up} \qquad \text{......7.5}$$

and

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$$m = 1 + \frac{n_{clean} A_{clean}}{v_{clean}(ATP\ Run\ Time)} \qquad \text{for ATP} \qquad ......7.6$$

where:

$v_{de\text{-}bulk}$ = the bagging rate for de-bulking
$n_{de\text{-}bulk}$ = the number of plies per de-bulking
$\overline{v_a}$ = the average rate for the other "area" dependent steps
n_a = the number of other "area" dependent steps
N = the number of plies thick the part will be
n_{clean} = the number of cleaning steps
A_{clean} = the area of the tool to be cleaned
v_{clean} = the cleaning rate for cleaning the tool.

To get specific values for each of the above entities in equations 7.1 through 7.6, Neoh depends on several different sources. For the hand lay-up part, the number of strips, N_L is given as 28, and the average length of each strip $\overline{L}$ is known to be 10 inches. The steady-state velocity—v_0—for hand lay up of composite strips is gleaned from a graph of lay-up rate versus tape width. That graph was created from "in-house experimental data." Another graph, showing the linear cumulative bend angle as a function of lay-up time was also developed by Neoh, based on laying up stringer shapes 18 inches long by 5 inches high by 6 inches wide. Based on the slope of this second graph, its ordinate intercept and values for N_L, and $\overline{L}$, the time per radian, b_j and thus ι_0 are determined. By substituting them into equation 7.3 a value for t_d is determined.

To determine the value for m for hand lay-up—equation 7.5—its input parameters are determined mostly through drawing analogies to standard steps in building construction. MEANS [25] has published time standards for several different industrial activities—including building construction—and their data is available in the public domain. Thus $v_{de\text{-}bulk}$ is determined by assuming that de-bulking is similar to laying down carpet. De-bulking is an operation required in the hand lay-up of composites, to remove entrapped air and to ensure that the individual strips have conformed to the part curvature [44]. In that sense, it is very similar to laying down carpet. So, if the rate for laying down carpet is X in^2/hr, than $v_{de\text{-}bulk}$ is assumed to also be X in^2/hr. The actual value for X is

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determined from the MEANS to be 5500 in^2/hr. De-bulking is done periodically, and therefore a "de-bulking rule" is chosen, i.e. how often will the de-bulking process be carried out. Neoh chooses $n_{de\text{-}bulk}$ = 4, that is de-bulk after laying down every 4th ply.

n_a, the total number of remaining steps, is available from the process plan. Values for v_a for each of the n_a steps are determined by drawing analogies for each of the process steps and steps in building construction. These 23 individual v_a values are averaged to get the final $\overline{v_a}$. By substituting respective values into equation 7.5, the multiplier m is determined. Values for t_d and m are then substituted into equation 7.1 to get an estimate of the time taken to hand lay-up a part using composite materials.

Fabrication time for ATP is similarly determined, by substituting the appropriate values for t_d and m respectively. However, in his thesis, Neoh is decidedly less clear on where input values for the ATP are derived from. *"Industry proprietary machine specifications"* are drawn upon to estimate the machine run-time—the most dominating step. To determine values for m, v_{clean} is determined by assuming that cleaning a tool is similar to cleaning walls. It is assumed—by Neoh—that n_{clean} and A_{clean} are known to the reader. Once again, by substituting respective values into equation 7.1, the time taken to fabricate a part using ATP can be closely determined.

7.1.2 Concluding Discussion As a part of the validation, Neoh and Gutawski [30] have made several comparisons between estimated part fabrication times from the Scaling Laws and those developed by other methods—such as the ACCEM model, actual fabrication, and company propriety data—and shown that the estimations strongly agree with actual times. There are several other publications by Neoh and Gutowski that discuss the merits of the Scaling Laws model [10, 21, 30]. That is, there is no denying that Scaling Law method of determining part fabrication time for composite materials is accurate.

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The problem is, the information needed to determine the part fabrication time using Scaling Laws is not exactly trivial. One needs to know a reasonable amount of specific information about the part being designed—such as:

- the part volume,
- the accurate nature of its design, to get an idea of the type and number of curvatures,
- the width of each composite strip,
- the thickness of the strip,
- the number of strips in each ply,
- the number of plies,
- v_0, the rate at which the strip can be laid down,
- lay-up time as a function of the cumulative bend angle

Given such specific information about a part, one can estimate the time taken to fabricate it. The question is: Can—and if so, How can—this method be used to determine the difference in fabricating the part using two different composite materials? And what if the user does not have much of an idea of the challenger composite material? Neoh uses values for lay-up rate based on experimental data. What if experimental data were unavailable? Is one to assume that the values available for an existing composite are applicable for a new, recently developed composite also? Such questions are not addressed in the Scaling Laws model.

Secondly, the accuracy of the Scaling Laws when determining complexity of newly developed materials would be considerably low, because the Scaling Laws have a very specific application. Neoh's work is targeted towards estimating the fabrication time of a composite part . In order to estimate the fabrication time, the Scaling Laws require specific process steps, in as much detail as possible—just as the X-NFR method does. However, other attributes of the X-NFR method are totally absent from the Scaling Laws approach. The Scaling Laws do not take into account the cost of the material. It is possible that a challenger material is as easily processable as the defender material—ι

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and v_0 values could be identical for the same part being fabricated by either material. However, the challenger could be considerably more—or less—expensive than the defender, and Scaling Laws would not account for this difference between the two materials.

Similarly, none of the several handling attributes—toxicity, outgassing, void presence, or chemical/solvent resistance, among others—that are absolutely critical to a part for potential aerospace applications, are even considered in the Scaling Laws. Just as with cost, a part could take the same processing time via either material, but one material could be prone to outgassing and void presence, and therefore of limited use in outer space. The Scaling Laws are not designed to identify this difference.

Furthermore, not only does the Scaling Laws approach not consider the database extent, it almost mandates that the database extent of the challenger be high. One would not be able to estimate ι and v_0 values for a composite material unless considerable experimental data were available on it. That is, Neoh's method would give considerably inaccurate results unless the user were familiar with the material being considered. This drawback alone disallows the Scaling Laws from being used accurately when evaluating newly developed composite materials.

Also, although the Scaling Laws do consider the various process steps, they do not account for the fact that some of the processing equipment can be extremely expensive, or that one material can be fabricated by more than one process. Thereby, the Scaling Laws simply cannot be used for general comparisons between two different composite materials. Finally, while the Scaling Laws do painstakingly account for the process complexity, tooling complexity and labor involved, the quality control factor is not given requisite importance. It is apparently assumed that the quality control effort involved in building construction steps is the same as that for composite fabrication steps.

In conclusion, one might say that the two methods—X-NFR method for determining the manufacturing complexity of advanced composite materials;

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and the Scaling Law method for estimating fabrication time of composite parts—are applications on two different paradigms. Based on the Scaling Laws alone, one cannot determine which composite material should be used to fabricate a part. Similarly, the X-NFR method is not very useful after the material is selected and the part is ready for production.

The X-NFR method is applicable at a "global" level, when comparatively little information is available on several different issues. Using this method, a high level decision can be made on which material to use to fabricate the part in question. At this time, presumably, the part design is not exactly finalized, and a greatly accurate list of process steps is unavailable.

Eventually, when the material has been decided upon, part design/drawings are available, and the manufacturing process plans are sufficiently in order, then adequate information is available to use the Scaling Laws and make a reasonably accurate estimate of the time required to fabricate the part in question. Thus, while one cannot replace the other, the X-NFR methodology can serve as a precursor to the Scaling Law models.

7.2. Manufacturing Complexity Generator of PRICE H[2]

The PRICE System™ is an extremely powerful and very popular suite of software, known as the family of Computer Aided Parametric Engineering (CAPE) products. The PRICE software are used for cost estimation at all phases of the hardware and software life cycle—system concept, system design and development, engineering and manufacturing, production, and operation support and maintenance. PRICE system was originally developed by RCA in the early 1960's for their in-house estimation purposes. It was established as a commercial software product in 1975, which merged with the General Electric Company in 1987 and later with the Martin Marietta Corporation in 1993. Today, it is a an entity of the Lockheed Martin conglomerate. The PRICE family

[2]The PRICE System related material in this chapter is drawn from three reference sources:
a) The PRICE System home page on the internet: www.pricesystems.com
b) PRICE System documentation published by the GE Corporation, © 1990
c) Telephone conversations with PRICE System technical consultants—at (800) 43-PRICE

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of CAPE products includes four member tools: PRICE H™ (Hardware), PRICE HL™ (Hardware Life Cycle), PRICE M™ (Electronic and Microcircuit Module) and PRICE S™ (Software).

A manufacturing complexity generator is available within PRICE H. The generator, which includes a table of heuristic manufacturing complexity values, serves as input to the PRICE H module. The X-NFR method, as intended in this thesis, is meant to develop the manufacturing complexity of defender and challenger materials. A corresponding figure developed via the PRICE H manufacturing complexity generator could also be used to validate—or invalidate—the results of the X-NFR. The rest of this section discusses general features of the PRICE System, the PRICE H module and the PRICE H manufacturing complexity—MCPLXS—feature. In section 7.2.1, heuristic values for the manufacturing complexity for two structures discussed in Chapter 5—the s/s adapter and the LOX tank—are drawn from a table of MCPLXS values, and compared to the X-NFR derived values. In section 7.2.2, equations in the MCPLXS generator are exploited for the same two structures. Manufacturing complexity values are developed for the s/s adapter and the LOX tank, and compared to the X-NFR results. Limitations that became evident during the development process are discussed concurrently in the two sections. Final conclusions are in section 7.2.3.

The PRICE modules are used extensively in the aerospace industry for financial analysis, cost analysis, cost estimation and risk estimation purposes. The PRICE System users enter input parameters based on available data, or draw upon industry average parameter values from tables embedded within the system. Such input data are used to develop appropriate cost estimating relationships (CER's). These CER's are parametric, such that a CER's value will change depending on not only its own inputs, but inputs from to other CER's as well.

The PRICE system is a traditional costing approach, and the accuracy of its results is based on the accuracy of the input data. Needless to say, given

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the uncertainty of composites, inaccurate input data leads to inaccurate cost models [8]. As a means of working with ambiguous input figures, the PRICE system products incorporate a rigorous risk analysis feature. Uncertain input data can be specified with one of four statistical distributions—normal, triangular, beta or uniform. In addition, two types of simulations—Monte Carlo and Latin Hypercube—are available. Thus, PRICE System users can quantify cost data by replacing point estimates with confidence measures.

The PRICE H (Hardware) model is used for deriving cost appraisals and schedules for electronic, electromechanical, mechanical hardware and structural assemblies and systems. Extensive quantitative and qualitative data, and schedule parameters serves as input to the PRICE H model. These inputs help generate initial CER's which drive built-in mathematical models. The outputs of PRICE H are a result of the mathematical equations alone. Therefore, the parametric nature of the inter-relationships between the different CER's results in dynamic cost models. That is, CER's track changes in parameters, and monitor their manifestations locally and globally. As an example, say tolerance of a very critical part or assembly has to drastically change. This could alter the manufacturing process and tooling. These three factors could impact the manufacturing schedule and cost. In addition, test equipment, quality and production schedules may be effected. In turn, fabrication of other parts, system integration, and even production management may experience different schedule and cost scenario's. Incorporation of such dynamic effects into a system wide perspective is the hallmark of the PRICE system's parametric approach to cost estimation.

Within PRICE H, a measure of an item's technology, producibility, yield, platform and labor is developed as the Manufacturing Complexity (MCPLXS) of a Structure. MCPLXS values are a major cost driver of the PRICE H module. The MCPLXS Generator™ is a program specifically designed to calculate manufacturing complexity—MCPLXS—values for parts fabricated using both conventional materials as well as composites. In addition to the Generator,

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PRICE H has embedded tables containing empirically derived MCPLXS values for typical mechanical assemblies and fabricated components.

Both the table values and those developed by the MCPLXS generator depend on the platform of the structure—a measure incorporating the structure's operating environment and associated reliability requirements. The platform of the part or structure has a significant impact on its MCPLXS values. Typical platforms are:

- Ground
- Mobile
- Airborne - Commercial
- Airborne - MIL spec
- Space - Unmanned

and

- Space - Manned.

Obviously, as the platform will change from Ground to Airborne to Manned Space, the MCPLXS value will correspondingly increase. PRICE H literature on input variables has typical, empirically derived platform values (PLTFM) for the above six operating environments.

7.2.1 THE MCPLXS TABLE™ Two tables containing heuristically derived MCPLXS values are available, one for typical mechanical assemblies, and the other for fabricated components. The values in the tables are segregated according to platform. For the Fabricated Components MCPLXS table, the appropriate MCPLXS value is chosen based on three parameters:

- process of fabrication
- type of material used in the fabrication

and

- the platform.

Both the LOX tank and the s/s adapter have the same process category—sheet metal fabrication, bending, riveting and welding. For both structures, aluminum is the fabricated material and platform is Unmanned

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Space. So, the appropriate MCPLXS value is 6.09. The same value is applicable for both the s/s adapter as well as the LOX tank. That is, according to the PRICE H methodology, the manufacturing complexity of both structures could be the same. Since we know that the two structures are considerably different from each other, should their manufacturing complexities also not be different? Thus, the MCPLXS table does not seem to be an appropriate tool for measuring the manufacturing complexities of the two structures.

Secondly, the physical significance of 6.09 is unavailable. PRICE H documentation does not elaborate on its MCPLXS value, other than to say that it is a technology index. Presumably, a higher MCPLXS value implies that the part is more complex to manufacture, and vise versa. However, without a basis for comparison, an isolated MCPLXS value of 6.09 does not mean much.

Telephone conversations with technical representatives at PRICE Systems were helpful in further understanding the MCPLXS values—both, the one given in the table, and that developed by the MCPLXS generator. The above two presumptions, that a value of 6.09 by itself does not mean much, and that a higher a MCPLXS value, the higher a structure's complexity, are both essentially true.

The MCPLXS value is developed only for use in the PRICE H analysis, and is to be used in conjunction with other inputs in the development of several Cost Estimating Relationships—CER's. By itself, that value can be directly compared with another MCPLXS value, provided that the two values were generated by the same user, for the same, or comparable structures. In other words, every value is supposed to be individually derived, and unless the user knows what she/he is doing, the value is not of much use. Also, the higher the MCPLXS value, the higher the manufacturing complexity.

This is similar to the X-NFR derived MCF value for a defender or a challenger. By itself, MCF does not mean much. Therefore, one would have to generate a MCPLXS value for a similar structure fabricated with aluminum-

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lithium to make sense of MCPLXS numbers. Except, that aluminum-lithium is not among the list of material types in the published MCPLXS table!

7.2.2 THE MCPLXS GENERATOR™ The MCPLXS generator is more adaptable than the MCPLXS table. It generates *"manufacturing complexities from physical and qualitative properties of mechanical and structural items"* [8]. In order to generate manufacturing complexity values via the MCPLXS generator, five main input parameters are required. These parameters, and the respective input values for the MCPLXS equations for the s/s adapter and the LOX tank, are given below.

- Precision of Fabrication (PRECI): This parameter is an indicator of the tolerances for the part being fabricated or assembled. Since close tolerance implies more human involvement, and vise versa, this value is representative of the labor involved in the manufacture or assembly of the part. Therefore, the final MCPLXS result is highly sensitive to the PRECI value, and hence it must be estimated as accurately as possible.

  For both the s/s adapter and the LOX tank, precision or tolerance values are unavailable in the two published papers, Kerr, et al., 1991 and Taketani and Bowman, 1991, respectively. Therefore, a value of 0.01 (1/100 of an inch) was assumed for both structures.

- Machinability of the Material (MI): This value is an indicator of the difficulty of machining the material used in fabricating the part. The PRICE system has adopted a scale established by the Batelle Memorial Institute. The scale assigns values—relative to the machinability of AISI B1110 steel—to the machinability of different materials. B1110 steel has a MI value of 100. Materials easier to machine than the reference steel have MI values greater than 100, and vise versa. Composite laminates were not included in the Batelle scale, and have been incorporated by PRICE System. A MI value of 18 is assigned to composite laminates. A scale of the machinability of several materials, is available in the MCPLXS generator manual.

  The machinability of 2024 aluminum alloy is 150. Aluminum-lithium

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alloys are not included in the table.

It is important to note that the Machinability Index judges the machining of the material only. Other production characterisicts, such as weldability or brake forming are not included in the machinability index nor are they accounted for in any other input factor of the MCPLXS Generator.

- Difficulty of Assembly (MATUR): This parameter takes into account close assembly tolerances, highly labor intensive assemblies, or otherwise expensive assembly operations. Tables in the MCPLXS generator manual give recommended MATUR values for different assembly and fabrication processes, forging, and castings, including investment castings. At one extreme, a MATUR value is 6 for simple self-gauging assembly, simple joining and no assembly tolerances type of parts. At the other extreme, a 1 is given to highest precision, tolerance less than 0.001, kind of assembly.

  Due to lack of more specific information on the two structures, a MATUR value of 2 was assumed, for *"assembly tolerances about 2X tougher than build tolerances of parts."*

- Number of Parts (NP): The actual number—or a reasonable estimate—of the number of parts in an assembly is the fourth input for the MCPLXS generator. Fasteners are not included in the NP count. A single part would imply NP = 1. A composite skin, regardless of the number of layers, would be a single part.

  In the case of the s/s adapter, no indication of the number of individual parts is available in the paper. From a photograph in the paper, it is estimated that 24 sheets seem to have been welded together to form the sheet and stringer payload adapter. From the Taketani and Bowman paper, it is clear that 4 plates were brake formed and welded together to form one tank.

- Specification Profile (PLTFM): As explained earlier, this value is the platform, a measure of the operating environment of the part or assembly. The PRICE system has a set of empirically derived PLTFM values for

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different operating environments. PLTFM values range from a low of 1.0 for a ground environment, to a high of 2.5 for a manned space environment.

Both the s/s adapter and LOX tank were to be used on unmanned space missions, so the appropriate PLTFM value from the table is a 2.

Given values for the above five input parameters, the MCPLXS generator uses the following equations to generate a MCPLXS value (8):

$$MCPLXS = \left(\frac{A}{B}\right) * \left[1 + \left\{(N - MATUR) * 0.60\right\}\right] \qquad ....7.7$$

Where:

$$A = 4.3 * \left(PLTFM^{0.32}\right) * \left(NP^{0.04}\right) \qquad ....7.8$$

$$B = 1.35 * \left(PRECI^{0.081}\right) * \left(MI^{0.024}\right) \qquad ....7.9$$

and $N = 3 \; if \; PLTFM \langle 2; \quad or \; 4 \; if \; PLTFM \rangle 2$ 7.10

Since PLTFM is 2 for both the s/s adapter and the LOX tank, the appropriate N value should be between 3 and 4, i.e. 3.5 is assumed in the calculations.

In addition to the above calculations, the MCPLXS generator incorporates certain extra specification requirements that might be imposed on the part or assembly. These extra specifications are:

- extra surface finish,
- weight adjustment for laminate composites,
- a percentage of extra material machined away—yield loss,
- close tolerances to be maintained over a large distance—length, or flatness, or out-of roundness being more than one inch of the length

and

- a calibration factor, if appropriate.

Maintaining tolerances over an inch of length of machining is necessary for both the s/s adapter and the LOX tank. MCPLXS calculates a Distance Factor from the following formula:

$$DISTANCE\ FACTOR = 0.10 * L^{0.6} \qquad ....7.11$$

where L is the length in inches. For the s/s adapter, no information on the length of the structure is available. Again, judging from the picture in the

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published paper, an estimated length of 20 feet is assumed. For the LOX tank, the length of the tank, 3.05 meters, is clearly available in the paper. Hence, it is used in the MCPLXS calculations.

In addition, the panels of the LOX tank were each machined into stiff isogrid configurations. The isogrid configuration is created by machining integrally stiffened triangles into a solid plate. Therefore, excess machining should be accounted for in the LOX value for MCPLXS. In the MCPLXS generator, this is done by adding 0.1 to the MCPLXS for each 10% yield loss above normal. Although specific yield loss numbers are unavailable, judging from a diagram in the Taketani and Bowman paper, a 50% yield loss is estimated, and a yield loss factor of 0.5 is added to the LOX value.

Table 7.1 below calculates the manufacturing complexity of the s/s adapter and the LOX tank via the MCPLXS generator. Values for the different input parameters are as available in the PRICE H literature, in the MCPLXS Generator literature, in the two published papers, or assumed, as discussed above. The relevant calculations are those developed in equations 7.7 through 7.11 above.

Table 7-1 — MCPLXS generated values for the s/s adapter and the LOX tank

Factor	S/S ADAPTER	LOX TANK
PRECI	0.01 (unknown, so assume)	0.01 (unknown, so assume)
MI	150 (for Aluminum)	150 (for Aluminum)
MATUR	2 (from Maturity Table)	2 (from Maturity Table)
NP	24 (unknown, so assume)	4 (4 plates welded into 1 tank)
PLTFM	2.0 (from PLTFM values table)	2.0 (from PLTFM values table)
Length	240" (assume, 20 ft.)	120.78 " (3.05 m long, given)
Distance Factor (DF) = $0.01 * (L)^{0.6}$	$= 0.01 * (240)^{0.6}$ = 0.2680	$= 0.01 * (120.78)^{0.6}$ = 0.1775
Yield Loss (factor for extra machining)	= 0.00 (assume)	= 0.50 (assume)
$A = 4.3\ (PLTFM)^{0.32} * (NP)^{0.04}$	$= 4.3\ (2)^{0.32} * (24)^{0.04}$ = 6.0955	$= 4.3\ (2)^{0.32} * (4)^{0.04}$ =5.6739

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Table 7-1 continued		
Factor	S/S ADAPTER	LOX TANK
$B = 1.35\,(PRECI)^{0.081} * (MI)^{0.024}$	$= 1.35\,(0.01)^{0.081} * (150)^{0.024}$ = 1.0485	$= 1.35\,(0.01)^{0.081} * (150)^{0.024}$ = 1.0485
N = 3, if PLTFM < 2, and = 4 if PLTFM >2 (What if PLTFM = 2 is not clear!) Since PLTFM = 2, assume N = 3.5 for both structures		
MCPLXS = (A/B) * [1 + { (N - MATUR) * 0.6}] + DF + Yield Loss	= (6.10/1.05)*[1+{(3.5-2)*0.6}]+ 0.155 + 0.00 = 11.31	= (5.67/1.05)*[1+{(3.5-2)*0.6}]+ 0.178 + 0.50 = 10.96

As can be seen, MCPLXS values obtained from the MCPLXS generator are considerably higher than those got from the MCPLXS table. Also, two structures now have different MCPLXS values, as can be expected. So, inherently, the MCPLXS generator is a better measure of manufacturing complexity than the empirical values of the MCPLXS table. However, in order to get the MCPLXS values for the s/s adapter and the LOX tank from the published literature, one needs to assume the following values:

- The machining precision of both structures has to be assumed.
- The maturity of both structures has to be assumed.
- Since it is not immediately clear what value the constant N should take when PRECI is exactly equal to 2, N also has to be assumed in the MCPLXS equation.
- The number of parts and machining length of the s/s adapter have to be assumed
- The yield loss for machining the LOX tank has to be assumed.

As discussed earlier, the MCPLXS generator within PRICE H would have links to the risk analysis modules, and therefore, the above assumptions would be subjected to statistical variations and simulations. However, assuming that all the above assumptions are correct, and no further risk analysis is attempted, the "stand-alone" complexity of machining aluminum to fabricate a s/s adapter is 11.31 units, while that of a LOX tank is 10.96 units.

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A quick analysis of the MCPLXS Generator's input values shows that only three factors—the number of parts, the length and yield loss—are different for the two structures. A brief sensitivity analysis of the MCPLXS equations was conducted, by individually varying input values for the above three factors. In isolation, each factor for the LOX tank was reduced by 10%, and the results noted. Changes in the overall result were as shown in the Table 7-2.

As can be seen from Table 7-2, of the three factors, the Yield Loss and the number of parts in a structure have some impact on the MCPLXS value. Yield loss can be expected to have a high impact since it is directly added to the calculated value if it is grater than 0.1. Of the other input values that are common to both the s/s adapter and the LOX tank, both precision and maturity have a substantial impact on the generated MCPLXS values. Assuming that the precision required were 0.001 instead of 0.01—a plausible estimate, considering that these are spacecraft structures—and, therefore, if the maturity value correspondingly dropped to 1, the new MCPLXS value for the s/s adapter is 17.78, or a jump of about 57%. If the precision or the maturity values change in isolation, the MCPLXS value increases by about 20% and 30% respectively.

Table 7-2 — Changing MCPLXS input factors for s/s adapter value

Factor Changed	Original Value	New Value	New MCPLXS	%change in MCPLXS between old and new s/s adapter values (old value:11.31)
# of parts	24	21.9	11.27	99.59%
Length of structure	240	216	11.29	99.85%
Yield Loss	0.0	0.1	11.41	100.88%

The two other parameters that were not guessed, are the Platform and the Machining Index (MI) values. As was mentioned earlier, the MCPLXS result is very sensitive to Platform values. If the platform changes to a manned space environment—PLTFM value of 2.5, N value of 4—the MCPLXS value for the s/s adapter jumps up by 24%. Conversely, an airborne, MIL spec. environment—PLTFM = 1.8, N = 3—drops the MCPLXS value by 20%. Still, since both the s/s adapter and the LOX tank are established as unmanned space environment

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structures, their PLTFM value of 2.0 is stable, and should not change. So, PLTFM should not be a contender in any sensitivity analyses.

However, the MI value is not only necessary, but a very important part of the sensitivity analysis. MCPLXS equations are tolerant of changing MI values, and so different MI values do not affect the MCPLXS results substantially. A 10% decrease in the MI value —i.e. the new material is harder to machine— increases the MCPLXS value of the s/s adapter by only 0.25%. The MI value has to drop by up to 65% before the MCPLXS value by increases by 1%. Although specific MI values for aluminum-lithium alloys are currently unavailable, these would be the only change to MCPLXS inputs when shifting from a conventional aluminum structure to an aluminum-lithium structure. According to the Kerr, et al. and the Taketani and Bowman papers, aluminum-lithium performed as well as conventional aluminum with relation to machining. Thus, although a specific MI value is unavailable at this time, it is safe to assume that this value should be close to that of conventional aluminum. Therefore, according to the MCPLXS generator equations, the difference between the two structures—all other parameters being equal—**should be less than 1%**.

Although a systematic, parametric sensitivity analysis study could be conducted and interactions between the different input variables studied, that effort would be digressing from the goals of this dissertation. Suffice it to say, that changing Precision, Maturity and Platform values have major impacts on MCPLXS results. Changes in the Yield Loss and Number of Parts have some effect, while the Machining Index and the Distance Factor have little to no effect on the MCPLXS results.

Therefore, if one were to use the MCPLXS generator to calculate how much more complex would it be to fabricate a part with an aluminum-lithium alloy than with a conventional aluminum alloy, it is safe to say that the results would be—at best—imprecise. Given the available information, two major contributors to the result would have to be guessed, since neither of the papers

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give a specific value. Secondly, neither of the papers say that precision required in fabricating aluminum-lithium is more than that required for conventional aluminum. For the s/s adapter, the same rough as well as precision machining methods were used on both metals. For the LOX tank, the NC tapes that were originally prepared for the aluminum panels were used on the aluminum-lithium panels, and the machining results were acceptable. Hence, PRECI and MATUR values for both structures should be the same for both defender and challenger materials.

Consequently, the only factor that establishes the change in complexity—the Machining Index—would not influence the result by more than 1%. However, the Kaminski, et al. paper establishes that there is an increase in complexity when shifting from a conventional aluminum alloy to a lighter aluminum-lithium alloy. So, the result generated by the MCPLXS generator—given the information easily available in published literature—is incorrect. On the other hand, the same information when applied to the X-NFR method, results in values much more realistic than those generated by MCPLXS.

According to the technical personnel at PRICE Systems, assuming that the only difference between the two structures—an old one using conventional aluminum, and the new one, using aluminum-lithium—was the material, a 1% change in MCPLXS value implies a 1% increase in complexity. However, a systematic PRICE H analysis would include several divergent parameters, such as the number and expertise of the people working on the projects, the delivery schedules, the cost and availability of the material, the number of pieces manufactured, experience with the old and new materials, and so on. The MCPLXS value would be considered along with several other parameters in generating the actual increase in cost between the two structures. Therefore, unless one has gone through the entire gamut of PRICE H analysis, one cannot accurately estimate the delta-increase in manufacturability or cost. Ergo, one cannot say that a delta-increase in the MCPLXS value is a delta-increase in

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complexity. So, comparing MCPLXS values to the X-NFR values is unfair to the MCPLXS Generator.

7.2.3 CONCLUDING DISCUSSION In conclusion, it is obvious that the MCPLXS Generator within PRICE H is a neat and handy tool to generate manufacturing complexity values. However, it is equally obvious that the equations used to generate MCPLXS values are meant for a very narrow application—the machining of a part. They do not consider other manufacturing operations, including welding, brake forming, heat treatment, chemical milling, and riveting/fastening that the s/s adapter and the LOX tank were subjected to. Furthermore, the MCPLXS generator and its values have to be considered in totality with the entire PRICE H system. So, in and of itself, the MCPLXS Generator is an inaccurate measure of the difference in manufacturing complexity when comparing defender and challenger materials for a part or structure.

Needless to say, the PRICE H module would be an excellent tool for such a global comparison. However, given the sophistication available in PRICE H, its use would be an overkill, if one desired to use PRICE H only for the type of comparison that the X-NFR is intended to provide. The cost associated with leasing PRICE H is considerable. The PRICE system products are not available for outright purchase, but can be leased for an annual fee. Although specific costs vary, a typical single user PRICE H platform may cost about $25,000 per year, while multi-user platforms are about $35,000 per year. The entire PRICE System's suite of software are available at rates of over $60,000 per year.

Therefore, the X-NFR method for generating manufacturing complexity is a useful analysis tool that—at a cost of a personal computer and a spread-sheet based software—can produce satisfactory results.

7.3 Conclusion

This chapter contrasts the X-NFR methodology with two popular approaches, the Scaling Laws model and the MCPLXS Generator of PRICE H.

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It is shown that both approaches are highly applicable within their individual domains. The Scaling Laws can accurately estimate the time to fabricate a composite part, given certain essential information on the part and the material being considered. However, based on the Scaling Laws model alone, one cannot make a determination on whether or not material A is more appropriate than material B for that part in question. The X-NFR is the more suitable tool for such a decision.

In contrast, the MCPLXS Generator can distinguish—based on machining characteristics—relative complexity of material A over material B. However, since it is restricted to the machining of the material for a part, a decision based on the MCPLXS Generator results would be narrow and of limited general value. The use of the MCPLXS Generator is intended to be within the gamut of the PRICE H system. On the other hand, the X-NFR is not limited to any one characteristic of the material, and hence offers more versatility than the MCPLXS Generator.

Therefore, as a "unified methodology" for selecting the most appropriate material from a given set of materials, the X-NFR is more applicable than either the Scaling Laws model or the MCPLXS Generator of PRICE H, specifically early on, in the preliminary design phases.

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CHAPTER VIII

CONCLUSIONS

In this thesis, a unified methodology—called the X-NFR—has been developed. This methodology should enable a potential user to choose from between two or more materials, the most appropriate material for his/her particular application. The methodology was tested by making six different selections between two materials. For two of the six selections, the appropriate choice was justified by drawing a comparison between this and another independent conclusion. The six comparisons included:

- testing the methodology on disparate materials—composite and conventional;
- by making general comparisons—when no particular parts or structure was in mind;

and

- by making a decision on two airplane parts and two aerospace structures.

Based on the above, the research hypothesis was accepted. Further developmental work on the methodology should include:

1. Making more comparisons between the results of the X-NFR and other material comparisons, so that the quantified difference between two materials that is available from the X-NFR can be corroborated elsewhere. Presently, out of six cases, only two were corroborated to a certain degree of conviction, and only one of them unmistakably so. Publishing results of the six comparisons is necessary, so that other actual material users can respond by agreeing or disagreeing with the results.

   Likewise, the methodology can be used to come to an actual decision, rather than hypothetical comparisons. This can possibly be accomplished by expanding the comparison to areas other than aerospace, such as the sports or automotive industries. As was discussed in Chapter 3, application

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of the X-NFR methodology is not limited to aerospace parts or structures. This is a definite avenue for further development of the X-NFR methodology.

2. Within the nuances of the X-NFR methodology, there are a few points that could be fine tuned. First, the Monte Carlo simulation. The MS Excel™ based set-up can be merged with the @RISK simulation package. Thereby, subtleties of the simulation can be exploited. These include the number of iterations before terminating the simulation, the nature of the random number generator, and the probability density functions of choice.
3. Nuances of the AHP should be studied. It is known that changing AHP weights will produce different X-NFR results. However, this general statement has not been quantified, and experimental runs would be helpful.
4. It is known that the use of AHP will result in consistent and meaningful weight distributions. However, if the potential users are more than one or two individuals, reaching a consensus among them may be problematic. Considering that accurate AHP weights are paramount to generating meaningful results, this might be a potential shortcoming of the X-NFR methodology. Therefore, future work must include studying alternatives to the AHP for assigning weights, such as using the multiattribute Utility Models (MAUM) or expert systems that draw upon in-house data and surveys to come up with quantified weights for different alternatives.
5. The X-NFR methodology has concentrated upon the differences between two materials to quantify how much more complex the processing or manufacturing of a material would be. This methodology does not presently include the benefits of the new material. A similar set-up could be developed to quantify the benefits of going from one material to the next. Hence, a more complete scenario could be developed, wherein one might say that material B is 27% more complex to fabricate than material A, but the quantified benefits of using material B over material A are 37%.

Although the benefits development is in its infancy, an attempt has been made to develop a "Delta Benefits Factor" to complement the "Delta

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Complexity Factor". Unlike the multi-factor multi-attribute hierarchy of the manufacturing complexity factors, the Benefits hierarchy presently has only two major attributes, namely PHYSICAL AND TANGIBLE BENEFITS and INTANGIBLE BENEFITS. For PHYSICAL/TANGIBLE BENEFITS sub-attributes include:

- DENSITY
- COMPRESSIVE STRENGTH
- GLASS TRANSITION TEMPERATURE
- CORROSION RESISTANCE
- TENSILE STRENGTH
- TENSILE MODULUS
- YIELD STRENGTH
- FATIGUE

and • COEFFICIENT OF THERMAL EXPANSION.

Similarly, INTANGIBLE BENEFITS sub-attributes be:

- RELIABILITY
- LIFE CYCLE

Three generic Benefit comparisons (i.e. not for any particular part or structure) have been developed. The actual set-up for these three comparisons is in Appendix E, and the results are shown in Table 8-1 on the following page. Some of the above benefits are "higher-the-better" characteristics, and some are "lower-the-better" characteristics, and therefore, appropriate equations have been used to calculate the relative benefits. Also, expert judgment has been substituted for the AHP in assigning weights for the attributes and sub-attributes.

Although this work is in its infancy, it can be seen from Table 8-1 that the benefits of PEEK are about 0.158 (1 - 0.842) units more than C-Epoxy. Or, in this comparison, PEEK is 15.8% better than C-Epoxy. Similarly, the aluminum-lithium alloy is about 8.7% better than the conventional aluminum alloy. Comparing composites to metals, C-Epoxy comes out to be about 48% better than Aluminum-Lithium.

Table 8-1 — Some Generic Benefit Comparisons

	Defender	Challenger	Δ Loss in Benefits
C-Epoxy v/s PEEk	0.882	0.743	0.842
Al 2040 v/s Al-Li 2090	0.523	0.477	0.913
C-Epoxy v/s Al-Li 2090	0.5005	0.743	1.484

This compares with the C-Epoxy v/s Aluminum-Lithium comparison for manufacturing complexity of the spoiler end-rib (Table 5-6, section 5.5). The

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end-rib is about 37% more complex to fabricate using C-Epoxy than using Aluminum-Lithium. One of the reasons Boeing may have decided to fabricate the end-rib using the more complex C-Epoxy is because of its benefits over aluminum-lithium, which are quantified as 48% in Table 8-1 above.

Future developmental work must include involvement of a "Delta Benefits Factor" or DBF along with a DCF when comparing two materials. Therefore, the "extended" hierarchy of X-NFR could be further extended by including benefits and dis-benefits—and the calculations, as appropriate—to come up with an overall DBF/DCF value.

6. In Chapter 2, an approach by Karbhari & Jones [18, 19] was discussed (Section 2.6) to identify and control cost of manufacturing composite materials. Karbhari & Jones proposed using Activity Based Costing, and the use of "cost pools" to assign the cost of different activities that contribute to the final cost of a composite part. They suggested that cost pools be used to identify activities that both contribute to the success of the part, and activities that could be targeted for elimination of waste and redundancy. A-bC in isolation does not address the lack of uncertainty associated with composites. However, the Karbhari/Jones approach is analogous to the 80/20 rule proposed by Gutowski [10, 30]. Possibly, cost pools could be exploited to include or highlight the few important process steps mentioned by Gutowski. Thereby, some link may be found between the Scaling Law models and the A-bC method of allocating cost to composite parts. This opens an avenue of research that combines two independent and contemporary areas which could be jointly developed for enhancing the utility of composite materials in industry.

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REFERENCES[1]

1. _____ "Model assesses cost effects of automating composites fabrication" *American Machinist & Automated Manufacturing*, Vol. 131, No. 2, pp. 27-29, 1987.
2. Bao, H. P. "Risk and Reliability of Manufacturing Processes as Related to Advanced Composite Materials for Spacecraft Structures" *ODU-HPB Technical Report, NASA/ASEE Summer Faculty Fellowship Program*, (August , 1995).
3. Canada, J.R., and Sullivan, W.G. *Economic and Multiattribute Evaluation of Advanced Manufacturing Systems* Prentice-Hall, Inc. 1989.
4. Datta, V., Sambasivarao, K.V., Kodali, R., and Deshmukh., S.G. "Multi-attribute Decision Model using the Analytic Hierarchy Process for the Justification of Manufacturing Systems", *Int. J. Production Economics*, Vol. 28, No. 2, pp. 227-234, 1992.
5. Devore, J. L. *Probability and Statistics for Engineers and Scientists*. Irwin. pp. 210-215, 1989.
6. Divecha, A.P. and Karmarkar, S.D. "The Search for Al-Li Alloys" *Advanced Materials and Processes,* Vol. 130, pp. 74-79, October, 1986.
7. Foley, M. F. "Techno-Economic Automated Composite Manufacturing Techniques", *SAMPE Quarterly*, Vol. 22, No. 2, pp. 61-68, 1991.
8. _____ "Price-H manual", *General Electric Company*, 1990.
9. Gutowski, T.G.; Henderson, R.; Shipp. , C. "Manufacturing Costs for Advanced Composites Aerospace Parts" *SAMPE Journal*, Vol. 27, No. 3, pp. 37-43, 1991.
10. Gutowski, T.G.; Neoh, E.T.; Dillon, G. "Design Scaling Laws for Advanced composites Fabrication Cost" *Proc. 5th. NASA/DoD Advanced Composites Technology Conference,* Seattle, UT., August 1994.
11. Hicks, J. P., "Composites" *Applied Optics*, Vol. 29, No.36, pp. 5310-5311, 20 December, 1990.
12. Hillier, F.S. and Liberman, G.J. *Introduction to Operations Research*, Holden-Day Inc., 4th. Ed. 1986.
13. Huang, P.Y. & Ghandforoush, P. "Procedures Given for Evaluating, Selecting Robots", *Industrial Engineering*, Vol. 6, No. 4, pp. 44-48, 1984.
14. Jones, M.S.; Malmborg, C.J.; Agee, M.H. "Decision Support System used for Robot Selection" *Industrial Engineering*, pp. 66-86, September, 1985.
15. Kalpakjian S, (1989) *Manufacturing Engineering & Technology* Addison-Wesley Publishing, 1989.

[1] *update:April 19, 1997*

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16. Kaminski, T. ; Willner, E.; Kerr, J. and Taketani, H. "Al-Li in Space App. lications" *Proc. of the 6th. Intl. Al-Li Confrence*, Verlang Publ., 1991.

17. Karbhari, V.M. "The Analytic Hierarchy Process: a viable decision tool for composite materials?" *Int. J. Technology Management*, Vol. 9, No. 1, pp. 77-93, 1994.

18. Karbhari, V.M. and Jones, S.K. "Cost information barriers and composite materials", *Int. J. of Materials and Product Technology*, Vol. 7, No. 3, pp. 215-231, 1992.

19. Karbhari, V.M. and Jones, S.K. (1992) "Activity-based costing and management in the composites product realization process", *Int. J. of Materials and Product Technology*, Vol. 7, No. 3, pp. 232-244, 1992.

20. Kerr, J.R.; Hall, I.K.; Mirda, S.E. and Yokota, M.J. "Application of 2090 Al-Li for a Payload Adapter on the Atlas Commercial Launch Vehicle" *Proc. of the 6th. Intl. Al-Li Confrence*, Verlang Publ., 1991.

21. Krolewski, S; Gutowski, T.G.; "Economic Comparison of Advanced Composite Fabrication Technologies" *Proc. 34th. International SAMPE Symposium*, pp. 329-340, May 1989.

22. Law, A.M.; Kelton, W.D. *Simulation Modeling & Analysis*, 2nd. Ed. McGraw-Hill., 1991.

23. Lee, E.W., Neu, C.E. and Kozol, J. "Al-Li Alloys and Ultrahigh-Strength Steels for U.S. Navy Aircraft" *JOM: The Journal of the Minerals, Metals and Materials Society*, Vol. 42, pp. 11-14, May, 1990.

24. Lee, E.W., Waldman, J.A., Witters, J.J., Rioja, R.J. and Divechia, A.P. "Development of 2090 & 8090 Al-Li Alloys for US Navy Aircraft" *Proc. of the 6th. Intl. Al-Li Confrence*, Verlang Publ., 1991.

25. Means Catalog, R. S. Means Company, Inc., 1995.

26. _____ "Shuttle may get extra boost from weldable Al-Li alloys" *Modern Metals*, Vol. 44, pp. 14-16, August, 1988.

27. _____ "Epoxy composite construction permits a more efficient helicopter blade" *Modern Plastics.*, pp. 33, September, 1988.

28. _____ *Microsoft Excel User's Guide*, Microsoft Corporation, 1993.

29. NASA Contractor Report, Silverman, E. M., Editor. *Composite Spacecraft Structures Design Guide* TRW Space & Electronics Group, Redondo Beach, California, 1995.

30. Neoh, E.T.; Gutowski, T.G.; Dillon, G. (1995) "Framework for estimating fabrication time of advanced composites manufacturing processes." *Proceedings of the 40th. International SAMPE Symposium & Exhibition*, Anaheim, CA. May 11, 1995.

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31. Neoh, Ein. Teck *Adaptive Framework for Estimating Fabrication Time*, Ph.D. Thiesis in Mechanical Engineering, the Massachusetts Institute of Technology, August, 1995.

32. Nnaji, B.O. "Evaluation Methodology for Performance and System Economics for Robotic Devices" *Computers in Industrial Engineering*, Vol. 14, No.1, pp. 27-39, 1988.

33. Norris, D.M. "A Study of JIT Implementation Techniques using the AHP Model", *Production & Inventory Management Journal*, Vol. 33, No. 3, pp. 49-53, 1992.

34. Pandya, S.Y. and Bao, H.P. "The 'X-NFR' Method for Determining Manufacturing Complexity of Newly Developed Materials" *Proceedings of the 1996 National Confrence of the American Society of Engineering Management*, October 10-13, Dallas, TX. pp. 107-115.

35. Pandya, S.Y. and Gulati, A. "Seven System Engineering Documents for an Unconventional System" *Proceedings of the 1996 National Confrence of the American Society of Engineering Management*, October 10-13, Dallas, TX. pp. 325-333.

36. Rioja, R.J. and Grahm, R.H. "Al-Li alloys find their niche" *Advanced Materials and Processes* Vol. 141, pp. 23-26, June, 1992.

37. _____ *Guide to Using @ Risk* Palisdale Corporation, 1996.

38. Saaty, T.L. "How to make a Decision: The AHP", *Interfaces*, Vol. 24, No. 6, pp. 19-43, 1994.

39. Saaty, T.L. *Decision Making for Leaders: The Analytical Hierarchy Process for Decisions in a Complex World*, Lifetime Learning, 1982.

40. Stoecklin, R.L. *Development of Manufacturing, and Test of Graphyte-Epoxy Composite Spoilers for Flight Service on 737 Transport Aircraft* Boeing Commercial Airplane Company, NASA Contractor Report: NASA CR 132682, October 1976.

41. Sutherland, G. "Properties of Al-Li alloy 2091-T3 sheet" *Advanced Materials and Processes*, Vol. 137, pp. 113-114, April, 1990.

42. Taketani, H. and Boman, J.J. "Al-Li Alloy 2090-T81 Space Vehicle Structure", *Proc. of the 6th. Intl. Al-Li Confrence*, Verlang Publ., 1991.

43. William T Morris, *Analysis of Management Decisions* Irwin, 1964.

44. Woodall, C.K.; Cha, Y.S.; Green, C.R.; Conrad, M.A.; Lenger, E.Y.; Engelbart, R.W. and Abel, D.L. *Low Cost Composite Weapons Program, Missile Airframe Guideline* McDonnell Douglas Missile Systems Company, P.O. Box 516, St. Louis, MO 63166-0516, 1991.

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APPENDICES

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Appendix A -- The AHP for weighting of attributes and sub-attributes

The following criteria is to be used for pairwise comparisons	
If x is .... as (than) y,	then preference number to assign is
equally important/preferred	1
weakly more important/preferred	3
strongly more important/preferred	5
very strongly important/preferred	7
absolutely more important/preferred	9
use even numbers -- 2, 4, 6 or 8 to rpresent compromises between preferences	

Instructions for comparing attributes.

1. Compare Rows with Column's.
2. If element in Row A is preferable to element in Row B, assign appropriate number in the cell.
3. If element in Row A is NOT preferable to element in Row B, leve that cell blank for now and move on the the next column (for eg. if Mat.Cost is Not preferred to Handling, leave that cell blank, and compare Mat.Cost to Dbase.Extent. Evaluate the Handling-Mat.Cost relationship in the Handling row.).
4. Do NOT put values into the bottom half of the matrix. Instead, enter the reciprocal in the corresponding top half of the matrix (i.e. suppose Handling is strongly preferable to Mat. Cost, and so the preference number is 5. Then, instead of puttiung 5 in the Handling-Mat.Cost cell, put a 0.2 in the Mat.Cost-Handling cell). This is required for consistency and calculation purposes.
5. Check consistency of entries with the CR value for each matrix. CR should be less than 0.1

Matrix 1 -- Comparison Between Main Attributes

Matrix Size 4

With Respect to: Manufacturing Cost	Material Cost	Handling Issues	Database Extent	Manuf. Issues					Row Sum	Priority Weights	C	D	
Material Cost	1	0.25	3	0.167	0.088	0.1	0.21	0.07	0.475	0.11875	0.4868	4.0998	
Handling	4	1	5	1	0.353	0.41	0.36	0.42	1.5408	0.3852	1.6232	4.214	
DBase Extent	0.333	0.2	1	0.2	0.029	0.08	0.07	0.08	0.267	0.06675	0.2692	4.0337	
Mfg. Issues	6	1	5	1	0.529	0.41	0.36	0.42	1.7173	0.42931	1.8607	4.3342	
Sum	11.33	2.45	14	2.367	1	1	1	1		1	AVG =	4.1704	CR
											CI =	0.0568	0.0631

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Appendix A -- The AHP for weighting of attributes and sub-attributes

Matrix 2 -- HANDLING sub-attributes
Matrix Size 8

With Respect to: Handling Issues	Proc. Temp	Toxcty	P/S Life	C/S Resist	Damg Toler	MoistResist	Outga	Voids	Priority Weights
Process Temperature	1	2	3	5	5	5	8	8	0.335
Toxicity	0.50	1	2	4	4	4	7	7	0.2354
Pot/Shelf Life	0.33	0.50	1	3	3	3	6	6	0.165
C/S Resist.	0.20	0.25	0.33	1	1	1	3	3	0.0693
Dmg. Toler.	0.20	0.25	0.33	1	1	1	3	3	0.0693
Moist. Resist.	0.20	0.25	0.33	1	1	1	3	3	0.0693
Out-gassing	0.13	0.14	0.17	0.33	0.33	0.33	1	1	0.0284
Void Pr.	0.13	0.14	0.17	0.33	0.33	0.33	1	1	0.0284
Sum	2.68	4.54	7.33	15.67	15.67	15.67	32	32	1

CR
0.0159

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Appendix A -- The AHP for weighting of attributes and sub-attributes

Matrix 3 -- MANUFACTURING sub-attributes
Matrix Size 3

With Respect to: Manufacturing Issues	Versatility	Manuf.ability	Equip Outlay	Prioroty Weights -- Row Avg.
Versatility	1	0.17	0.33	0.096
Manuf.ability	6	1	3	0.653
Equip. Outlay	3	0.33	1.00	0.251
Sum	10	1.5	4.33	1

CR 0.0158

Matrix 4 -- MANUFACTURABILITY sub-attributes
Matrix Size 4

With Respect to: Manufactur-ability	Process	Tooling	Labor	QC Required	Prioroty Weights -- Row Avg.
Process	1	2	3	4	0.4538
Tooling	0.50	1	2.00	3	0.2677
Labor	0.33	0.5	1.00	4	0.1959
QC Required	0.25	0.33	0.25	1	0.0826
Sum	2.08	3.83	6.25	12	1

CR 0.0582

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Appendix B General Comparison between Epoxy/PEEK, no Monte Carlo Simulation

General Comparison between carbon fiber (Fibrite 934)-epoxy and P75/PEEK -- Old 1&5 values

T Level 1		Level 2		Level 3		Level 4		Defender Carbon-Epoxy		Challenger PEEK		
Fact	Weight	Fact	Weight	F+E21act	Weight	Fact	eig	Rank	Valu	Rank	Valu	
Manufacturing Complexity Factor									0.4077		0.5923	1.0000
Delta Cost Factor (Defender > Challenger) =									1.4526			
Mat Cost	0.106							1	0.1667	5	0.8333	
Material Cost -- Complexity Factor									0.0177		0.0883	0.1060
												mtl. cost
Handling	0.3759											
Handling Complexity Factor									0.1798		0.1961	0.3759
												handling
		P Temp	0.3350					1	0.0558	5	0.2792	
		Toxicity	0.2354					5	0.1177	5	0.1177	
		P/S Life	0.1650	Pot life not applicable for PEEK				5	0.1375	1	0.0275	
		C/R Resi	0.0693					3	0.0520	1	0.0173	
		D Toler	0.0693					3	0.0416	2	0.0277	
		M. Resist	0.0693					5	0.0433	3	0.0260	
		Outgassin	0.0284					4	0.0162	3	0.0122	
		Void Pres	0.0284					3	0.0142	3	0.0142	
			1.0000									
Dbse Ext	0.0778							1	0.2500	3	0.7500	
Database Extent Complexity Factor									0.0195		0.0584	0.0778
												dbase extent

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Appendix B General Comparison between Epoxy/PEEK, no Monte Carlo Simulation

Mfg Iss 0.4402

Manufacturing Issues ComplexityFactor									
				0.1908		0.2495	0.4403		
							mgf. complexity		

Versatality 0.096

Versatality Factor		s		0.0517		0.0443	0.0960		
							versatility		
Layup F	1	0.30952	1	0.5385	1	0.4615	1.0000	1	1
RTM	1		1		0			1	0
CM-disc	1		1		0			1	0
CM-cont	1		1		1			1	1
FW	1		1		1			1	1
Pult	1		1		1			1	1
ThermF	1		0		1			0	1
Dia M	1		0		1			0	1
Inj M	1		0	6	1	7		0	1

Versatility: "sheer #" measure. the matls simply ranked a 1 for each procs. it can be procsd by. then values depend on sum of 1's. If def/chal have sums of x&y, then s=(1/x+1/y) & resp. values are: def=1/(x*s) and chal=1/(y*s)

Eqip Outly 0.251

Equipment Outlay Factor				0.0942		0.1568	0.2510		
							equip. outlay		
Layup F	1		1	0.0083	3	0.0250		1	2
RTM	2	n/a for peek	3	0.0250	5	0.0417		3	5
CM-dis	4		1	0.0333	3	0.1000		1	5
CM-cont	4		1	0.0222	5	0.1111		1	2
FW	4		1	0.0267	4	0.1067		1	3
Pult	4		2	0.0444	4	0.0889		2	3
ThermF	3	n/a for Gr-epoxy	5	0.0556	4	0.0444		5	3
Dia M	3		5	0.0556	4	0.0444		5	2
Inj M	5		5	0.1042	3	0.0625		5	1

Equipment Outlay. a measure incorporating the expense of a process. processes are individually rated between 1-5 on how expensive/complicated they are to operate. respective materials are rated on how compatable they are to the process in question -- same rating as given in the **Manuf.ability-process** sub-factor.

the calculation proceeds as normal.

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Appendix B General Comparison between Epoxy/PEEK, no Monte Carlo Simulation

Mfct-ility 0.653

Manufacturability Issues Complexity Factor			0.2876		0.3656	0.6532 mfg. issues

Processe 0.514

Processes Complexity Factor			0.1966		0.3174	0.5140 process
Layup F	3	1	0.0278	3	0.0833	
RTM	3	3	0.0417	5	0.0694	
CM -disc	3	1	0.0278	3	0.0833	
CM -cont	3	1	0.0185	5	0.0926	
FW	3	1	0.0222	4	0.0889	
Pult	3	2	0.0370	4	0.0741	
ThermF	3	6	0.0667	4	0.0444	
Dia M	3	6	0.0667	4	0.0444	
Inj M	3	6	0.0741	3	0.0370	

Tool 0.1314

Tooling Complexity Factor			0.0670		0.0644	0.1314 tooling
Layup F	3	2	0.0556	2	0.0556	
RTM	3	3	0.0417	5	0.0694	
CM-disc	3	3	0.0417	5	0.0694	
CM-cont	3	3	0.0417	5	0.0694	
FW	3	2	0.0556	2	0.0556	
Pult	3	5	0.0556	5	0.0556	
ThermF	3	5	0.0694	3	0.0417	
Dia M	3	5	0.0794	2	0.0317	
Inj M	3	5	0.0694	3	0.0417	

Tooling Cost has an influence on weights

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Appendix B General Comparison between Epoxy/PEEK, no Monte Carlo Simulation

Labor weights dependent on labor involvement/cost in respective processes

Labor 0.2632

Labor ComplexityFactor			0.1312		0.1320	0.2632
						labor
Layup F	3	5	0.0556	5	0.0556	
RTM	3	3	0.0417	5	0.0694	
CM-disc	3	3	0.0556	3	0.0556	
CM-cont	3	3	0.0417	5	0.0694	
FW	3	4	0.0556	4	0.0556	
Pult	3	2	0.0556	2	0.0556	
ThermF	3	5	0.0694	3	0.0417	
Dia M	3	5	0.0617	4	0.0494	
Inj M	3	5	0.0617	4	0.0494	

QA 0.0917

QA Complexity Factor			0.0457		0.0460	0.0917
						qa
Layup F	3	3	0.0556	3	0.0556	
RTM	3	4	0.0494	5	0.0617	
CM-disc	3	3	0.0556	3	0.0556	
CM-cont	3	3	0.0417	5	0.0694	
FW	3	2	0.0556	2	0.0556	
Pult	3	1	0.0556	1	0.0556	
ThermF	3	5	0.0617	4	0.0494	
Dia M	3	5	0.0617	4	0.0494	
Inj M	3	5	0.0617	4	0.0494	

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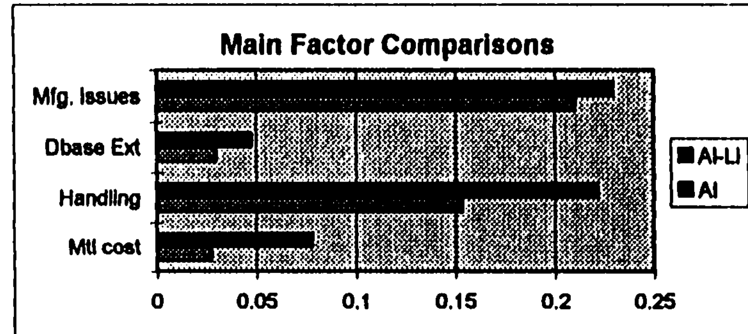
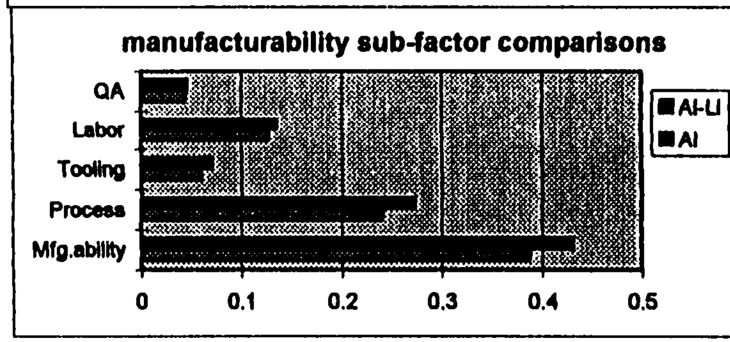
Appendix C-1 Al 2024 v/s Al-Li 2090 comparisons for skin/stringer

Al 2024 v/s Al-Li 2090 comparison for skin/stringer structure.

	MCF		DCF
	Al	Al-Li	
1st value	0.401572	0.598437	1.490236
Mean	0.422028	0.577981	1.369532
Median	0.420924	0.579085	1.375747
Mode	#N/A	#N/A	#N/A
Std. Dev.	0.026081	0.026081	
Min.	0.356257	0.472336	1.325828
Max.	0.527673	0.643751	1.219982

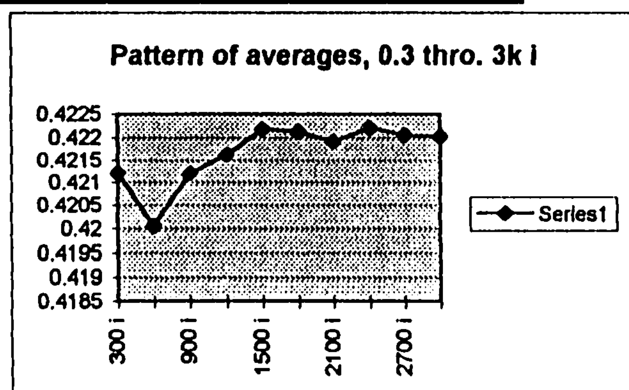


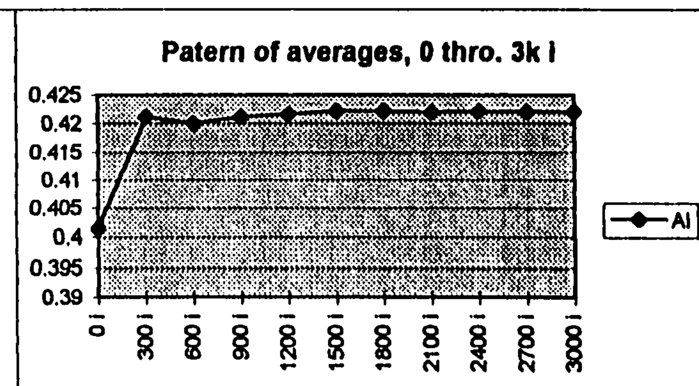
	Mtl cost	Handling	Dbase Ext	Mfg. issues
Al	0.02767	0.153835	0.029995	0.210527
Al-Li	0.07833	0.222065	0.047805	0.229781
DCF	2.830819	1.443526	1.59374	1.091458



	Mfg.ability	Process	Tooling	Labor	QA
Al	0.38842	0.240848	0.060411	0.127406	0.044825
Al-Li	0.43216	0.273152	0.070989	0.135794	0.046875
DCF	1.11261	1.134128	1.175095	1.065843	1.045712

means	Al
0 i	0.401572
300 i	0.421216
600 i	0.420055
900 i	0.421204
1200 i	0.421612
1500 i	0.422175
1800 i	0.422129
2100 i	0.421919
2400 i	0.422204
2700 i	0.422056
3000 i	0.422028





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Appendix C-1 Al 2024 v/s Al-Li 2090 comparisons for skin/stringer

DEFENDER - Al 2024.

	Mtl cost	Handling	Dbase Ext	Mfg. Issue	Versatialit	Equip Outl	Mfg. Issue	Process	Tooling	Labor	QA
1st. value	0.0212	0.144416	0.025933	0.210022	0.089833	0	0.387272	0.238643	0.060694	0.12784	0.044914
Mean	0.02767	0.153835	0.029995	0.210527	0.089833	0	0.38842	0.240848	0.060411	0.127406	0.044825
Median	0.0265	0.151577	0.025933	0.210419	0.089833	0	0.388175	0.238643	0.060396	0.12784	0.044914
Mode	0.0212	0.133676	0.025933	#N/A	0.089833	0	#N/A	0.232524	0.060694	0.12784	0.04585
Std. Dev.	0.008894	0.021546	0.008714	0.007798	6.25E-09	0	0.017716	0.020225	0.003026	0.005735	0.003323
Min.	0.017667	0.10564	0.01945	0.184154	0.089833	0	0.328509	0.171333	0.048076	0.111233	0.033623
Max.	0.053	0.229994	0.051867	0.242666	0.089833	0	0.461429	0.325533	0.069871	0.143014	0.055737

CHALLENGER -- Al-Li 2090

	Mtl cost	Handling	Dbase Ext	Mfg. Issue	Versatialit	Equip Outl	Mfg. Issue	Process	Tooling	Labor	QA
1st. value	0.0848	0.231484	0.051867	0.230286	0.089833	0	0.433307	0.275357	0.070706	0.13536	0.046786
Mean	0.07833	0.222065	0.047805	0.229781	0.089833	0	0.43216	0.273152	0.070989	0.135794	0.046875
Median	0.0795	0.224323	0.051867	0.229889	0.089833	0	0.432405	0.275357	0.071004	0.13536	0.046786
Mode	0.0848	0.242224	0.051867	0.233606	0.089833	0	0.440849	0.269238	0.068918	0.13536	0.04585
Std. Dev.	0.008894	0.021546	0.008714	0.007798	6.25E-09	0	0.017716	0.020225	0.003026	0.005735	0.003323
Min.	0.053	0.145906	0.025933	0.197642	0.089833	0	0.35915	0.188467	0.061529	0.120186	0.035963
Max.	0.088333	0.27026	0.05835	0.256154	0.089833	0	0.492071	0.342667	0.083324	0.151967	0.058077

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Appendix C-1 Al v/s Al-Li values for s/s adapter

Al v/s Al-Li for Skin/Stringer assy. Values revised 4 Sept.

T Level 1 Fact	Level 1 Weight	Level 2 Fact	Level 2 Weight	Level 3 Fact / Weight, Level 4 Fact / eig	Defender AL - 2024 Rank	Defender AL - 2024 Value	Challenger AL-LI 2090 for s/s structure Rank	Challenger AL-LI 2090 Value			Defend AL - 20 Rank	Challenger AL-LI 2090 f Rank
											ORIGINAL VALUES	
Manufacturing Complexity Factor						0.4698		0.5302	1.0000			
Delta Cost Factor (Defender > Challenger) =						1.1286						
Mat Cost	0.106			al-li is 3-4 times more expensive, so simulate	1	0.3333	2	0.6667			1	4
Material Cost -- Complexity Factor						0.0353		0.0707	0.1060			
Handling	0.3759			s/b of 2090 is equivalent to 2024, however, 2090 is better than 2024 with the bend axis parallel to rolling direction. so al is 2 and al-li is 3 for s/b strength.								
Handling Complexity Factor						0.1810		0.1949	0.3759	handling		
	ok	Ductility	0.43553		1	0.2178	1	0.2178			1	2
	ok	S/B Stren	0.28573		2	0.1905	1	0.0952			3	2
	ok	Extra Han	0.19434	4 is actually 3-4, so simulate accor	1	0.0486	3	0.1458			1	3
	ok	Ingot Qual	0.0422		1	0.0141	2	0.0281			1	3
	ok	Scrap	0.0422		1	0.0106	3	0.0317			1	4
			1.0000									
Dbse Ext	0.0778				1	0.5000	1	0.5000		dbase	1	2
Database Extent Complexity Factor						0.0389		0.0389	0.0778			

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Appendix C-1 Al v/s Al-Li values for s/s adapter

Mfg. Iss	0.4402				
Manufacturing Issues ComplexityFactor		0.2146	0.2257	0.4403	
Versatility	0.17967				
Versatility Factor		0.0898	0.0898	0.1797	

Versatility: "sheer #" measure. the matls simply ranked a 1 for each procs. it can be procsd by. then values depend on sum of 1's. If def/chal have sums of x&y, then s=(1/x+1/y) & resp. values are: def=1/(x*s) and chal=1/(y*s)

Process		s								
Sheet For	1	0.28571	1	0.5000	1	0.5000	1.0000	versat	1	1
Machinin	1		1		1				1	1
Heat Trea	1		1		1				1	1
Chemical	1		1		1				1	1
Fastening	1		1		1				1	1
Inspectio	1		1		1				1	1
Cleaning/	1		1	7	1	7			1	1

Equip Outl	0			
Equipment Outlay Factor		0.0000	0.0000	0.0000

EQUIPMENT OUTLAY Factor
Should be 0 for the skin/stringer assembly, because it was stressed that processes/equipment were the same for Al and Al-Li 2090.

Process								
Forging	1	1	0.0101	2	0.0202	equip ou	1	2
Extrusion	2	2	0.0242	3	0.0364		2	3
Conv M/c	4	1	0.0404	2	0.0808		1	2
Chem Mil	4	1	0.0303	3	0.0909		1	3
Pres Brke	4	1	0.0303	3	0.0909		1	3
Strch for	4	1	0.0303	3	0.0909		1	3
riveting	3	3	0.0455	3	0.0455		3	3
welding	3	3	0.0455	3	0.0455			
clean/fins	3	3	0.0455	3	0.0455		3	3
heat treat	5	3	0.0909	2	0.0606		3	2

Equipment Outlay. a measure incorporating the expense of a process. Processes are individually rated between 1-5 on how expensive/complicated they are to operate. Respective materials are rated on how compatible they are to the process in question -- same rating as given in the **Manuf.ability-process** sub-factor.

The calculation proceeds as normal.

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Appendix C-1 Al v/s Al-Li values for s/s adapter

Mfct-ility 0.82033

Manufacturability Issues Complexity Factor				0.3977		0.4229	0.8206			
Processe 0.514			1.000							
Processes Complexity Factor				0.2570		0.2570	0.5140			
The sheet-forming process specs. were revised to require a 1.5 to 3% permanent set during the streach stress relieving operation. so, al-li	Sheet For	3	1	0.0714	1	0.0714		process	1	2
both metals suffered during hand operations, so both get	Machinin	3	1	0.0714	1	0.0714			2	2
ht descriptions only fro al-li, so give that a 2 v.s a 1 for al	Heat Trea	3	1	0.0714	1	0.0714			1	2
	Chemical	3	1	0.0714	1	0.0714			1	1
	Fastening	3	1	0.0714	1	0.0714			1	1
	Inspectio	3	1	0.0714	1	0.0714			1	1
	Cleaning/	3	1	0.0714	1	0.0714			1	1
Tool 0.1314			1.270							
Tooling Complexity Factor				0.0579		0.0735	0.1314			
	Sheet For	3	1	0.0476	2	0.0952		tooling	2	3
	Machinin	3	1	0.0357	3	0.1071			2	4
	Heat Trea	3	2	0.0714	2	0.0714			3	3
	Chemical	3	3	0.0714	3	0.0714			4	4
	Fastening	3	3	0.0714	3	0.0714			4	4
	Inspectio	3	4	0.0714	4	0.0714			5	5
	Cleaning/	3	1	0.0714	1	0.0714			1	1

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Appendix C-1 Al v/s Al-Li values for s/s adapter

Labor	0.2632			1.100							
Labor ComplexityFactor					0.1253		0.1379	0.2632			
		Sheet For	3	1	0.0476	2	0.0952		labor	2	3
		Machinin	3	1	0.0714	1	0.0714			2	2
		Heat Trea	3	2	0.0714	2	0.0714			3	3
		Chemical	3	2	0.0714	2	0.0714			3	3
		Fastening	3	2	0.0714	2	0.0714			3	3
		Inspectio	3	2	0.0714	2	0.0714			3	3
		Cleaning/	3	3	0.0714	3	0.0714			4	4
QA	0.0917			1.059							
QA Complexity Factor					0.0445		0.0472	0.0917			
		Sheet For	3	1	0.0714	1	0.0714		qa	2	2
		Machinin	3	1	0.0714	1	0.0714			2	2
		Heat Trea	3	2	0.0571	3	0.0857			3	4
		Chemical	3	2	0.0714	2	0.0714			3	3
		Fastening	3	2	0.0714	2	0.0714			3	3
		Inspectio	3	1	0.0714	1	0.0714			2	2
		Cleaning/	3	1	0.0714	1	0.0714			1	1

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Appendix C-2 Al v/s Al-Li comparsion for s/s adapter - when material cost is not considered

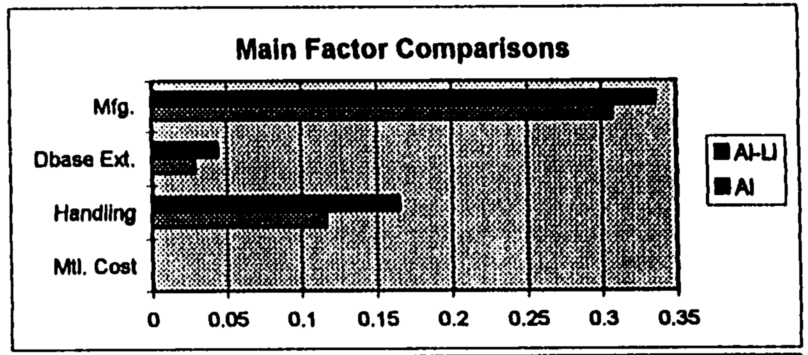
Al v/s Al-Li for sheet/stringer simulation. NO mtl. cost. factor

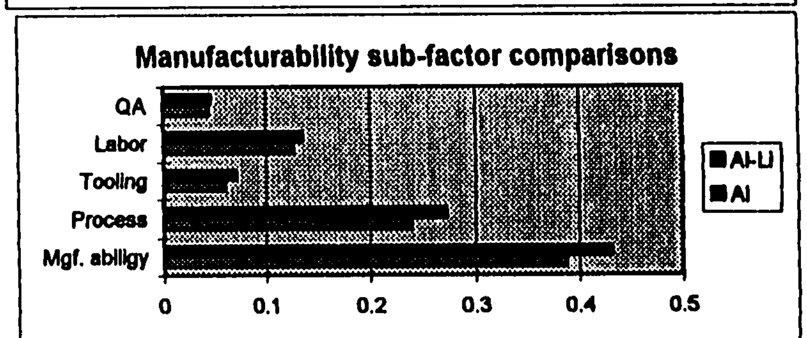
	MCF		DCF
	Al	Al-Li	
1st. value	0.436989	0.563169	1.288749
Mean	0.453173	0.546985	1.207012
Median	0.452148	0.548011	1.212017
Mode	#N/A	#N/A	#N/A
Std. Dev.	0.021809	0.021809	
Min.	0.394088	0.471892	1.197428
Max.	0.528267	0.60607	1.147281

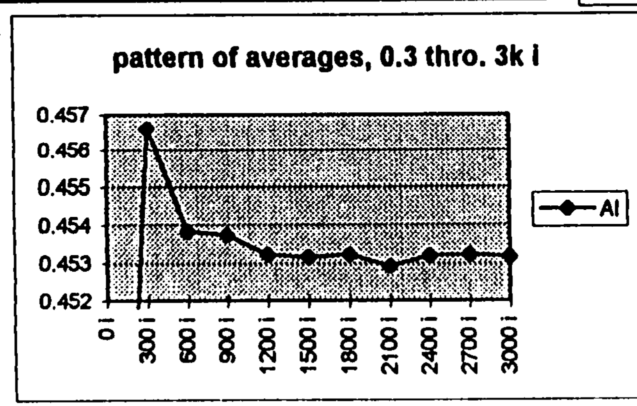
	Mtl. Cost	Handling	Dbase Ext	Mfg.
Al	0	0.116906	0.028735	0.307533
Al-Li	0	0.165933	0.045037	0.336015
DCF	#DIV/0!	1.419377	1.567334	1.092615

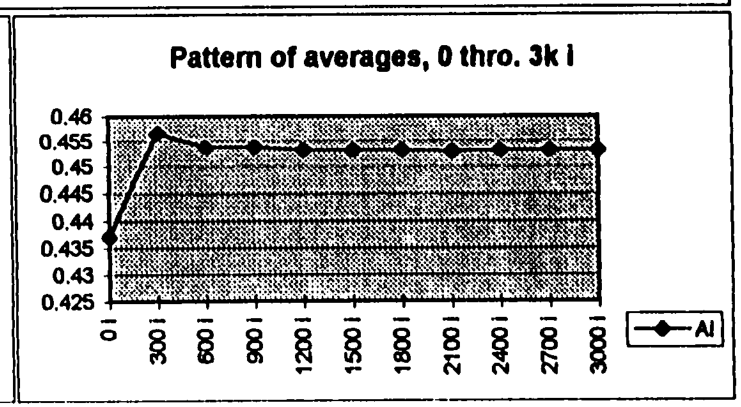
	gf. abilig	Process	Tooling	Labor	QA
Al	0.388155	0.240447	0.060395	0.12744	0.044885
Al-Li	0.432424	0.273553	0.071005	0.13576	0.046815
DCF	1.11405	1.137682	1.175664	1.06528	1.04302

means	Al
0 i	0.436989
300 i	0.456599
600 i	0.45383
900 i	0.453742
1200 i	0.45323
1500 i	0.453151
1800 i	0.453228
2100 i	0.452914
2400 i	0.453182
2700 i	0.453229
3000 i	0.453173









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Appendix C-2 Al v/s Al-Li comparsion for s/s adapter - when material cost is not considered

DEFENDER Al 2024 run without Mtl. Cost values, skin/stringer

	Mtl. Cost	Handling	Dbase Ext	Mfg.	Versatility	Equip.	Mgf. abilig	Process	Tooling	Labor	QA
1st. value	0	0.108663	0.024591	0.303735	0.089833	0	0.382253	0.232524	0.060694	0.12784	0.044914
Mean	0	0.116906	0.028735	0.307533	0.089833	0	0.388155	0.240447	0.060395	0.12744	0.044885
Median	0	0.114836	0.024591	0.307414	0.089833	0	0.387971	0.238643	0.060396	0.12784	0.044914
Mode	0	0.101577	0.024591	0.298427	0.089833	0	0.374002	0.257	0.063823	0.12784	0.04585
Std. Dev.	0	0.016517	0.008274	0.011512	6.25E-09	0	0.017892	0.020607	0.003127	0.005582	0.003371
Min.	0	0.079487	0.018443	0.272277	0.089833	0	0.333359	0.177452	0.049707	0.111233	0.031658
Max.	0	0.17206	0.049181	0.348679	0.089833	0	0.452108	0.31819	0.071346	0.143014	0.054947

CHALLENGER Al-Li 2090 run with NO Mtl. Cost. skin/stringer

	Mtl. Cost	Handling	Dbase Ext	Mfg.	Versatility	Equip.	Mgf. abilig	Process	Tooling	Labor	QA
1st. value	0	0.174176	0.049181	0.339812	0.089833	0	0.438327	0.281476	0.070706	0.13536	0.046786
Mean	0	0.165933	0.045037	0.336015	0.089833	0	0.432424	0.273553	0.071005	0.13576	0.046815
Median	0	0.168003	0.049181	0.336133	0.089833	0	0.432608	0.275357	0.071004	0.13536	0.046786
Mode	0	0.181262	0.049181	0.345121	0.089833	0	0.446577	0.269238	0.067577	0.13536	0.048033
Std. Dev.	0	0.016517	0.008274	0.011512	6.25E-09	0	0.017892	0.020607	0.003127	0.005582	0.003371
Min.	0	0.110779	0.024591	0.294868	0.089833	0	0.368472	0.19581	0.060054	0.120186	0.036753
Max.	0	0.203352	0.055329	0.37127	0.089833	0	0.48722	0.336548	0.081693	0.151967	0.060042

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Appendix C-2 Al v/s Al-Li comparison for s/s adapter, NO material Cost

Al v/s Al-Li for Skin/Stringer assy. No Material Cost.

Level 1 Fact	Level 1 Weight	Level 2 Fact	Level 2 Weight	Level 3 Fact	Level 3 Weight	Level 4 Fact	Level 4 eig	Defender AL - 2024 Rank	Defender AL - 2024 Value	Challenger AL-Li 2090 for s/s adapter Rank	Challenger AL-Li 2090 for s/s adapter Value			Defend AL Rank	Challenger AL-Li Rank
Manufacturing Complexity Factor									0.4867		0.5135	1.0002		ORIGINAL VALUES	
Delta Cost Factor (Defender > Challenger) =									1.0550				1.0002		
Mat Cost	0							1	0.2000	4	0.8000			1	4
Material Cost -- Complexity Factor									0.0000		0.0000	0.0000			
Handling	0.283	1													
Handling Complexity Factor									0.1362		0.1467	0.2828	handling		
ok		Ductility	0.43553					1	0.2178	1	0.2178			1	2
ok		S/B Stren	0.28573					2	0.1905	1	0.0952			3	2
ok		Extra Han	0.19434	4 is actually 3-4, so simulate accor				1	0.0486	3	0.1458			1	3
ok		Ingot Qual	0.0422					1	0.0141	2	0.0281			1	3
ok		Scrap	0.0422					1	0.0106	3	0.0317			1	4
			1.0000												
Dbse Ext	0.074							1	0.5000	1	0.5000		dbase	1	2
Database Extent Complexity Factor									0.0369		0.0369	0.0738			

al-li is 3-4 times more expensive, so simulate accordingly

s/b of 2090 is equivalent to 2024, however, 2090 is better than 2024 with the bend axis parallel to rolling direction. so al is 2 and al-li is 3 for s/b strength.

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Appendix C-2 Al v/s Al-Li comparison for s/s adapter, NO material Cost

Mfg. Iss	0.643	0.6435	1.0518							
Manufacturing Issues ComplexityFactor					0.3136		0.3299	0.6435		
Versatility	0.17967									
Versatility Factor					0.0898		0.0898	0.1797		
			s							
Sheet For	1		0.28571	1	0.5000	1	0.5000	1.0000	versat	1	1
Machinin	1			1		1				1	1
Heat Trea	1			1		1				1	1
Chemical	1			1		1				1	1
Fastening	1			1		1				1	1
Inspectio	1			1		1				1	1
Cleaning/	1			1	7	1	7			1	1

Versatility: "sheer #" measure. the matls simply ranked a 1 for each procs. it can be procsd by. then values depend on sum of 1's. If def/chal have sums of x&y, then s=(1/x+1/y) & resp. values are: def=1/(x*s) and chal=1/(y*s)

Equip Outl	0								
Equipment Outlay Factor			0.0000		0.0000	0.0000			
Forging	1	1	0.0101	2	0.0202		equip ou	1	2
Extrusion	2	2	0.0242	3	0.0364			2	3
Conv M/c	4	1	0.0404	2	0.0808			1	2
Chem Mil	4	1	0.0303	3	0.0909			1	3
Pres Brke	4	1	0.0303	3	0.0909			1	3
Strch for	4	1	0.0303	3	0.0909			1	3
riveting	3	3	0.0455	3	0.0455			3	3
welding	3	3	0.0455	3	0.0455				
clean/fins	3	3	0.0455	3	0.0455			3	3
heat treat	5	3	0.0909	2	0.0606			3	2

EQUIPMENT OUTLAY Factor
Should be 0 for the skin/stringer assembly, because it was stressed that processes/equipment were the same for Al and Al-Li 2090.

Equipment Outlay. a measure incorporating the expense of a process. Processes are individually rated between 1-5 on how expensive/complicated they are to operate. Respective materials are rated on how compatible they are to the process in question -- same rating as given in the **Manuf.ability-process** sub-factor.

The calculation proceeds as normal.

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Appendix C-2 Al v/s Al-Li comparison for s/s adapter, NO material Cost

Mfct-ility 0.82033 0.8206

Manufacturability Issues Complexity Factor			0.3977		0.4229	0.8206			
Processe 0.514									
Processes Complexity Factor			0.2570		0.2570	0.5140			
Sheet For	3	1	0.0714	1	0.0714		process	1	2
Machinin	3	1	0.0714	1	0.0714			2	2
Heat Trea	3	1	0.0714	1	0.0714			1	2
Chemical	3	1	0.0714	1	0.0714			1	1
Fastening	3	1	0.0714	1	0.0714			1	1
Inspectio	3	1	0.0714	1	0.0714			1	1
Cleaning/	3	1	0.0714	1	0.0714			1	1
Tool 0.1314									
Tooling Complexity Factor			0.0579		0.0735	0.1314			
Sheet For	3	1	0.0476	2	0.0952		tooling	2	3
Machinin	3	1	0.0357	3	0.1071			2	4
Heat Trea	3	2	0.0714	2	0.0714			3	3
Chemical	3	3	0.0714	3	0.0714			4	4
Fastening	3	3	0.0714	3	0.0714			4	4
Inspectio	3	4	0.0714	4	0.0714			5	5
Cleaning/	3	1	0.0714	1	0.0714			1	1

The sheet-forming process specs. were revised to require a 1.5 to 3% permanent set during the streach stress relieving operation. so, al-li

both metals suffered during hand operations, so both get

ht descriptions only fro al-li, so give that a 2 v.s a 1 for al

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Appendix C-2 Al v/s Al-Li comparison for s/s adapter, NO material Cost

Labor	0.2632									
Labor ComplexityFactor				0.1253		0.1379	0.2632			
	Sheet For	3	1	0.0476	2	0.0952		labor	2	3
	Machinin	3	1	0.0714	1	0.0714			2	2
	Heat Trea	3	2	0.0714	2	0.0714			3	3
	Chemical	3	2	0.0714	2	0.0714			3	3
	Fastening	3	2	0.0714	2	0.0714			3	3
	Inspectio	3	2	0.0714	2	0.0714			3	3
	Cleaning/	3	3	0.0714	3	0.0714			4	4
QA	0.0917									
QA Complexity Factor				0.0445		0.0472	0.0917			
	Sheet For	3	1	0.0714	1	0.0714		qa	2	2
	Machinin	3	1	0.0714	1	0.0714			2	2
	Heat Trea	3	2	0.0571	3	0.0857			3	4
	Chemical	3	2	0.0714	2	0.0714			3	3
	Fastening	3	2	0.0714	2	0.0714			3	3
	Inspectio	3	1	0.0714	1	0.0714			2	2
	Cleaning/	3	1	0.0714	1	0.0714			1	1

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Appendx C-3 Al 2024 v/s Al-Li 2090 comparisons for LOX tank

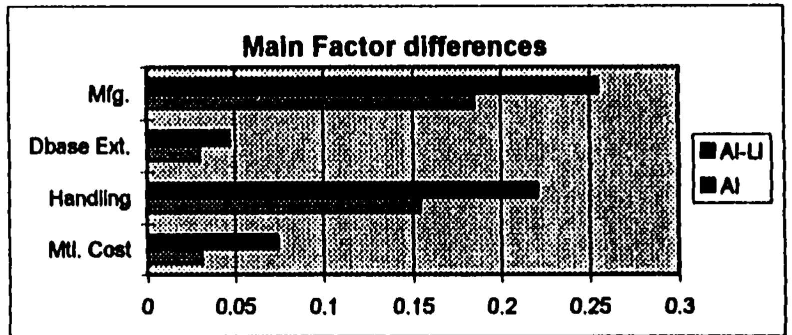
Al 2024 v/s Al-Li 2090 comparison for LOX tank

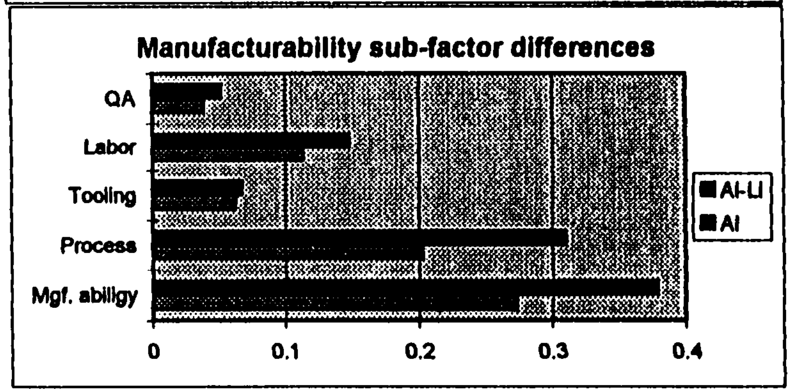
	MCF		DCF
	Al	Al-Li	
1st value	0.376005	0.623981	1.659501
Mean	0.401649	0.598338	1.489704
Median	0.400729	0.599258	1.49542
Mode	#N/A	#N/A	#N/A
Std. Dev.	0.022567	0.022567	
Min.	0.333788	0.513075	1.53713
Max.	0.486911	0.666199	1.368214

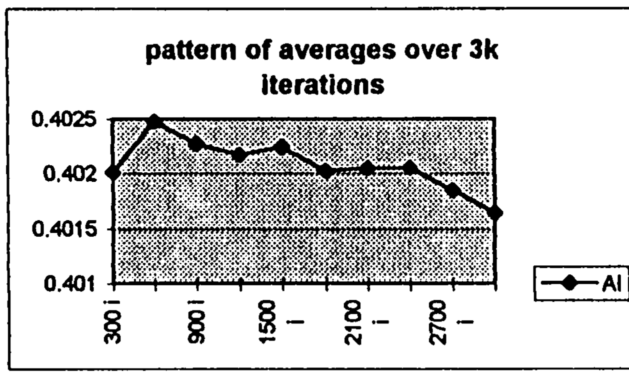
	Mtl. Cost	Handling	Dbase Ext	Mfg.
Al	0.03133	0.154704	0.030352	0.185262
Al-Li	0.074672	0.2212	0.047449	0.255024
DCF's	2.383381	1.429823	1.563286	1.376555

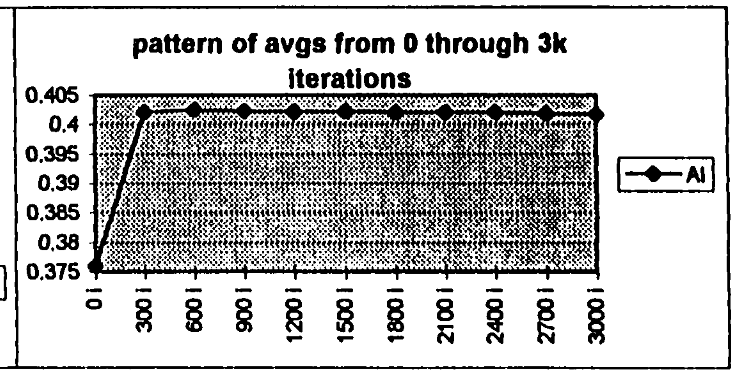
	gf. abilig	Process	Tooling	Labor	QA
Al	0.273992	0.202931	0.063194	0.114227	0.039238
Al-Li	0.379204	0.311064	0.068212	0.148973	0.052461
DCF's	1.383995	1.532857	1.079401	1.304185	1.337007

values	Al
0 i	0.376005
300 i	0.402016
600 i	0.402479
900 i	0.402277
1200 i	0.402171
1500 i	0.402247
1800 i	0.402023
2100 i	0.40205
2400 i	0.402054
2700 i	0.401846
3000 i	0.401649









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Appendx C-3 Al 2024 v/s Al-Li 2090 comparisons for LOX tank

DEFENDER Al 2024

	Mtl. Cost	Handling	Dbase Ext	Mfg.	Versatility	Equip.	gf. abilig	Process	Tooling	Labor	QA
1st value	0.0212	0.146343	0.025933	0.182529	0.048	0.096366	0.270283	0.197339	0.063354	0.114053	0.039164
Mean	0.03133	0.154704	0.030352	0.185262	0.048	0.098867	0.273992	0.202931	0.063194	0.114227	0.039238
Median	0.0265	0.153985	0.025933	0.185002	0.048	0.098483	0.273213	0.202846	0.063354	0.114053	0.039164
Mode	0.0265	0.155771	0.025933	#N/A	0.048	0.096366	#N/A	0.197339	0.0657	0.114053	0.039164
Std. Dev.	0.007424	0.017923	0.008872	0.008917	0	0.011396	0.016939	0.021852	0.005227	0.012005	0.004553
Min.	0.0265	0.105214	0.01945	0.155739	0.048	0.067979	0.220906	0.139208	0.04745	0.077498	0.023744
Max.	0.053	0.220087	0.051867	0.217226	0.048	0.138448	0.338041	0.282088	0.081343	0.155622	0.054128

CHALLENGER Al-Li 2090

	Mtl. Cost	Handling	Dbase Ext	Mfg.	Versatility	Equip.	gf. abilig	Process	Tooling	Labor	QA
1st value	0.0848	0.229557	0.051867	0.257758	0.048	0.154634	0.382913	0.316661	0.068046	0.149147	0.052536
Mean	0.074672	0.2212	0.047449	0.255024	0.048	0.152132	0.379204	0.311064	0.068212	0.148973	0.052461
Median	0.0795	0.221915	0.051867	0.255284	0.048	0.152517	0.379983	0.310848	0.068046	0.149147	0.052536
Mode	0.0795	0.220129	0.051867	#N/A	0.048	0.154634	#N/A	0.316661	0.0657	0.149147	0.052536
Std. Dev.	0.007423	0.017919	0.008873	0.00892	0	0.011396	0.01694	0.021858	0.005223	0.012003	0.004554
Min.	0.053	0.155813	0.025933	0.223061	0.048	0.112552	0.315155	0.231912	0.050057	0.107578	0.037572
Max.	0.0795	0.270686	0.05835	0.284547	0.048	0.183021	0.43229	0.374792	0.08395	0.185702	0.067956

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Appendix C-3 Al v/s Al-Li comparison for LOX tank.

values for al v/s al-li for lox tank. 1st 3k iteration -- rev. 4-sept.

T Level 1 Fact	Level 1 Weight	Level 2 Fact	Level 2 Weight	Level 3 Fact	Level 3 Weight	Level 4 Fact	Level 4 eig	Defender For LOX tank AL	Defender Value	Challenger AL-LI	Challenger Value			Defend For LOX tank AL	Challenger AL-LI 2090
								FORMULAE						Original Values	
Manufacturing Complexity Factor									0.4213		0.5786	1.0000			
Delta Cost Factor (Defender > Challenger) =									1.3733						
Mat Cost	0.106			3 to 4 times				1	0.3333	2	0.6667			1	4
Material Cost -- Complexity Factor									0.0353		0.0707	0.1060			
Handling	0.3759														
Handling Complexity Factor									0.1679		0.2080	0.3759			
													handling		
weld strength is lower than al., but		Ductility	0.04899		0.1782			1	0.0245	1	0.0245			1	1
		S/B Stren	0.2118					1	0.1059	1	0.1059			2	1
		Weld Stre	0.28764					1	0.1438	1	0.1438			1	2
		Extra Han	0.09225	4 is actually 3-4, so simulate accor				1	0.0231	3	0.0692			1	3
		Ingot Qual	0.17816					1	0.0891	1	0.0891			1	2
		Scrap	0.18116					1	0.0604	2	0.1208			1	3
			1.0000												
Dbse Ext	0.0778							1	0.5000	1	0.5000		dbase	1	2
Database Extent Complexity Factor									0.0389		0.0389	0.0778			

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Appendix C-3 Al v/s Al-Li comparison for LOX tank.

Mfg. Iss 0.4402										
Manufacturing Issues ComplexityFactor				0.1792		0.2611	0.4403			
Versatility 0.096										
Versatility Factor				0.0480		0.0480	0.0960			
		s								
Conventl	1	0.5	1	0.5000	1	0.5000	1.0000	versat	1	1
Press Bra	1		1		1				1	1
Welding	1		1		1				1	1
Clean/fini	1		1	4	1	4			1	1
Equip Outl 0.251										
Equipment Outlay Factor				0.0962		0.1548	0.2510			
0										
Conv M/c	5		2	0.2083	2	0.2083		equip. o	3	3
Pres Brke	3		1	0.0500	4	0.2000			2	5
welding	3		1	0.0833	2	0.1667			1	3
Clean/fini	1		1	0.0417	1	0.0417			1	1

Versatility: "sheer #" measure. the matls simply ranked a 1 for each procs. it can be procsd by. then values depend on sum of 1's. If def/chal have sums of x&y, then s=(1/x+1/y) & resp. values are:
def=1/(x*s) and chal=1/(y*s)

Equipment Outlay. a measure incorporating the expense of a process. processes are individually rated between 1-5 on how expensive/complicated they are to operate. respective materials are rated on how compatible they are to the process in question -- same rating as given in the **Manuf.ability-process** sub-factor.
the calculation proceeds as normal.

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Appendix C-3 Al v/s Al-Li comparison for LOX tank.

Mfct-ility 0.653									
Manufacturability Issues Complexity Factor			0.2628		0.3904	0.6532			
Processe 0.514		1.609							
Processes Complexity Factor			0.1970		0.3170	0.5140			
Conventl	4	2	0.1250	2	0.1250		process	3	3
Press Bra	4	1	0.0500	4	0.2000			2	5
Welding	4	1	0.0833	2	0.1667			1	3
Clean/fini	4	1	0.1250	1	0.1250			1	1
Tool 0.1314									
Tooling Complexity Factor			0.0624		0.0690	0.1314			
Conventl	4	2	0.1250	2	0.1250		tooling	3	3
Press Bra	4	3	0.1250	3	0.1250			4	4
Welding	4	2	0.1000	3	0.1500			3	4
Clean/Fin	4	1	0.1250	1	0.1250			1	1

Iso-grid machining was done using OLD MDSSC NC tapes.

PBr. -- No dies, so tooling was not extra. However, cracks were formed, and shimming was reduced, giving an anticlastic curvature, so porcess must be a 5. But, "dog-bone braces" had to be installed. So, labor and qa must be 5.

welding tooling must be 5, as VPPA was dropped because of fixture cost

Al-Li given a 5 for tooling because of a statement in the 1st paper which talks of the LOX tank. It says that "additional non-recurring costs for new tooling -- make switching to Al-Li a financially unattactive option."

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Appendix C-3 Al v/s Al-Li comparison for LOX tank.

Labor 0.2632

Weld- they needed trials, initially cracks were observed, etc. so it is higher.

Labor ComplexityFactor			0.1067		0.1565	0.2632			
Conventi	5	2	0.1667	2	0.1667		labor	3	3
Press Bra	4	2	0.0889	4	0.1778			3	5
Welding	3	1	0.0500	3	0.1500			2	4
Clean/fini	3	1	0.1000	1	0.1000			2	2

QA 0.0917

PBr requires extra qc as cracks wre found in 2 panels.

Few welds required to establish procedures. Simulation probabilities: 40%-1, 50%-2, 10%-3. Set for both Labor and QA.

QA Complexity Factor			0.0363		0.0554	0.0917			
Conventi	4	1	0.1250	1	0.1250		qa	2	2
Press Bra	4	2	0.0833	4	0.1667			3	5
Welding	4	1	0.0625	3	0.1875			2	4
Clean/fini	4	1	0.1250	1	0.1250			1	1

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Appendix C-4 LOX tank, NO mtl. cost factor

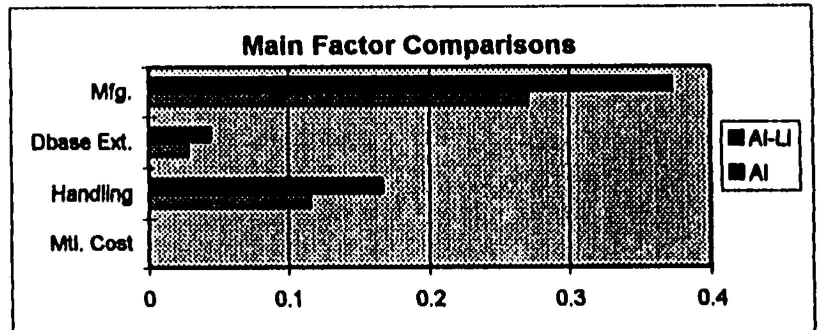
Al v/s Al-Li for LOX tank, NO mtl. cost factor.

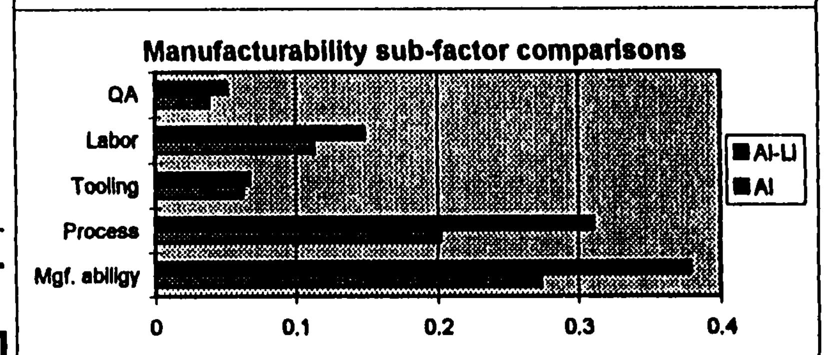
	MCF		DCF
	Al	Al-Li	
1st. value	0.401485	0.598641	1.491069
Mean	0.414845	0.585281	1.410844
Median	0.41442	0.585706	1.413314
Mode	#N/A	#N/A	#N/A
Std. Dev.	0.020297	0.020297	
Min.	0.344007	0.49917	1.451048
Max.	0.500956	0.656119	1.309735

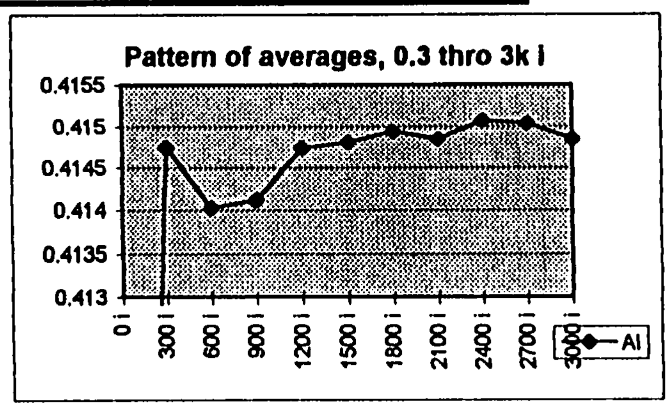
	Mtl. Cost	Handling	Dbase Ext	Mfg.
Al	0	0.11572	0.028521	0.270604
Al-Li	0	0.167119	0.045251	0.372911
DCF	#DIV/0!	1.444173	1.586586	1.378068

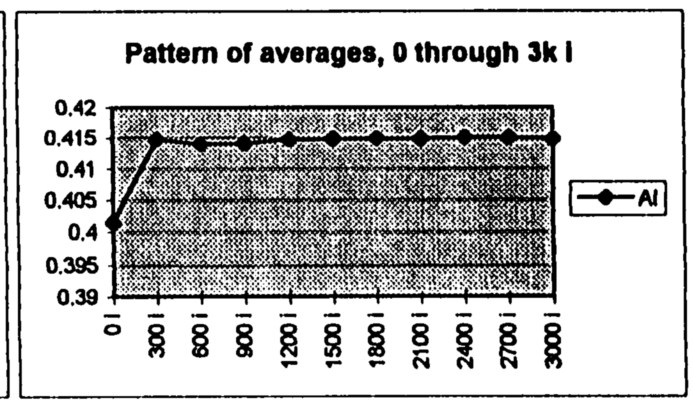
	gf. abilig	Process	Tooling	Labor	QA
Al	0.273645	0.202527	0.063383	0.113931	0.039218
Al-Li	0.379551	0.311473	0.068017	0.149269	0.052482
DCF	1.387018	1.537934	1.073123	1.310178	1.3382

mean	Al
0 i	0.401485
300 i	0.414744
600 i	0.414023
900 i	0.414118
1200 i	0.414742
1500 i	0.414808
1800 i	0.414942
2100 i	0.41485
2400 i	0.415073
2700 i	0.415036
3000 i	0.414845









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Appendix C-4 LOX tank, NO mtl. cost factor

DEFENDER Al 2024 run without Mtl. Cost values, LOX

	Mtl. Cost	Handling	Dbase Ext	Mfg.	Versatility	Equip.	gf. abilig	Process	Tooling	Labor	QA
1st. value	0	0.110113	0.024591	0.266781	0.048	0.096366	0.270283	0.197339	0.063354	0.114053	0.039164
Mean	0	0.11572	0.028521	0.270604	0.048	0.098947	0.273645	0.202527	0.063383	0.113931	0.039218
Median	0	0.114898	0.024591	0.270721	0.048	0.098483	0.273382	0.202846	0.063354	0.114053	0.039164
Mode	0	0.098825	0.024591	#N/A	0.048	0.096366	#N/A	0.197339	0.0657	0.114053	0.039164
Std. Dev.	0	0.013311	0.008261	0.012977	0	0.011552	0.016614	0.021562	0.00521	0.011975	0.004523
Min.	0	0.077609	0.018443	0.23005	0.048	0.064842	0.223132	0.132783	0.047359	0.072986	0.025654
Max.	0	0.162935	0.049181	0.315633	0.048	0.138448	0.332268	0.275204	0.081343	0.148269	0.054128

CHALLENGER Al-Li 2090 run with NO Mtl. Cost. LOX

	Mtl. Cost	Handling	Dbase Ext	Mfg.	Versatility	Equip.	gf. abilig	Process	Tooling	Labor	QA
1st. value	0	0.172726	0.049181	0.376734	0.048	0.154634	0.382913	0.316661	0.068046	0.149147	0.052536
Mean	0	0.167119	0.045251	0.372911	0.048	0.152053	0.379551	0.311473	0.068017	0.149269	0.052482
Median	0	0.167941	0.049181	0.372793	0.048	0.152517	0.379814	0.311154	0.068046	0.149147	0.052536
Mode	0	0.184014	0.049181	#N/A	0.048	0.154634	#N/A	0.316661	0.0657	0.149147	0.052536
Std. Dev.	0	0.013311	0.008261	0.012977	0	0.011552	0.016614	0.021562	0.00521	0.011975	0.004523
Min.	0	0.119904	0.024591	0.327882	0.048	0.112552	0.320928	0.238796	0.050057	0.114931	0.037572
Max.	0	0.20523	0.055329	0.413465	0.048	0.186158	0.430064	0.381217	0.084041	0.190214	0.066046

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Appendix C-4 LOX tank comparisons, NO material Cost

values for al v/s al-li for lox tank. 1st 3k iteration -- rev. 4-sept.

Level 1 Fact	Level 1 Weight	Level 2 Fact	Level 2 Weight	Level 3 Fact	Level 3 Weight	Level 4 Fact	eig	Defender For LOX tank AL	Defender Value	Challenger AL-LI	Challenger Value			Defend For LOX tank AL	Challenger AL-LI 2090 f
														Original Values	
Manufacturing Complexity Factor									0.4251		0.5750	1.0001			
Delta Cost Factor (Defender > Challenger) =									1.3525						
Mat Cost	0			3 to 4 times				1	0.3333	2	0.6667			1	4
Material Cost -- Complexity Factor									0.0000		0.0000	0.0000			
Handling	0.2828														
Handling Complexity Factor									0.1264		0.1565	0.2828			
													handling		
		Ductility	0.04899		0.1782			1	0.0245	1	0.0245			1	1
		S/B Stren	0.2118					1	0.1059	1	0.1059			2	1
0.28284		Weld Stre	0.28764					1	0.1438	1	0.1438			1	2
0.07377		Extra Han	0.09225	4 is actually 3-4, so simulate accor				1	0.0231	3	0.0692			1	3
0.64339		Ingot Qual	0.17816					1	0.0891	1	0.0891			1	2
		Scrap	0.18116					1	0.0604	2	0.1208			1	3
			1.0000												
Dbse Ext	0.0738							1	0.5000	1	0.5000		dbase	1	2
Database Extent Complexity Factor									0.0369		0.0369	0.0738			

weld strength is lower than al., but adequate
for this application -- last paper

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Appendix C-4 LOX tank comparisons, NO material Cost

Mfg. Iss 0.6434										
Manufacturing Issues ComplexityFactor				0.2619		0.3816	0.6435			
Versatility 0.096										
Versatility Factor				0.0480		0.0480	0.0960			
		s								
Conventi	1	0.5	1	0.5000	1	0.5000	1.0000	versat	1	1
Press Bra	1		1		1				1	1
Welding	1		1		1				1	1
Clean/fini	1		1	4	1	4			1	1
Equip Outl 0.251										
Equipment Outlay Factor				0.0962		0.1548	0.2510			
Conv M/c	5		2	0.2083	2	0.2083		equip. o	3	3
Pres Brke	3		1	0.0500	4	0.2000			2	5
welding	3		1	0.0833	2	0.1667			1	3
Clean/fini	1		1	0.0417	1	0.0417			1	1

Versatility: "sheer #" measure. the matls simply ranked a 1 for each procs. it can be procsd by. then values depend on sum of 1's. If def/chal have sums of x&y, then s=(1/x+1/y) & resp. values are:
def=1/(x*s) and chal=1/(y*s)

Equipment Outlay. a measure incorporating the expense of a process. processes are individually rated between 1-5 on how expensive/complicated they are to operate. respective materials are rated on how compatible they are to the process in question -- same rating as given in the **Manuf.ability-process** sub-factor.
the calculation proceeds as normal.

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Appendix C-4 LOX tank comparisons, NO material Cost

Mfct-ility 0.653										
Manufacturability Issues Complexity Factor				0.2628		0.3904	0.6532			
Processe 0.514			1.609							
Processes Complexity Factor				0.1970		0.3170	0.5140			
	Conventl	4	2	0.1250	2	0.1250		process	3	3
	Press Bra	4	1	0.0500	4	0.2000			2	5
	Welding	4	1	0.0833	2	0.1667			1	3
	Clean/fini	4	1	0.1250	1	0.1250			1	1
Tool 0.1314										
Tooling Complexity Factor				0.0624		0.0690	0.1314			
	Conventl	4	2	0.1250	2	0.1250		tooling	3	3
	Press Bra	4	3	0.1250	3	0.1250			4	4
	Welding	4	2	0.1000	3	0.1500			3	4
	Clean/Fin	4	1	0.1250	1	0.1250			1	1
Labor 0.2632										
Labor ComplexityFactor				0.1067		0.1565	0.2632			
	Conventl	5	2	0.1667	2	0.1667		labor	3	3
	Press Bra	4	2	0.0889	4	0.1778			3	5
	Welding	3	1	0.0500	3	0.1500			2	4
	Clean/fini	3	1	0.1000	1	0.1000			2	2
QA 0.0917										
QA Complexity Factor				0.0363		0.0554	0.0917			
	Conventl	4	1	0.1250	1	0.1250		qa	2	2
	Press Bra	4	2	0.0833	4	0.1667			3	5
	Welding	4	1	0.0625	3	0.1875			2	4
	Clean/fini	4	1	0.1250	1	0.1250			1	1

Iso-grid machining was done using OLD MDSSC NC tapes.

PBr. -- No dies, so tooling was not extra. However, cracks were formed, and shimming was reduced, giving an anticlastic curvature, so porcess must be a 5. But, "dog-bone braces" had to be installed. So, labor and qa must be 5.

welding tooling must be 5, as VPPA was dropped because of fixture cost

Al-Li given a 5 for tooling because of a statement in the 1st paper which talks of the LOX tank. It says that "additional non-recurring costs for new tooling -- make switching to Al-Li a financially unattactive option."

Weld- they needed trials, initially cracks were observed, etc. so it is higher.

PBr requires extra qc as cracks wre found in 2 panels.

Few welds required to establish procedures. Simulation probabilities: 40%-1, 50%-2, 10%-3. Set for both Labor and QA.

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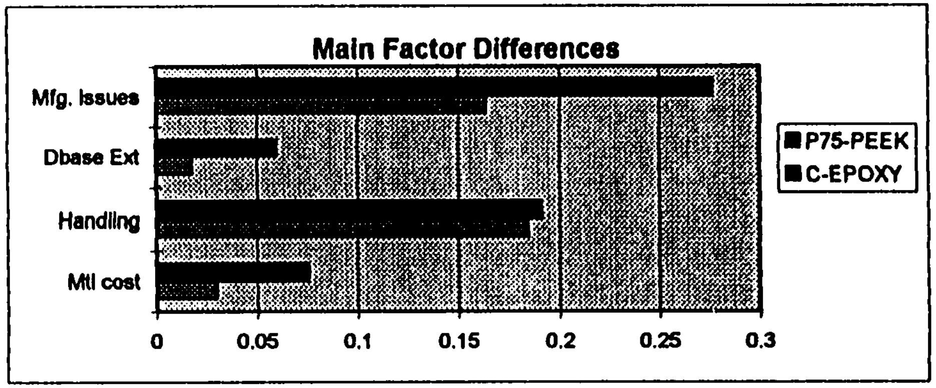
Appendiox C-5 C-EPOXY v/s PEEK comparison for Aircraft Wing Spoiler

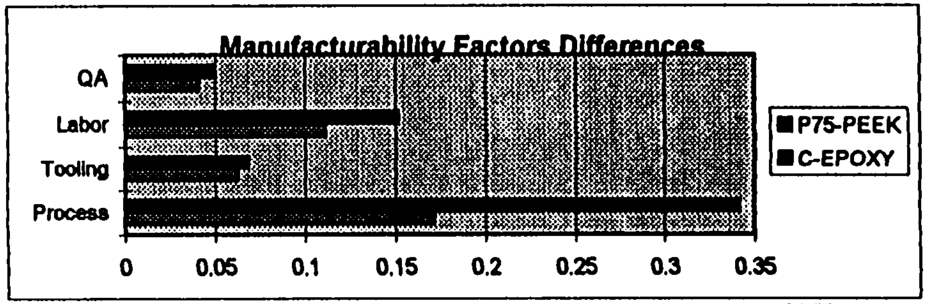
	MCF		DCF
	C-EPOXY	P75-PEEK	
Mean	0.396725	0.603261	1.520604
Median	0.396951	0.603035	1.519167
Mode	#N/A	#N/A	#N/A
Std. Dev	0.019773	0.019773	
Min	0.333313	0.542143	1.626525
Max	0.457844	0.666673	1.456115

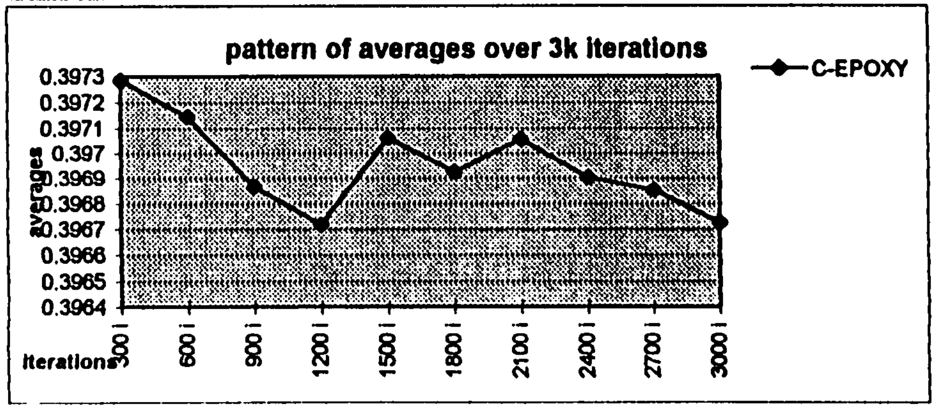
	Mtl cost	Handling	Dbase Ext	fg. issues
C-EPOXY	0.030387	0.184766	0.017987	0.163584
P75-PEEK	0.075613	0.191134	0.059813	0.276702

	Process	Tooling	Labor	QA
C-EPOXY	0.171976	0.062542	0.111325	0.041394
P75-PEEK	0.342024	0.068858	0.151875	0.050306

means	C-EPOXY
300 i	0.397285
600 i	0.397145
900 i	0.396866
1200 i	0.396718
1500 i	0.39706
1800 i	0.396927
2100 i	0.397055
2400 i	0.396903
2700 i	0.396853
3000 i	0.396725







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Appendiox C-5 C-EPOXY v/s PEEK comparison for Aircraft Wing Spoiler

C-EPOXY values for Spoiler

	Mtl cost	Handling	Dbase Ext	fg. Issue	Versatalty	quip Outla	fg. Issue	Process	Tooling	Labor	QA
Mean	0.030387	0.184768	0.017987	0.163584	0.048	0.070747	0.252866	0.171976	0.062542	0.111325	0.041394
Median	0.030286	0.186073	0.01556	0.163321	0.048	0.068129	0.252203	0.171333	0.062415	0.111312	0.041183
Mode	0.030286	0.187417	0.01556	#N/A	0.048	0.065738	#N/A	0.19275	0.0657	0.117892	0.041074
Std. Dev	0.008222	0.014531	0.0049	0.009692	0	0.011813	0.018584	0.024185	0.00681	0.012296	0.003889
Min.	0.017667	0.146238	0.012967	0.13232	0.048	0.047297	0.190867	0.106675	0.03942	0.073738	0.028747
Max.	0.045429	0.221436	0.03112	0.200275	0.048	0.113718	0.315329	0.261895	0.08541	0.146953	0.052643

P75-PEEK values for Spoiler

	Mtl cost	Handling	Dbase Ext	fg. Issue	Versatalty	quip Outla	fg. Issue	Process	Tooling	Labor	QA
Mean	0.075613	0.191134	0.059813	0.276702	0.048	0.180253	0.40033	0.342024	0.068858	0.151875	0.050306
Median	0.075714	0.189827	0.06224	0.276966	0.048	0.182871	0.400993	0.342667	0.068985	0.151888	0.050517
Mode	0.075714	0.188483	0.06224	#N/A	0.048	0.185262	#N/A	0.32125	0.0657	0.145308	0.050626
Std. Dev	0.008222	0.014531	0.0049	0.009892	0	0.011813	0.018584	0.024185	0.00681	0.012296	0.003889
Min.	0.060571	0.154464	0.04668	0.240011	0.048	0.137282	0.337867	0.252105	0.04599	0.116247	0.039057
Max.	0.088333	0.229662	0.064833	0.307966	0.048	0.203703	0.462329	0.407325	0.09198	0.189462	0.062953

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Appendix C-5 C-EPOXY v/s PEEK for Aircraft Wing Spoiler

Carbon-Epoxy v/s PEEK comparison for Boeing Spoiler, Classical Monte-Carlo Simul.

Th Level 1 Fact	Level 1 Weight	Level 2 Fact	Level 2 Weight	Level 3 F+E21act	Level 3 Weight	Level 4 Fact	Level 4 eig	Defender C-Epoxy Rank	Defender C-Epoxy Value	Challenger PEEK Rank	Challenger PEEK Value			original values Defend C-Epo Rank	original values Challenger PEEK Rank
Manufacturing Complexity Factor									0.3728		0.6272	1.0000			
Delta Cost Factor (Defender > Challenger) =									1.6825						
Mat Cost	0.106							1	0.2000	4	0.8000			2	5
Material Cost -- Complexity Factor									0.0212		0.0848	0.1060			
Handling	0.3759														
Handling Complexity Factor									0.1750		0.2009	0.3759	handling		
		P Temp	0.43553					1	0.0871	4	0.3484			2	5
		Txlity	0.28573					4	0.1633	3	0.1225			5	4
		P/S Life	0.19434	not applicable for peek				4	0.1555	1	0.0389			5	1
		O gas	0.0422					3	0.0317	1	0.0106			4	2
		Void P	0.0422					2	0.0281	1	0.0141			3	2
			1.0000												
Dbse Ext	0.0778							1	0.2500	3	0.7500		dbase	1	4
Database Extent Complexity Factor									0.0195		0.0584	0.0778			

Versatility: "sheer #" measure. the materials simply ranked a 1 for each process that it can be processed by. then values depend on sum of 1's. If def/chal have sums of x&y respectively, then s=(1/x+1/y) & the respective values are:
def=1/(x*s) and chal=1/(y*s)

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Appendix C-5 C-EPOXY v/s PEEK for Aircraft Wing Spoiler

Mfg. Iss 0.4402											
Manufacturing Issues ComplexityFactor					0.1571		0.2832	0.4403			
Versatility 0.096											
Versatility Factor					0.0480		0.0480	0.0960			
			s								
	Layup/Au	1	0.66667	1	0.5000	1	0.5000	1.0000	versat	1	1
	Drilling	1		1		1				1	1
	Ultrosonic	1		1	3	1	3			1	1
Equip Outl 0.251											
Equipment Outlay Factor					0.0711		0.1799	0.2510			
autoclave cost high, fig. 5-9	Layup/Au	5		1	0.1786	3	0.5357		equip ou	1	4
	Drilling	1		2	0.0571	3	0.0857			3	4
	Ultrosonic	1		1	0.0476	2	0.0952			2	3

Equipment Outlay. a measure incorporating the expense of a process. processes are individually rated between 1-5 on how expensive/complicated they are to operate. respective materials are rated on how compatible they are to the process in question -- same rating as given in the **Manuf.ability-process** sub-factor.

the calculation proceeds as normal.

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Appendix C-5 C-EPOXY v/s PEEK for Aircraft Wing Spoiler

Mfct-ility 0.653									
Manufacturability Issues Complexity Factor			0.2378		0.4154	0.6532			
Processe 0.514									
Processes Complexity Factor			0.1621		0.3519	0.5140			
Layup/Au	5	1	0.1042	3	0.3125		process	1	4
Drill/Debu	3	2	0.1000	3	0.1500			3	4
Inspect	4	1	0.1111	2	0.2222			2	3
Tool 0.1314									
Tooling Complexity Factor			0.0602		0.0712	0.1314			
Layup/Au	5	2	0.2083	2	0.2083		tooling	3	3
Drill/Debu	3	1	0.0833	2	0.1667			2	3
Inspect	4	2	0.1667	2	0.1667			3	3
Labor 0.2632									
Labor ComplexityFactor			0.1024		0.1608	0.2632			
Layup/Au	5	2	0.1389	4	0.2778		labor	3	5
Drill/Debu	3	1	0.0833	2	0.1667			2	3
Inspect	4	2	0.1667	2	0.1667			3	3
QA 0.0917									
QA Complexity Factor			0.0395		0.0522	0.0917			
Layup/Au	5	2	0.1389	4	0.2778		qa	3	5
Drill/Debu	3	2	0.1250	2	0.1250			3	3
Inspect	4	2	0.1667	2	0.1667			3	3

for peek, higher process temp. requires more autoclav/curing effort.

for peek & other tp's, stock should be machined equally on opposite faces, so effort more. but, coolant not nececssary, so .....

for peek, hand lay-up only. so, labor/qa should be high. also, tooling may be less. Figure 4-34.

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Appendix C-6 Epoxy v/s PEEK, General Comparison, Classical M-C, RESULTS

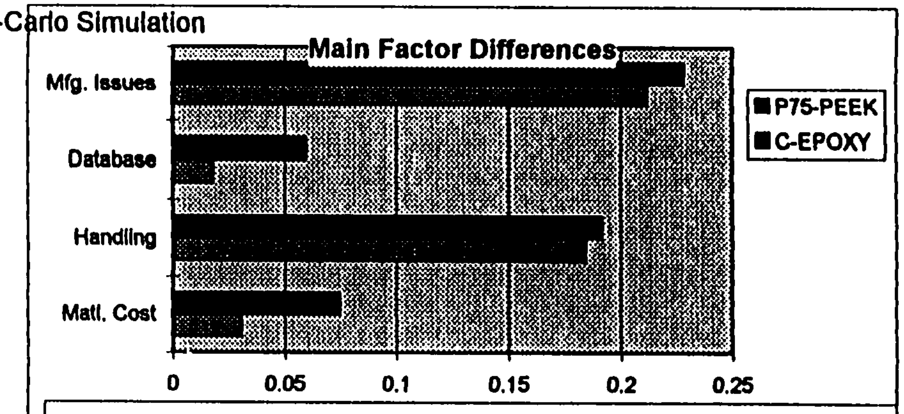
C-EPOXY v/s PEEK General Comparison, Classical Monte-Carlo Simulation

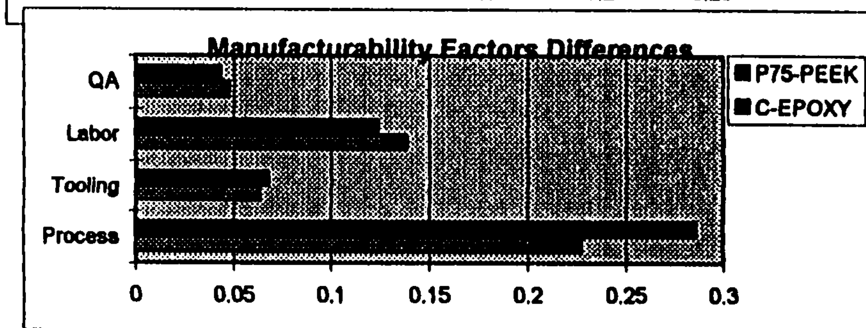
	MCF		DCF
	C-EPOXY	PEEK	
Mean	0.445	0.554986	1.24716
Median	0.445167	0.554819	1.24716
Mode			
Std. Dev.	0.018576	0.018576	
Min.	0.386998	0.494584	1.278001
Max.	0.505402	0.612988	1.212871

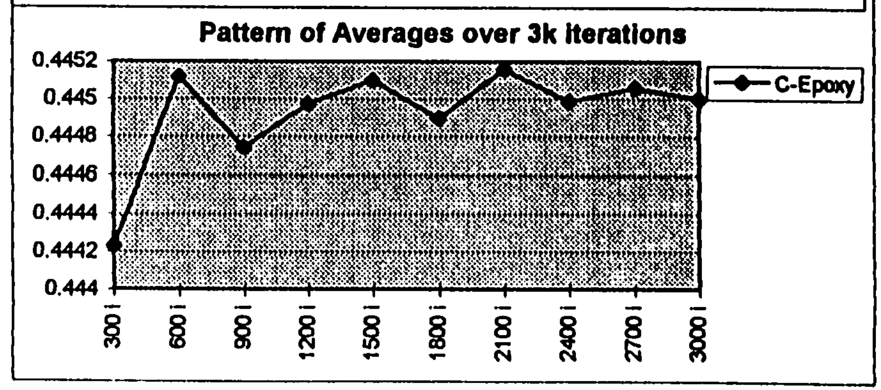
	Matl. Cost	Handling	Database	fg. Issues
C-EPOXY	0.030714	0.184302	0.018045	0.211939
P75-PEEK	0.075286	0.191598	0.059755	0.228347

	Process	Tooling	Labor	QA
C-EPOXY	0.227559	0.063658	0.139057	0.048041
P75-PEEK	0.286441	0.067742	0.124143	0.043659

means	C-Epoxy
300 i	0.44423
600 i	0.445119
900 i	0.444741
1200 i	0.444971
1500 i	0.445096
1800 i	0.444895
2100 i	0.445154
2400 i	0.444987
2700 i	0.445054
3000 i	0.445







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Appendix C-6 Epoxy v/s PEEK, General Comparison, Classical M-C, RESULTS

Statistics for C-EPOXY

	Matl. Cost	Handling	Database	fg. Issue	Versat	Equip. Out	Mfg.	Process	Tooling	Labor	QA
Mean	0.030714	0.184302	0.018045	0.211939	0.051692	0.117429	0.312339	0.227559	0.063658	0.139057	0.048041
Median	0.030286	0.185725	0.01556	0.211901	0.051692	0.117201	0.312008	0.227175	0.063635	0.139155	0.047973
Mode	0.030286	0.18145	0.01556	#N/A	0.051692	0.117307	#N/A	0.228784	0.064761	0.142567	0.047326
Std. Dev.	0.008168	0.014564	0.005021	0.005892	2.43E-09	0.008325	0.010715	0.014669	0.003172	0.006389	0.002477
Min.	0.017667	0.14157	0.012967	0.192087	0.051692	0.092968	0.269861	0.181509	0.051487	0.115098	0.038249
Max.	0.045429	0.220907	0.03112	0.23375	0.051692	0.146667	0.35155	0.285714	0.076129	0.160862	0.057745

Statistics for P75-PEEK

	Matl. Cost	Handling	Database	fg. Issue	Versat	Equip. Out	Mfg.	Process	Tooling	Labor	QA
Mean	0.075286	0.191598	0.059755	0.228347	0.044308	0.133571	0.340857	0.286441	0.067742	0.124143	0.043659
Median	0.075714	0.190175	0.06224	0.228385	0.044308	0.133799	0.341188	0.286825	0.067765	0.124045	0.043727
Mode	0.075714	0.19445	0.06224	#N/A	0.044308	0.133693	#N/A	0.280456	0.065335	0.123767	0.042878
Std. Dev.	0.008168	0.014564	0.005021	0.005892	7.62E-09	0.008325	0.010715	0.014669	0.003172	0.006389	0.002477
Min.	0.060571	0.154993	0.04668	0.206536	0.044308	0.104333	0.301645	0.228286	0.055271	0.102338	0.033955
Max.	0.088333	0.23433	0.064833	0.248199	0.044308	0.158032	0.383335	0.332491	0.079913	0.148102	0.053451

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Appendix C-6 General Comparison between C-Epoxy and PEEK

General Comparison between carbon fiber (Fibrite 934)-epoxy and P75/PEEK -- Old 1&5 values

T Level 1 Fact	Level 1 Weight	Level 2 Fact	Level 2 Weight	Level 3 F+E21act	Level 3 Weight	Level 4 Fact	Level 4 eig	Defender Carbon-Epoxy Rank	Defender Carbon-Epoxy Valu	Challenger PEEK Rank	Challenger PEEK Valu		Defend Carbon-E Rank	alleng PEEK Rank
Manufacturing Complexity Factor									0.4364		0.5636	1.0000	ORIGINAL VALUES	
Delta Cost Factor (Defender > Challenger) =									1.2916					
Mat Cost	0.106							1	0.2000	4	0.8000		2	5
Material Cost -- Complexity Factor									0.0212		0.0848	0.1060		
												mtl. cost		
Handling	0.3759													
Handling Complexity Factor									0.1750		0.2009	0.3759		
												handling		
		P Temp	0.43553					1	0.0871	4	0.3484		2	5
		Toxicity	0.28573					4	0.1633	3	0.1225		5	4
		P/S Life	0.19434	Pot life not applicable for PEEK				4	0.1555	1	0.0389		5	1
		Outgassin	0.0422					3	0.0317	1	0.0106		4	2
		Void Pres	0.0422					2	0.0281	1	0.0141		3	2
			1.0000											
Dbse Ext	0.0778							1	0.2500	3	0.7500		1	4
Database Extent Complexiity Factor									0.0195		0.0584	0.0778		
												dbase extent		

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Appendix C-6 General Comparison between C-Epoxy and PEEK

Mfg Iss 0.4402

Manufacturing Issues ComplexityFactor				0.2207		0.2196	0.4403 mgf. complexity		
Versatality 0.096									
Versatality Factor				0.0517		0.0443	0.0960 versatility		
		s							
Layup F	1	0.30952	1	0.5385	1	0.4615	1.0000	1	1
RTM	1		1		0			1	0
CM-disc	1		1		0			1	0
CM-cont	1		1		1			1	1
FW	1		1		1			1	1
Pult	1		1		1			1	1
ThermF	1		0		1			0	1
Dia M	1		0		1			0	1
Inj M	1		0	6	1	7		0	1

Versatality: "sheer #" measure. the matls simply ranked a 1 for each procs. it can be procsd by. then values depend on sum of 1's. If def/chal have sums of x&y, then s=(1/x+1/y) & resp. values are: def=1/(x*s) and chal=1/(y*s)

Eqip Outly 0.251

0

Equipment Outlay Factor				0.1275		0.1235	0.2510 equip. outlay		
Layup F	5		1	0.0806	1	0.0806		1	2
RTM	3	n/a for peek	2	0.0387	3	0.0581		3	5
CM-dis	2		1	0.0161	3	0.0484		1	5
CM-cont	5		1	0.0806	1	0.0806		1	2
FW	3		1	0.0323	2	0.0645		1	3
Pult	3		1	0.0323	2	0.0645		2	3
ThermF	3	n/a for Gr-epoxy	3	0.0581	2	0.0387		5	3
Dia M	5		3	0.1210	1	0.0403		5	2
Inj M	2		3	0.0484	1	0.0161		5	1

Equipment Outlay. a measure incorporating the expense of a process. processes are individually rated between 1-5 on how expensive/complicated they are to operate. respective materials are rated on how compatable they are to the process in question -- same rating as given in the **Manuf.ability-process** sub-factor.
the calculation proceeds as normal.

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Appendix C-6 General Comparison between C-Epoxy and PEEK

Mfct-ility 0.653									
Manufacturability Issues Complexity Factor				0.3221		0.3311	0.6532		
							mfg. issues		
Processe 0.514									
Processes Complexity Factor				0.2437		0.2703	0.5140		
							process		
	Layup F	3	1	0.0556	1	0.0556		1	2
	RTM	3	2	0.0444	3	0.0667		3	5
	CM -disc	3	1	0.0278	3	0.0833		1	5
	CM -cont	3	1	0.0556	1	0.0556		1	2
	FW	3	1	0.0370	2	0.0741		1	3
	Pult	3	1	0.0370	2	0.0741		2	3
	ThermF	3	3	0.0667	2	0.0444		5	3
	Dia M	3	3	0.0833	1	0.0278		5	2
	Inj M	3	3	0.0667	2	0.0444		5	3
Tool 0.1314									
Tooling Complexity Factor				0.0622		0.0692	0.1314		
							tooling		
	Layup F	3	1	0.0429	1	0.0429		2	2
	RTM	3	2	0.0343	3	0.0514		3	5
	CM-disc	5	2	0.0571	3	0.0857		3	5
	CM-cont	5	2	0.0476	4	0.0952		3	5
	FW	3	1	0.0429	1	0.0429		2	2
	Pult	5	4	0.0714	4	0.0714		5	5
	ThermF	3	3	0.0514	2	0.0343		5	3
	Dia M	3	3	0.0643	1	0.0214		5	2
	Inj M	5	3	0.0612	4	0.0816		5	5

Tooling Cost has an influence on weights

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Appendix C-6 General Comparison between C-Epoxy and PEEK

Labor weights dependent on labor involvement/cost in respective processes

Labor 0.2632

Labor ComplexityFactor			0.1391		0.1241	0.2632		
						labor		
Layup F	5	4	0.0833	4	0.0833		5	5
RTM	4	2	0.0533	3	0.0800		3	5
CM-disc	3	2	0.0400	3	0.0600		3	5
CM-cont	5	2	0.0833	2	0.0833		3	3
FW	3	3	0.0600	2	0.0400		4	3
Pult	2	1	0.0333	1	0.0333		2	1
ThermF	3	3	0.0750	1	0.0250		5	2
Dia M	3	3	0.0600	2	0.0400		5	3
Inj M	2	3	0.0400	2	0.0267		5	3

QA 0.0917

QA Complexity Factor			0.0484		0.0433	0.0917		
						qa		
Layup F	3	2	0.0556	2	0.0556		3	3
RTM	3	3	0.0556	3	0.0556		4	5
CM-disc	3	2	0.0444	3	0.0667		3	5
CM-cont	3	2	0.0556	2	0.0556		3	3
FW	3	1	0.0556	1	0.0556		2	2
Pult	3	1	0.0556	1	0.0556		1	1
ThermF	3	3	0.0833	1	0.0278		5	2
Dia M	3	3	0.0556	3	0.0556		5	4
Inj M	3	3	0.0667	2	0.0444		5	3

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Appendix C-7 Comparison between Carbon-EPOXY and Al-Li for spoiler End-Rib

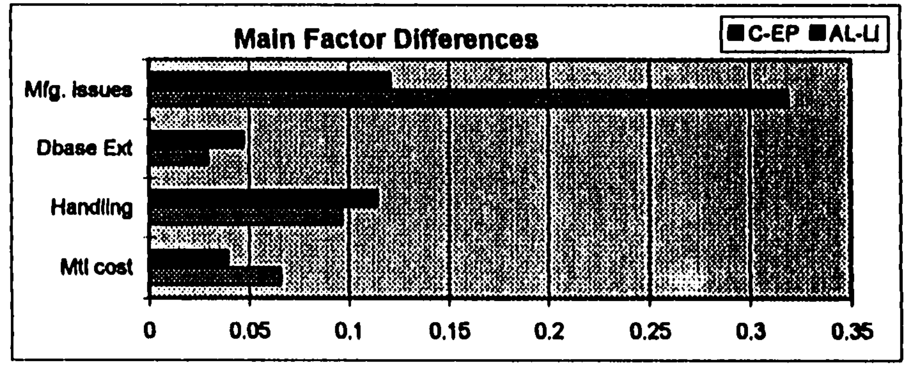
C-EPOXY v/s Al-Li 2090 comparison for spoiler End-rib

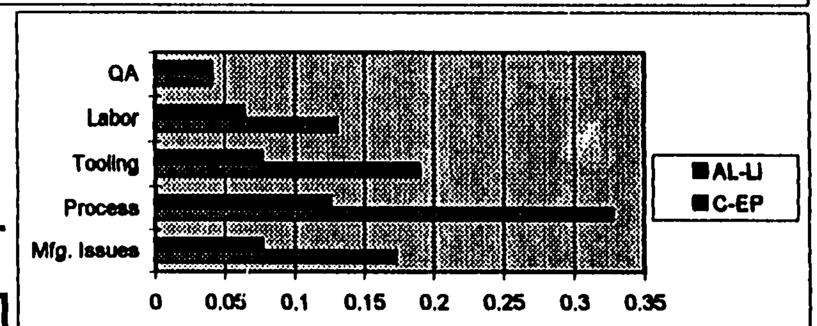
	MCF		DCF
	C-EP	Al-Li	
1st value	0.513841	0.321367	0.62542
Mean	0.511817	0.323391	0.631849
Median	0.514436	0.320772	0.623541
Mode	#N/A	#N/A	#N/A
Std. Dev.	0.022199	0.022199	
Min.	0.42743	0.25857	0.604941
Max.	0.576638	0.407778	0.707164

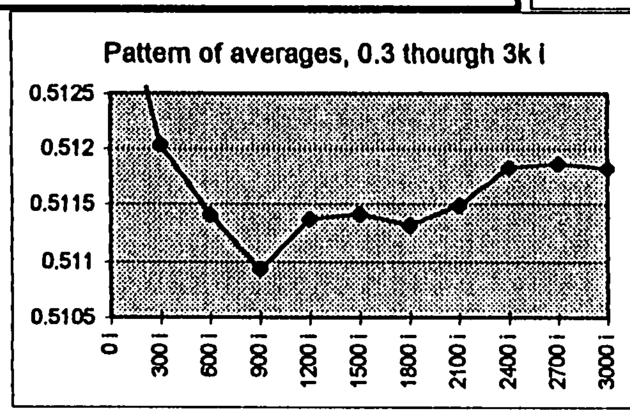
	Mtl cost	Handling	Dbase Ext	fg. issues
C-EP	0.06624	0.096631	0.029924	0.319023
AL-Li	0.03976	0.114577	0.047876	0.121177
DCF	0.600253	1.185725	1.599922	0.379839

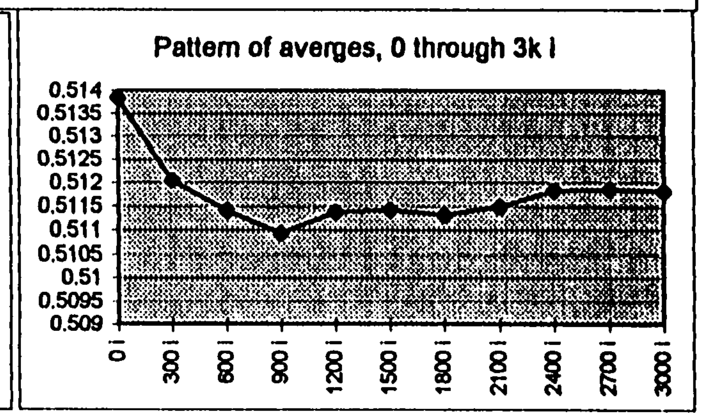
	fg. Issue	Process	Tooling	Labor	QA
C-EP	0.173374	0.327875	0.190466	0.131152	0.04125
AL-Li	0.077623	0.125893	0.077252	0.06479	0.041323
DCF	0.447718	0.383968	0.405593	0.49401	1.001759

means	C-EPOXY
0 i	0.513841
300 i	0.512035
600 i	0.511406
900 i	0.510933
1200 i	0.511368
1500 i	0.511414
1800 i	0.511315
2100 i	0.511487
2400 i	0.511825
2700 i	0.511859
3000 i	0.511817









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Appendix C-7 Comparison between Carbon-EPOXY and Al-Li for spoiler End-Rib

DEFENDER -- C-Epoxy

	Mtl cost	Handling	Dbase Ext	fg. Issue	Versatility	quip Outla	fg. Issue	Process	Tooling	Labor	QA
1st. val	0.06625	0.094236	0.025933	0.327422	0.048006	0.522393	0.173404	0.327721	0.191227	0.130628	0.041286
Mean	0.06624	0.096631	0.029924	0.319023	0.048006	0.503342	0.173374	0.327875	0.190466	0.131152	0.04125
Median	0.06625	0.095678	0.025933	0.325071	0.048006	0.522393	0.173404	0.327721	0.191227	0.130628	0.041286
Mode	0.06625	0.094236	0.025933	0.327422	0.048006	0.522393	0.173404	0.327721	0.191227	0.130628	0.041286
Std. Dev.	0.002312	0.009509	0.008712	0.018029	0	0.04016	0.008095	0.016062	0.020605	0.017979	0.007055
Min.	0.061833	0.071727	0.01945	0.259748	0.048006	0.391795	0.146813	0.306441	0.152981	0.097971	0.027524
Max.	0.070667	0.132914	0.051867	0.346762	0.048006	0.54416	0.19722	0.352178	0.223098	0.163285	0.055048

CHALLENGER -- Al-Li

	Mtl cost	Handling	Dbase Ext	fg. Issue	Versatility	quip Outla	fg. Issue	Process	Tooling	Labor	QA
1st value	0.03975	0.116972	0.051867	0.112778	0.048006	0.130598	0.077593	0.126047	0.076491	0.065314	0.041286
Mean	0.03976	0.114577	0.047876	0.121177	0.048006	0.149649	0.077623	0.125893	0.077252	0.06479	0.041323
Median	0.03975	0.115529	0.051867	0.115129	0.048006	0.130598	0.077593	0.126047	0.076491	0.065314	0.041286
Mode	0.03975	0.116972	0.051867	0.112778	0.048006	0.130598	0.077593	0.126047	0.076491	0.065314	0.041286
Std. Dev.	0.002312	0.009509	0.008712	0.018029	0	0.04016	0.008095	0.016062	0.020605	0.017979	0.007055
Min.	0.035333	0.078294	0.025933	0.093438	0.048006	0.108832	0.053777	0.10159	0.04462	0.032657	0.027524
Max.	0.044167	0.13948	0.05835	0.180452	0.048006	0.261197	0.104185	0.147327	0.114736	0.097971	0.055048

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Appendix C-7 C-EPOXY v/s Al-Li comparison for Boeing Spoiler End-Rib

Comparison between C-Epoxy and Al-Li over Spoiler end-rib -- classical monte-carlo simulation

Level 1 Fact	Level 1 Weight	Level 2 Fact	Level 2 Weight	Level 3 Fact	Level 3 Weight	Level 4 Fact	Level 4 eig	Defender FiberG-Epoxy Rank	Defender FiberG-Epoxy Value	Challenger AL-LI 2090 Rank	Challenger AL-LI 2090 Value			Defend FiberG-E	Challenger AL-LI 20
Manufacturing Complexity Factor									0.5273		0.3079	0.8352			
Delta Cost Factor (Defender > Challenger) =									0.5839						
Mat Cost	0.106							70	0.6364	40	0.3636			75	45
Material Cost -- Complexity Factor									0.0675		0.0385	0.1060			
Handling	0.3759														
Handling Complexity Factor									0.1008		0.1104	0.2112			
		Pot/Shelf Life	0.0431	(n/a for Al-Li)				4	0.0344	1	0.0086		handling	5	1
		Process Temperatu	0.0803					2	0.0535	1	0.0268			3	2
		Toxicity	0.0683	Al-Li 1 because of no reference to				5	0.0569	1	0.0114			5	1
		Ingot / Tape Qual.	0.1145					1	0.0382	2	0.0763			2	3
		Scrap Disposal	0.2557					1	0.0852	2	0.1705			1	3
			0.5619												
Dbse Ext	0.0778							1	0.5000	1	0.5000		dbase	1	2
Database Extent Complexity Factor									0.0389		0.0389	0.0778			

FORMULAE

ORIGINAL VALUES

Costs are approximate, 1994 dollars, and can vary based on negotiations, and quantity requirements.

Process Temperature: TP's Tg is 50-100 deg F below Tg for Thermosets. Also, service temp. depends on moisture resistance. As epoxy has bad moist resistance, its process temp. is also bad.

For the end-rib, Fiberglass-EPOXY, gave problems with the pre-preg tapes. These problems were later resolved. So some problems, 2.

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Appendix C-7 C-EPOXY v/s Al-Li comparison for Boeing Spoiler End-Rib

Mfg. Iss 0.4402										
Manufacturing Issues ComplexityFactor				0.3201		0.1201	0.4402			
Versatility 0.09601										
Versatility Factor				0.0480		0.0480	0.0960			
		s								
Gen. Versatility	1	2	1	0.5000	1	0.5000	1.0000	versat	1	1
	0		0	1	0	1			0	0
Equip Outl 0.65299										
Equipment Outlay Factor				0.4897		0.1632	0.6530			
Gen. Equip. Outlay	3		3	0.7500	1	0.2500		equip ou	4	1
	0		99	0.0000	99	0.0000			1	1

!!!!! FOR THIS COMPARISON ONLY !!!!!
EQUIPMENT OUTLAY and **VERSATILITY** Factors Should have no sub-factors because there are no specific processes to compare the two materials against. The two cadidates should be ranked against each other "in gneral". The basis is the number of process steps to be taken to fabricate the part, and their respective outlay. That is, in general, gr-epoxy needs only 3 basic steps to fabricate the rib -- layup, autoclave and trim. So, versatility for this application is 1. However, layup-autoclave is by-far an expensive process, and so equip. outlay is 4. Similarly, Al-Li needs 4 steps -- stamping of 2 different prices, cut, bend and weld. However, they are all mostly very common process steps and equipment. So, Al-Li is a 1 on versatility and 1 on equip. outlay -- FOR THIS PARTICULAR PART.

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Appendix C-7 C-EPOXY v/s Al-Li comparison for Boeing Spoiler End-Rib

Mfct-ility 0.251										
Manufacturability Issues Complexity Factor				0.1894		0.0616	0.2510			
Processe 0.4538										
Processes Complexity Factor				0.3522		0.1016	0.4538			
	Hours to fabricate	3	5.2	0.7761	1.5	0.2239		process	5.2	2
		0	99	0.0000	99	0.0000			99	99
Tool 0.2677										
Tooling Complexity Factor				0.2142		0.0535	0.2677			
	Tooling complexity	3	4	0.8000	1	0.2000		tooling	5	2
		0	99	0.0000	99	0.0000			99	99
Labor 0.1959										
Labor ComplexityFactor				0.1470		0.0490	0.1959			
	Labor Involved	3	3	0.7500	1	0.2500		labor	4	2
		0	99	0.0000	99	0.0000			99	99
QA 0.0826										
QA Complexity Factor				0.0413		0.0413	0.0826			
	QA carried out	3	2	0.5000	2	0.5000		qa	3	3
		0	99	0.0000	99	0.0000			99	99

Process Complexity is based on the actual time taken to fabricate this part. 1.5 hrs for Al, AL-Li would require a little more because of anistorpic properties, which require special attention. Also, in welding, "operators need to view every inch of weld as it is deposited" Kuvin, Welding Design & Fabrication, July

Difficulty in seting up the tooling

Labor involved in fabricating the part. Ge-EP is 4 on labor. Little less because of the tool available, not too less, because tool needs to be set-up. Al-Li requires orientation of the part before stamping. So, its labor is

QA efforts would be equally rigorous on both parts. Both would be 100% inspected, some parts subjected to destructive testing, etc. etc.

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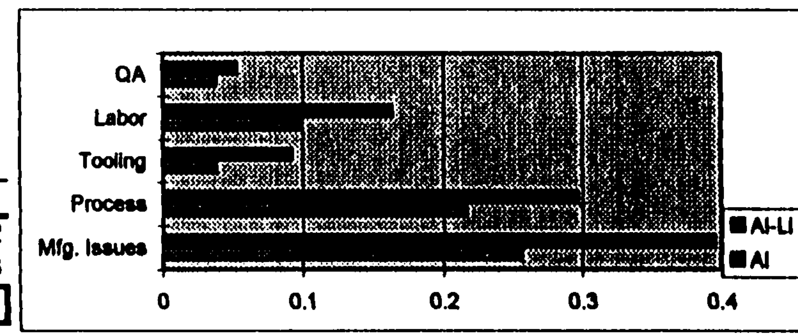
Appendix C-8 Al v/s Al-Li, General Comparison.

Al v/s Al-Li GENERAL comparison

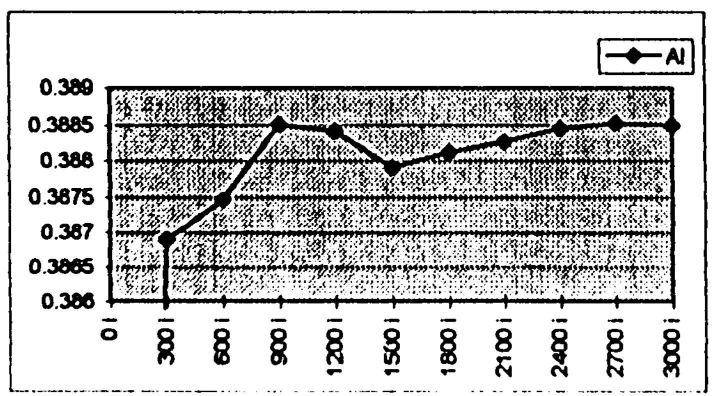
	MCF		DCF
	Al	Al-Li	
1st. Value	0.364527	0.63546	1.743246
Mean	0.388495	0.611491	1.573997
Median	0.38737	0.612616	1.581474
Mode	#N/A	#N/A	#N/A
Std. Dev.	0.022626	0.022626	
Min.	0.324467	0.52418	1.61551
Max.	0.475807	0.675519	1.419735

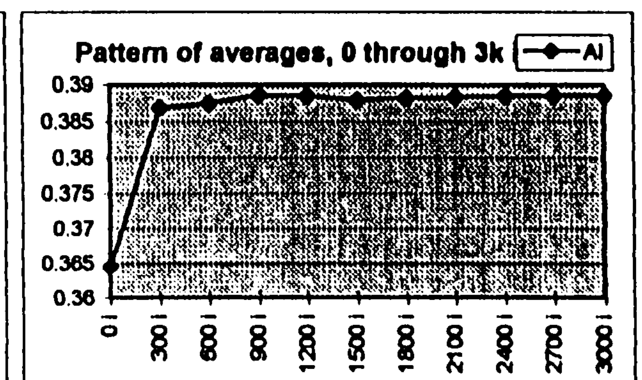
	Mtl cost	Handling	Dbase Ext	fg. Issues
Al	0.027848	0.148347	0.030226	0.182075
Al-Li	0.078152	0.227553	0.047574	0.258212
DCF	2.80634	1.533923	1.573977	1.418164

	fg. Issue	Process	Tooling	Labor	QA
Al	0.256927	0.216859	0.038949	0.099337	0.038312
Al-Li	0.396268	0.297141	0.092451	0.163863	0.053388
DCF	1.542336	1.370202	2.373672	1.649554	1.393521



means	Al
0 i	0.364527
300 i	0.386898
600 i	0.387456
900 i	0.388508
1200 i	0.388416
1500 i	0.387911
1800 i	0.38812
2100 i	0.388267
2400 i	0.388449
2700 i	0.388525
3000 i	0.388495





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Appendix C-8 Al v/s Al-Li, General Comparison.

DEFENDER -- Al 2024 -- VALUES for general comparison

	Mtl cost	Handling	Dbase Ext	fg. Issue	Versatalty	quip Outla	fg. Issue	Process	Tooling	Labor	QA
1st. Value	0.0265	0.140763	0.025933	0.171331	0.048	0.102048	0.239163	0.201317	0.035259	0.092997	0.03668
Mean	0.027848	0.148347	0.030226	0.182075	0.048	0.10869	0.256927	0.216859	0.038949	0.099337	0.038312
Median	0.0265	0.147397	0.025933	0.181997	0.048	0.10864	0.256871	0.216737	0.038763	0.099139	0.038208
Mode	0.0212	0.140763	0.025933	#N/A	0.048	0.115992	0.264606	0.21845	0.035916	0.096068	0.038973
Std. Dev.	0.008999	0.017386	0.008729	0.006396	0	0.008375	0.012122	0.016804	0.003082	0.007092	0.002344
Min.	0.017667	0.095571	0.01945	0.161373	0.048	0.082399	0.214279	0.160197	0.030222	0.076328	0.030108
Max.	0.053	0.208746	0.051867	0.212221	0.048	0.139698	0.3067	0.2827	0.051277	0.129845	0.047378

CHALLENGER Al-Li values for GENERAL COMPARISON

	Mtl cost	Handling	Dbase Ext	fg. Issue	Versatalty	quip Outla	fg. Issue	Process	Tooling	Labor	QA
1st. Value	0.0795	0.235137	0.051867	0.268955	0.048	0.148952	0.414033	0.312683	0.096141	0.170203	0.05502
Mean	0.078152	0.227553	0.047574	0.258212	0.048	0.14231	0.396268	0.297141	0.092451	0.163863	0.053388
Median	0.0795	0.228503	0.051867	0.258289	0.048	0.14236	0.396325	0.297263	0.092637	0.164061	0.053492
Mode	0.0848	0.235137	0.051867	#N/A	0.048	0.140712	0.38859	0.291267	0.096141	0.167132	0.054256
Std. Dev.	0.008999	0.017386	0.008729	0.006396	0	0.008375	0.012122	0.016804	0.003082	0.007092	0.002344
Min.	0.053	0.167154	0.025933	0.228065	0.048	0.111302	0.346496	0.2313	0.080123	0.133355	0.044322
Max.	0.088333	0.280329	0.05835	0.278913	0.048	0.168601	0.438917	0.353803	0.101178	0.186872	0.061592

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Appendix C-8 General comparison between conventional Aluminum and Aluminum-Lithium

Generic comparison between al ad al-li -- classical monte-carlo simulation								GENERAL COMPARISON						GENERAL COMPARISON	
T Level 1		Level 2		Level 3		Level 4		Defender AL - 2024		Challenger AL-LI 2090				Defend AL - 20	Challenger -LI 2090
Fact	Weight	Fact	Weight	Fact	Weight	Fact	eig	Rank	Value	Rank	Value			Rank	Rank
Manufacturing Complexity Factor									0.3645		0.6355	1.0000		ORIGINAL VALUES	
Delta Cost Factor (Defender > Challenger) =									1.7432						
Mat Cost	0.106			3-4 times more expensive				1	0.2500	3	0.7500			1	3
Material Cost -- Complexity Factor									0.0265		0.0795	0.1060			
Handling	0.3759					2									
Handling Complexity Factor									0.1408		0.2351	0.3759	handling		
		Ductility	0.04899		0.1782			1	0.0245	1	0.0245			1	1
		S/B Stren	0.2118					2	0.1412	1	0.0706			2	1
		Weld Stre	0.28764					1	0.0959	2	0.1918			1	2
		Extra Han	0.09225	4 is actually 3-4, so simulate accor				1	0.0231	3	0.0692			1	3
		Ingot Qual	0.17816					1	0.0445	3	0.1336			1	3
		Scrap	0.18116					1	0.0453	3	0.1359			1	3
			1.0000												
Dbse Ext	0.0778							1	0.3333	2	0.6667		dbase	1	2
Database Extent Complexity Factor									0.0259		0.0519	0.0778			

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Appendix C-8 General comparison between conventional Aluminum and Aluminum-Lithium

Mfg. Iss	0.4402									
Manufacturing Issues ComplexityFactor				0.1713		0.2690	0.4403			

Versatility	0.096									
Versatility Factor				0.0480		0.0480	0.0960			
		s								
Forging	1	0.2	1	0.5000	1	0.5000	1.0000	versat	1	1
Extrusion	1		1		1				1	1
Conventional Millin	1		1		1				1	1
Chemical Milling	1		1		1				1	1
Press Brake Formi	1		1		1				1	1
Streach Forming	1		1		1				1	1
Riveting/Fastening	1		1		1				1	1
Welding	1		1		1				1	1
Heat Treating	1		1		1				1	1
Cleaning/Finishing	1		1	10	1	10			1	1

Equip Outl	0.251									
Equipment Outlay Factor				0.1020		0.1490	0.2510			
Forging	1		1	0.0101	2	0.0202		equip ou	1	2
Extrusion	2		1	0.0202	2	0.0404			1	2
Conventional Millin	4		1	0.0606	1	0.0606			1	1
Chemical Milling	4		1	0.0606	1	0.0606			1	1
Pres Brke Forming	4		1	0.0404	2	0.0808			1	2
Strch Forming	4		1	0.0404	2	0.0808			1	2
Riveting/Fastening	3		1	0.0455	1	0.0455			1	1
Welding	3		1	0.0303	2	0.0606			1	2
Heat Treating	3		1	0.0227	3	0.0682			1	3
Cleaning/Finishing	5		1	0.0758	1	0.0758			1	1

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Appendix C-8 General comparison between conventional Aluminum and Aluminum-Lithium

Mfct-ility 0.653									
Manufacturability Issues Complexity Factor			0.2392		0.4140	0.6532			
Processe 0.514									
Processes Complexity Factor			0.2013		0.3127	0.5140			
Forging	3	1	0.0333	2	0.0667		process	1	2
Extrusion	3	1	0.0333	2	0.0667			1	2
Conventional Milli	3	1	0.0500	1	0.0500			1	1
Chemical Milling	3	1	0.0500	1	0.0500			1	1
Press Brake Formi	3	1	0.0333	2	0.0667			1	2
Streach Forming	3	1	0.0333	2	0.0667			1	2
Riveting/Fastening	3	1	0.0500	1	0.0500			1	1
Welding	3	1	0.0333	2	0.0667			1	2
Heat Treating	3	1	0.0250	3	0.0750			1	3
Cleaning/Finishing	3	1	0.0500	1	0.0500			1	1
Tool 0.1314									
Tooling Complexity Factor			0.0353		0.0961	0.1314			
Forging	3	1	0.0167	5	0.0833		tooling	1	5
Extrusion	3	1	0.0167	5	0.0833			1	5
Conventional Milli	3	1	0.0250	3	0.0750			1	3
Chemical Milling	3	1	0.0200	4	0.0800			1	4
Press Brake Formi	3	1	0.0200	4	0.0800			1	4
Streach Forming	3	1	0.0167	5	0.0833			1	5
Riveting/Fastening	3	1	0.0500	1	0.0500			1	1
Welding	3	1	0.0200	4	0.0800			1	4
Heat Treating	3	1	0.0333	2	0.0667			1	2
Cleaning/Finishing	3	1	0.0500	1	0.0500			1	1

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Appendix C-8 General comparison between conventional Aluminum and Aluminum-Lithium

Labor	0.2632								
Labor ComplexityFactor				0.0930		0.1702	0.2632		
	Forging	3	1	0.0500	1	0.0500	labor	1	1
	Extrusion	3	1	0.0500	1	0.0500		1	1
	Conventional Milli	3	1	0.0250	3	0.0750		1	3
	Chemical Milling	3	1	0.0250	3	0.0750		1	3
	Press Brake Formi	3	1	0.0250	3	0.0750		1	3
	Streach Forming	3	1	0.0500	1	0.0500		1	1
	Riveting/Fastening	3	1	0.0200	4	0.0800		1	4
	Welding	3	1	0.0333	2	0.0667		1	2
	Heat Treating	3	1	0.0250	3	0.0750		1	3
	Cleaning/Finishing	3	1	0.0500	1	0.0500		1	1

QA	0.0917								
QA Complexity Factor				0.0367		0.0550	0.0917		
	Forging	3	1	0.0333	2	0.0667	qa	1	2
	Extrusion	3	1	0.0333	2	0.0667		1	2
	Conventional Milli	3	1	0.0500	1	0.0500		1	1
	Chemical Milling	3	1	0.0500	1	0.0500		1	1
	Press Brake Formi	3	1	0.0250	3	0.0750		1	3
	Streach Forming	3	1	0.0333	2	0.0667		1	2
	Riveting/Fastening	3	1	0.0500	1	0.0500		1	1
	Welding	3	1	0.0500	1	0.0500		1	1
	Heat Treating	3	1	0.0250	3	0.0750		1	3
	Cleaning/Finishing	3	1	0.0500	1	0.0500		1	1

Process	Covered in		
	LOX	kin/Str	Neither
Forging			X
Extrusion			X
Conventional Milli	X		
Chemical Milling		X	
Pres Brke Formin	X		
Strch Forming		X	
Riveting/Fastenin	X		
Welding		X	
Heat Treating		X	
Cleaning/Finishing	X	X	

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Appendix D ANOVA Results

ANOVA results: DCF values and Al's MCF values.

Same ranks -- LOX tank -- across three different ahp weights

ANOVA: Single Factor, alpha = 0.05 for DCF values, LOX tank

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
ORIGINAL	3001	4494.117606	1.497540022	0.019583414
EQUAL	3001	4994.504346	1.664280022	0.061453167
NEW	3001	4783.329412	1.593911833	0.039625607

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	42.0554494	2	21.0277247	522.8081426	1.5727E-215	2.996728199
Within Groups	361.9865624	9000	0.040220729			
Total	404.0420118	9002				

Tuckey's Procedure, the "*T*" Method

I = 3, L = 3001

Q(alpha, I, I(J-1) =	Q(0.05,3,inf.)=	3.31
	MSE =	0.040220729
	MSE/J =	1.34024E-05
	sqrt(MSE/J) =	0.003660935
w = Q * sqrt(MSE/J	w =	0.012117694

Since all three means differ bu MUCH more than w (0.0121), they are significantly different from each other.

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Appendix D ANOVA Results

ANOV: Single Factor, alpha = 0.05 for Al's MCF values, LOX tank

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
ORIGINAL	3001	1205.347818	0.401648723	0.000509249
EQUAL	3001	1136.491622	0.378704306	0.001315122
NEW	3001	1163.854419	0.387822199	0.00089938

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.801021927	2	0.400510964	441.1316864	1.7274E-183	2.996728199
Within Groups	8.171253129	9000	0.000907917			
Total	8.972275056	9002				

Tuckey's Procedure, the "*T*" Method

	I = 3, L = 3001	
Q(alpha, I, I(J-1) =	Q(0.05,3,Inf.)=	3.31
	MSE =	0.000907917
	MSE/J =	3.02538E-07
	sqrt(MSE/J) =	0.000550035
w = Q * sqrt(MSE/J	w =	0.001820615

Since all three means differ bu MUCH more than w (0.002), they are significantly different from each other.

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Appendix D ANOVA Results

Same ranks -- skin/stringer assembly -- across three different ahp weights

ANOV: Single Factor, alpha = 0.05 for DCF values for skin/stringer assembly

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
ORIGINAL	3001	4136.918991	1.378513493	0.021274994
EQUAL	3001	4862.546305	1.620308665	0.065700875
NEW	3001	4683.329176	1.560589529	0.053028336

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	95.21469152	2	47.60734576	1020.126768	0	2.996728199
Within Groups	420.0126152	9000	0.046668068			
Total	515.2273067	9002				

ANOV: Single Factor, alpha = 0.05 for Al's MCF values for skin/stringer assembly

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
ORIGINAL	3001	1266.505127	0.4220277	0.000680212
EQUAL	3001	1156.578341	0.385397648	0.001485253
NEW	3001	1181.633888	0.393746714	0.00127642

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.212018877	2	1.106009438	964.0148395	0	2.996728199
Within Groups	10.32565531	9000	0.001147295			
Total	12.53767419	9002				

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Appendix D ANOVA Results

Same weights across two different ranks, LOX and skin/stringer

ANOV: Single Factor, alpha = 0.05 for DCF values for ORIGINAL weights

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
LOX tank	3001	4494.117606	1.497540022	0.019583414
S/S assy	3001	4136.918991	1.378513493	0.021274994

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	21.25805575	1	21.25805575	1040.571928	1.1416E-210	3.843013019
Within Groups	122.5752214	6000	0.020429204			
Total	143.8332772	6001				

ANOV: Single Factor, alpha = 0.05 for DCF values for EQUAL weights

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
LOX tank	3001	4994.504346	1.664280022	0.061453167
S/S Assy	3001	4862.546305	1.620308665	0.065700875

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.901187056	1	2.901187056	45.63263599	1.56091E-11	3.843013019
Within Groups	381.462126	6000	0.063577021			
Total	384.3633131	6001				

Tuckey's Procedure, the "*T*" Method Q(alpha, I, I(J- (0.05,3,inf.)= 2.77 w = Q * sqrt(

I = 3, L = 3001

MSE = 0.063577021

MSE/J = 2.11853E-05

sqrt(MSE/J) = 0.004602747

w = 0.01275

In this case, the two means differ by 0.044, while the w value is 0.015, so they are still different from each other, although not as significantly as in the earlier cases.

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Appendix D ANOVA Results

Same weights across same ranks, different simulation runs.

ANOV: Single Factor, alpha = 0.05 for AI's Processing values on LOX, for three different runs where where weights for the Process sub-factor were unchanged

SUMMARY

Groups	Count	Sum	Average	Variance
ORIGINAL	3001	608.9951548	0.202930741	0.000477513
EQUAL	3001	608.929681	0.202908924	0.000455226
NEW	3001	608.9738911	0.202923656	0.000482746

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	7.43474E-07	2	3.71737E-07	0.000787865	0.999212445	2.996728199
Within Groups	4.246453735	9000	0.000471828			
Total	4.246454478	9002				

In both these cases, F is less than Script. which indicates that there are no differences between the averages for the three runs.

ANOV: Single Factor, alpha = 0.05 for AI's Processing values on skin/stringer, for three different runs where where weights for the Process sub-factor were unchanged

SUMMARY

Groups	Count	Sum	Average	Variance
ORIGINAL	3001	722.7843524	0.240847835	0.00040907
EQUAL	3001	722.9618048	0.240906966	0.000421863
NEW	3001	721.1297619	0.240296488	0.000436823

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.000680389	2	0.000340194	0.80503116	0.447106186	2.996728199
Within Groups	3.803268222	9000	0.000422585			
Total	3.803948611	9002				

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Appendix D ANOVA Results

ANOV: Single Factor for s/s adapter v/s LOX tank v/s C-EPOXY gen. comparison
same weights, different ranks, for 10,000 iterations

SUMMARY

Groups	Count	Sum	Average	Variance
s/s assy	10001	4229.285949	0.422886306	0.000714647
LOX tank	10001	3977.74221	0.397734448	0.000557822
C-EPOXY	10001	4453.060284	0.445261502	0.000335677

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.30808512	2	5.654042562	10547.62592	0	2.996031867
Within Groups	16.08146497	30000	0.000536049			
Total	27.3895501	30002				

ANOVA RESULTS FOR TWO VALIDITY RUNS: S/S & NO COST. Input data from files: VSNC AND VSNC2

ANOV: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Old Wts.	3001	1359.972532	0.45317312	0.000475638
New Wts.	3001	1323.050718	0.440868949	0.000865714

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.227127678	1	0.227127678	338.6549884	1.28856E-73	3.843013019
Within Groups	4.024054325	6000	0.000670676			
Total	4.251182004	6001				

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Appendix D ANOVA Results

These two comparisons are for ALSC and ALSC2: Same main factor and new sub-factor weights.
ANOV: Single Factor, Comparison between MCF AI values for s/s adapte

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Old Wts	3001	1266.505127	0.4220277	0.000680212
New subWts	3001	1191.803798	0.397135554	0.000408225

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.929738177	1	0.929738177	1708.39111	0	3.843013019
Within Groups	3.265311457	6000	0.000544219			
Total	4.195049634	6001				

s/s adapter, Manufacturability Factor weights when only sub-factor weights were changed
ANOVA: Single Factor, Comparison between the main factor whose weights did NOT change

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Old Wts	3001	631.7914552	0.210526976	6.08163E-05
New subWts	3001	690.9789738	0.230249575	9.081E-05

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.583665839	1	0.583665839	7698.741553	0	3.843013019
Within Groups	0.454878893	6000	7.58131E-05			
Total	1.038544732	6001				

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Appendix E Some Delta Benefits Factor (DBF) Results

METALS V/S METALS

Kaminski et al, Al-Li in space Appl., MDSS paper;

						Al 2040		Al-Li 2090		
Material Benefits Factor							0.5229		0.4771	1.0000
Delta Benefits Factor (Defender > Challenger) =							0.9125			
Physical and Tangible benefits		0.7					0.3395		0.3605	0.7000
										handling
L-t-B	Density (lb/cuft)	0.714286		5		0.058	0.3719	0.0534	0.3424	
H-t-B	Ultimate Tensile Stre	0.142857		1		230	0.0484	118	0.0944	
H-t-B	Yield Strength (mPa)	0.142857		1		350	0.0647	290	0.0781	
		1		7						
Other Physical benefits		0.3					0.1833		0.1167	0.3000
										handling
H-t-B	Fatigue	0.333333		1		1	0.1111	2	0.2222	
H-t-B	Corrosion Resistance	0.666667	al is C on scale of A-	2		3	0.5000	1	0.1667	
		1		3						

COMPOSITES V/S METALS

Kaminski et al, Al-Li in space Appl., MDSS paper; 1991.

						comp.-EPOXY		AL-LI 2090		
Material Benefits Factor							0.5005		0.7429	1.2434
Delta Benefits Factor (Defender > Challenger) =							1.4843			
Physical and Tangible benefits		1								
Physical and Tangible benefits							0.5005		0.4995	1.0000
									handling	
L-t-B	Density (lb/cuft)	0.625		5		0.058	0.2401	0.093	0.3849	
H-t-B	Ultimate Tensile Stre	0.375		3		230	0.2605	523	0.1145	
		1		8						
Other Physical benefits		0					0.0000		0.0000	0.0000
									handling	
H-t-B	Fatigue	0 2		1		1	0.0667	2	0.1333	
H-t-B	Corrosion Resistance	0.8	al good - Kalpakjian	4		1	0.4000	1	0.4000	

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Appendix E Some Delta Benefits Factor (DBF) Results

COMPOSITES V/S CMPOSITES				C-EPOXY		PEEK		
Manufacturing Complexity Factor					0.8821		0.7429	1.6250
Delta Benefits Factor (Defender > Challenger) =					0.8422			
Physical and Tangible benefits		1						
Physical and Tangible benefits					0.8821		0.7429	1.6250
								handling
L-t-B	Density (lb/cu-in)	0.625	5	0.058	0.3254	0.0534	0.2996	
H-t-B	Tensile Strength (ksi)	0.125	1	230	0.0424	118	0.0826	
H-t-B	Tensile Modulus (msi)	0.625	5	21.9	0.4173	44	0.2077	
H-t-B	Comp. Strength (ksi)	0.125	1	88.3	0.0404	42.1	0.0846	
H-t-B	Glass Tran. Temp Tg,	0.125	1	350	0.0566	290	0.0684	
		1.625	13					
H-t-B	Comp. Modulus (msi)	NO idea of specific value for PEEK	2	17.7	0.0535	1	0.9465	1
ltb	Coeff. of Therm Exp.		2	1.32 in/in/0F		-0.53x10e6 in/in/0F		

Not included in study, as it is relevant for a particular fiber-matrix combination only. mdmsc, 4-6

benefits of composite materials -- Lower the Better measures

L-t-B :Lower - the - Better

H-t-B :Higher - the - Better

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VITA

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