An Economic and Environmental Evaluation of Aluminum Designs for Automotive Structures

by

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Abstract

This study examines alternative automobile body-in-white designs. Steel and aluminum unibodies are compared to three all-aluminum spaceframe designs on the basis of monetary costs and airborne emissions. The metal mining and refining, structure production, use and post-use stages are considered.

Results show that aluminum bodies-in-white are less expensive to produce at very low production volumes. Furthermore, the lighter aluminum designs reduce lifetime fuel expenditures. These cost savings may offset the cost burden arising from the structure's production, especially in Europe. Aluminum designs lead to a reduction in CO_2, CO, NO_x and hydrocarbons. These use-linked pollutants are the dominant environmental consequence of the automobile. However, particulate and SO_x emissions increase, due to emissions generated during the mining and refining of aluminum.

No attempt was made to synthesise dissimilar attributes [cost and emissions] into a single basis for comparison. However, even if the potential competitive advantage of pollution reduction is disregarded, certain aluminum designs appear competitive with the currently standard steel unibody.

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1. Introduction

1.1. Background

The automobile, as we know it today, first took shape in the 1890s. Since then a variety of technologies have been employed in order to render passenger vehicles safer, more efficient and, to some extent, less expensive. Technological innovation has been a key element in enhancing the merits of the automobile. For instance, internal combustion engines have replaced steam-driven power plants and have yielded better performance. Electronic systems have allowed better control of the fuel combustion process and they have also increased passenger safety through collision avoidance systems, e.g. the anti-block (ABS) braking system. At present, technological change still concerns automotive manufacturers. [Appel, 1984] The investment of automakers in research and development activities clearly portrays this concern.

Technological innovation is driven by several forces. Firstly, one can identify the competition between rivalling firms. Since the 1950s, foreign manufacturers have attempted to capture an increasing share of the North American automobile market. Imports retail sales accounted for only 15% of the total sales in 1970, but by 1990 this share had risen to approximately 33%. [DOC, 1991][Yanik, 1992] Furthermore, the fierce competition introduced predominantly by Japanese firms has led the Federal Government to impose tariffs and quotas for these imports, in order to protect domestic manufacturers. General Motors, Ford and Chrysler have recently found themselves in financial dire straits. Their profitability in recent years has been far from enviable, as can be deduced from Figure 1. Technological innovation may be a solution strategy, because it has the potential to differentiate products from their substitutes and it can, hence, establish a competitive advantage. [Porter, 1980]

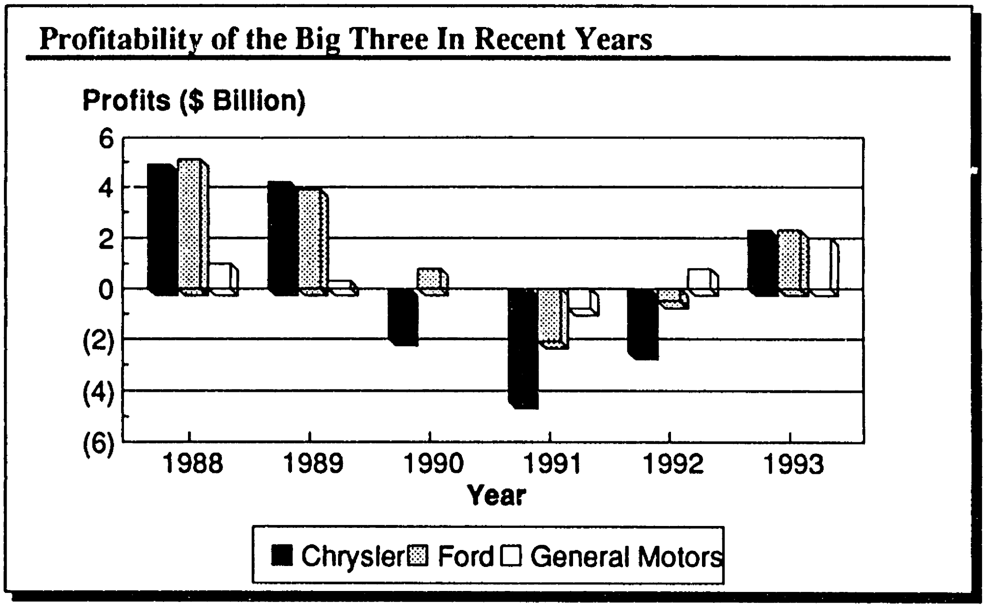

Figure 1.

Secondly, customer preferences provide a strong incentive for continued progress. Most customers would welcome improvements in the areas of fuel efficiency, performance, comfort and safety. [Seiffert, 1991] The general trend in customer wishes is also marked by the request for higher product quality with the lowest possible purchase price [U. Michigan, 1992] The need to meet customer preferences is aggravated by the competitive nature of the automotive industry. A well-selling product could be consequential to the prosperity of the individual carmaker. [Seiffert, 1991]

Thirdly, the Federal Government has promulgated regulations which attempt to aggregate the individual interests of the public. This collective power has been utilised in the past over matters that mostly focus on social efficiency. [Adams, 1982] The most prominent topics in this field have been automotive air pollution and smog, automotive safety and fuel consumption. The most pervasive regulatory actions in recent years have been the introduction of fuel consumption standards, the CAFE (Corporate Average Fuel Economy) standards and the implementation of the Clean Air Act along with its Amendments in 1990 [Sel. Env. Law Statutes, 1993]. The objective has been to, directly or indirectly, decrease the amount of harmful substances emitted during the use of the automobile. In the face of ever more stringent regulations[1] automotive manufacturers opted for technological advancement. Their reaction has evolved around three areas: tailpipe emission controls, more fuel efficient internal combustion engines and light weighing.

1.2. Incremental Innovation

In general, the pressures discussed above have forced automotive manufacturers to evolve in order either to meet the specified requirements, or to gain the competitive edge over their rivals. One of the methods utilised has been technological innovation. There have been three distinct patterns of innovation. [Appel, 1984] The first one is called process efficiency and is related to the management of the production chain. The second

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[1] All respondents in the *Delphi IV Forecast and Analysis of the US Automotive Industry* anticipate more restrictive standards by the end of the century. [U. Michigan, 1992]

one is market placement and concerns the benefits associated with the integration of world-wide production facilities. The third one, and the one this study solely addresses, is product technology. This type of innovative change is related to the individual characteristics of each automobile design.

On attempting to assess the degree of product technology innovation in the automotive industry, one has to note that this industry is not a high technology one. During most of the post-war period, no significant technological advancement has taken place, especially in the United States. Furthermore, the predominant path for change has been incremental innovation. [Appel, 1984] In this type of innovation, the technological advancements affect minor components of the product, i.e. the automobile. The advances are alterations to the previously existing design solutions. Moreover, this path to innovation is characterised by additional components which aid in achieving the desired objective.

Typical examples of incremental innovation are the styling changes of modern automobiles. Although a large portion of styling changes have been purely cosmetic, some have resulted after technological assessment of other alternatives. [Adams, 1982] Therefore, many interior and exterior parts of the current passenger vehicles are manufactured using lighter plastic materials instead of heavier metals. [Seiffert, 1991] The plastic components do not differ significantly from the metal counterparts. The new designs constitute incremental innovation as the redesigning is limited to the few areas where the plastic components do not meet specifications.

Other examples portraying how additional technological devices enhance the merits of the car are three-way catalysts and airbags. These devices were introduced in order to meet the ever more stringent regulatory standards. Through catalytic converters, automotive producers have successfully managed to decrease carbon monoxide and nitrogen oxide tailpipe emissions. [Seiffert, 1991] Driver and passenger-side airbags have succeeded in reducing the fatalities resulting from frontal collisions.

Another pattern in recent years has been lightweighing. The benefit of a lighter vehicle is mainly that it requires less energy during its lifetime. Therefore, its fuel economy is enhanced. [Davis, 1991] This solution strategy has been predominantly applied to meet federal standards, especially the CAFE standard.

A potential innovative change along the lines of lightweighing is the introduction of alternative, lighter materials for major automotive components. Compared to steel, both aluminum and plastics have lower densities and could potentially aid in reducing the weight of the automobile. However, the application of lightweight materials has not been extensive. Despite their potential merits, these materials are still limited to a small number of components and their weight fraction for the complete passenger vehicle is fairly small. [U. Michigan, 1992]

The introduction of these lighter materials for more substantial components of the automobile has been studied in the past two decades. [Ostermann, 1993] Aluminum has generally been considered as the most probable substitute to steel, because the material characteristics of aluminum are not as dissimilar to steel as the ones of plastic thermosets and thermoplastics are. Essentially, both aluminum and steel are metallic materials and the forming processes utilised for steel can be adequately modified to suit aluminum. [Ostermann, 1993] Several experimental prototypes have been constructed, in which the steel body-in-white[2] has been substituted by an aluminum one, in a monocoque or unibody design. General Motors and Reynolds Company constructed a Corvette with an all aluminum body in 1975. [Glaser, 1974] Audi and Alcoa produced and aluminum version of the Audi 100 model in 1985. [Hasler, 1987] The Austin Rover Metro achieved a weight reduction of 46% on the vehicle body by material substitution. However, all these innovative designs should be classified under incremental innovation. The material substitution occurred on a one-to-one basis, i.e. each part of the steel design was exchanged by a single analogous part in aluminum. Design alterations were implemented only in the areas where aluminum did not satisfy the structural requirements and where reinforcements were required.

1.3. Radical Innovation

Despite the predominant pattern of incremental innovation, some designs envisaging radical change have been put forward. A typical example of incremental innovation is the fuel injection system, which most currently sold vehicles possess. The electrical-mechanical components that controlled the composition of the air-fuel combustion mixture were replaced by more accurate electronic devices. The result has

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[2] The BIW consists of the parts which contribute to the torsional and bending stiffness of the automobile.

been a more efficient internal combustion engine, as now the fuel mixture is almost completely burnt. In addition, this type of engine releases smaller amounts of post-combustion pollutants, because it requires smaller amounts of fuel. [Yanik, 1992]

In the area of material substitution, there have been examples of considerable innovations by attempting to substitute materials for major vehicle components. Substitution with aluminum has also been accompanied by drastic redesign of the body-in-white, in the case of the aluminum spaceframe. The concept of the spaceframe exploits the formability characteristics of aluminum, especially through the extrusion process. Hollow sections are extruded and joined to form the structural frame of the passenger vehicle. Other production processes, such as stamping and casting, are utilised to manufacture the remaining parts of the body-in-white. [Wheeler, 1987]

The success of the spaceframe design is probably more extensive than the one of the monocoque one. At least three models employing the spaceframe design have advanced to the production stage. The most notable one is the GM Pontiac Fiero, although this model utilised steel for the extruded structural frame and plastics for the exterior panels. Examples of all aluminum spaceframes are the Honda NSX sportscar and most recently the flagship for Audi, the A8 model.

1.4. Implementation of Innovation

Automotive manufacturers have engaged in technological advancement in order to meet the demands and pressures in the automotive market. The carmakers have predominantly selected the path of incremental innovation probably because it involves less risk than the path of radical innovation. The alterations to the final product, which is the passenger automobile, are, in general, less pronounced. Furthermore, the requirements for additional or new investment are, by and large, lower for incremental than for radical innovation. As Alfred Sloan, Jr. put it, radical product innovation entails the "risk of untried experiment".

However, radical innovation can lead to a passenger vehicle with a higher degree of merit. The consumers have parameters, or attributes, that they value in the car they buy. For instance, these attributes can be purchase price, product quality, performance, safety, reparability, fuel efficiency, adverse impact to the environment and aesthetics. [U. Michigan, 1992] Radical innovation has the potential of significantly affecting these attributes and making the new design more desirable than its competitors. Consequently, the market success of such an improved design will be relatively higher. [Pindyck, 1992]

Therefore, the implementation of radical innovation requires a thorough examination of the merits of the innovative concept. It seems wise to know the repercussions of the new design on the most important attributes. This information can aid in juxtaposing the design alternatives and it can assist in making rational choices.

2. Problem Statement

The purpose of this study is to ameliorate the process of material selection for automotive applications by thoroughly analysing the benefits and drawbacks of a certain design. This design is the all-aluminum spaceframe vehicle, which takes advantage of the formability characteristics of the material and the associated manufacturing processes.

The application chosen for aluminum is the automotive Body-In-White (BIW). The contribution of this assembly of components to the total weight of the vehicle is significant, approximately in the order of 20 to 30% of the curb weight. Therefore, even small percentage weight reductions for the BIW matter to the total weight of the car. [Seiffert, 1991] In the past, aluminum has been examined as a "direct" substitute to steel, in the aluminum unibody design. [Han, 1994] Although this is a perfectly acceptable approach, it fails to capture the entire range of benefits that can be accrued by material substitution. The unibody design has been introduced for steel and is tailored to the properties of this material. A "one-to-one" substitution might produce a viable solution, but there is no guarantee that this solution is the optimal one for aluminum.

This study attempts to assess the extent to which the radical innovation introduced by the aluminum spaceframe affects the attributes associated with the automobile. In general, aluminum designs have been disclaimed because the cost of manufacturing these designs seems higher. [Brichaut, 1994][Appel, 1984] The primary reason is that the material cost for aluminum is significantly higher than the one for steel. However, aluminum spaceframe designs have reached the market, even though they have penetrated a niche segment; both the Honda NSX and the Audi A8 have been targeted towards the luxury vehicle market.

On the other hand, the aluminum designs require less fuel during their useful lifetime. Hence, lower expenses are required during the use phase of the automobile. Potentially, the cost savings arising from the use stage could outbalance the cost burden in the production stage. Furthermore, the lighter design is considered a "cleaner" design, because lower fuel consumption leads to reduced pollutant emissions during use.

Therefore, it is essential to analyse both the traditional (monetary) and non-traditional (environmental) costs associated with each of the designs examined. This thesis is divided into two sections. The first one concentrates upon the monetary costs of the automotive body-in-white. These costs include all the stages in the lifetime of the BIW, from cradle to grave. The second part of the thesis addresses the repercussions of aluminum designs in terms of airborne emissions.

The objective of this thesis is, therefore, to point out the strengths and weaknesses of the aluminum spaceframe design, in terms of its competitive advantages and its ability to meet regulatory standards. By comparing the steel unibody, aluminum unibody and aluminum spaceframe BIW on traditional and non-traditional costs, any relevant interest groups, such as the automotive producers, the consumers and the Federal Government, can make informed policy choices.

[Komatsu, 1991] In this one-on-one substitution example, the part has to maintain its strength and rigidity. The aluminum part has to fall inside the feasible (shaded) region, otherwise it does not qualify as a potential substitute. As a result, the 43% weight reduction line marks the maximum benefit possible through this material substitution.

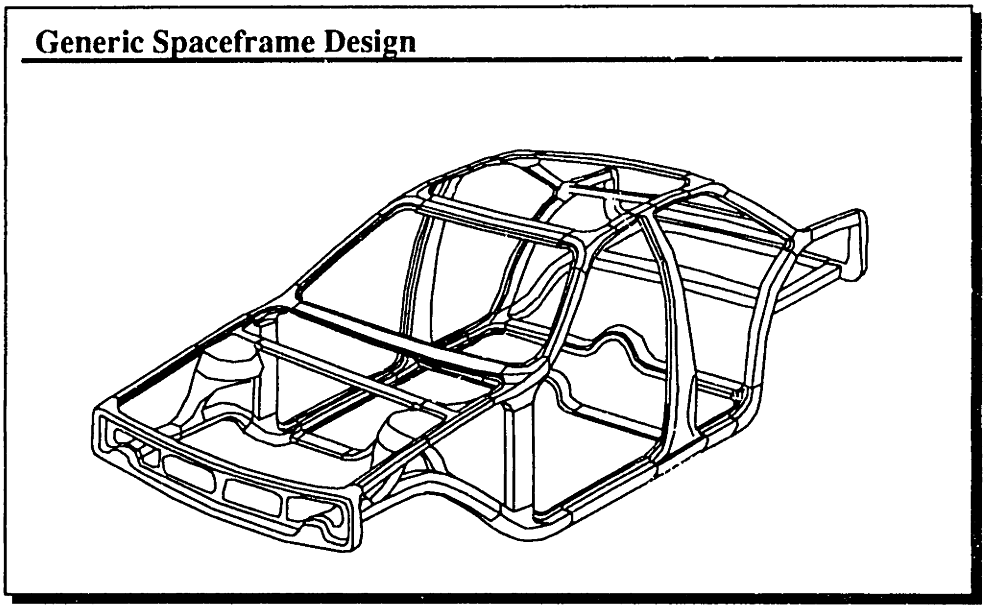

Generic Spaceframe Design

Figure 3.

Also, efficient use of the material calls for a diversified use of the forming operations. The large variety of forms in which aluminum is supplied -- extruded sections, cast components and sheet -- facilitates the purpose-related use of the material. The combination of such processes may result in a design with a high degree of geometrical and functional integration. [Automotive Engineering, 1/94] The concept of the aluminum spaceframe was thus born. At present, this type of design is commercially available only for low volume production models. It seems as though, joining components manufactured by different methods, not to mention from different alloys, could prove a major obstacle to achieving the degree of process automation demanded in high volume production.

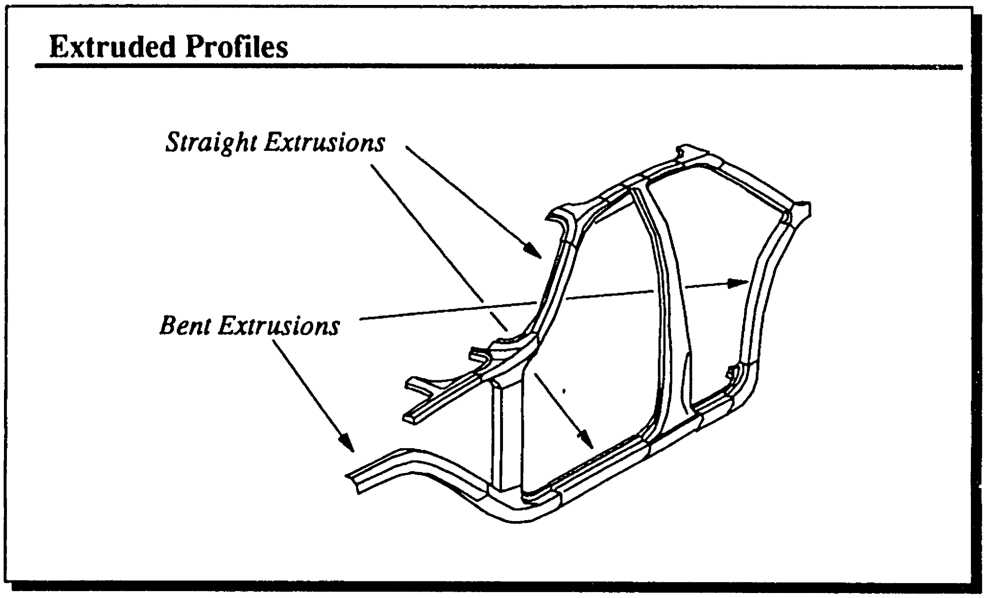


Figure 4.

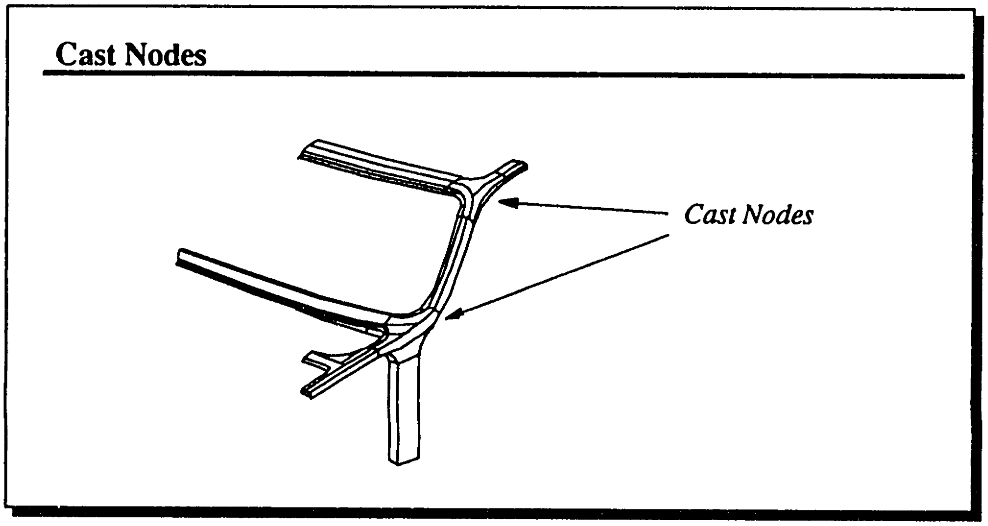


Figure 5.

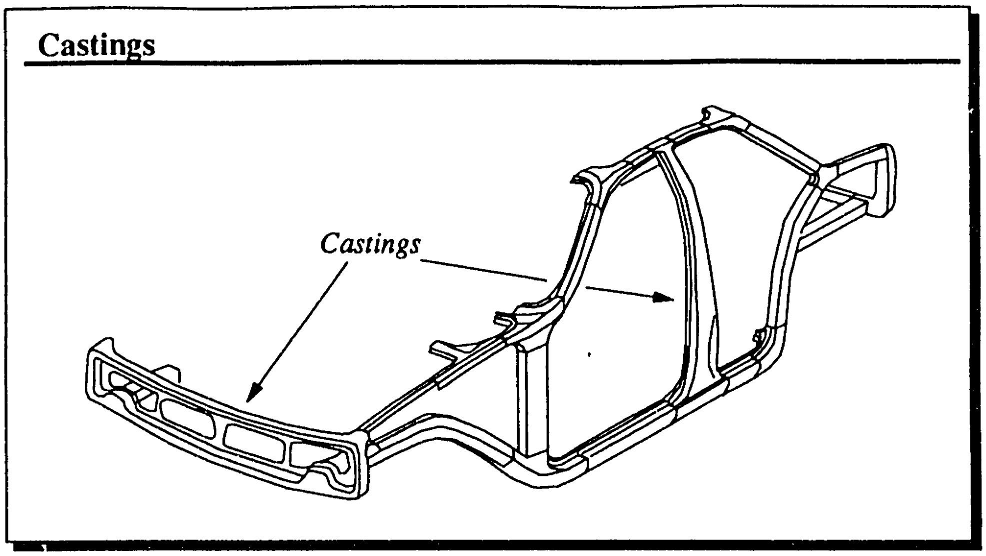


Figure 6.

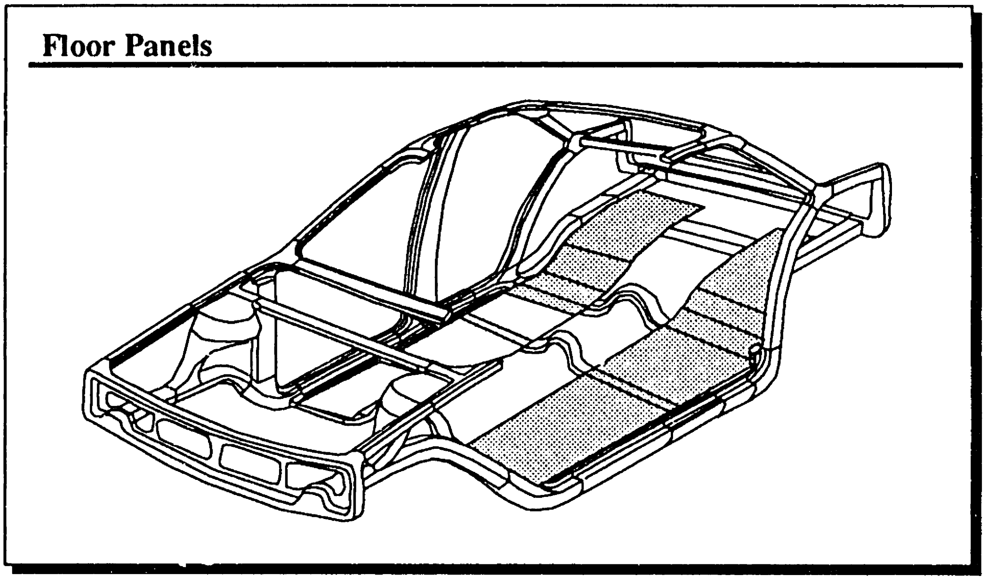


Figure 7.

In general, the aluminum spaceframe design (Figure 3) is composed of extrusions, stampings and castings. The structural importance of each class of components is unique. In most designs, the extrusions form the predominant load transmitting paths. The frame structure consists of straight and curved extruded profiles (Figure 4) which are primarily joined by cast nodes (Figure 5). These nodes enhance the local rigidity of the structure and ensure the effective transmittal of loads from the chassis and subframe mounts. Furthermore, castings can be used in areas where the complexity of the design prohibits the use of extrusion, such as is the case with grille openings (Figure 6). Finally, stamped panels complete the design. The panels form the floor (Figure 7) and the curved surfaces, with class-A finish, all around the vehicle. The structural role of stamped panels depends upon the rationale of the designer; in some cases the panels are considered load bearing components, in others not. In the latter case, they are called hang-ons and their limiting requirement is dent resistance.

If the approach to part forming operations shows a degree of commonalty between designs, the concept of joining these parts has designers split. [Automotive Engineer, Feb-Mar 1994] The techniques utilised for the steel unibody design do not prove adequate for joining aluminum, at least for a cost-effective production model. [Brichaut, 1994][Nordmark, 1993][Han, 1994] Spot welding still remains a potential choice, but other options such as arc welding, adhesive bonding, riveting, bolting and mechanical clinching also seem appropriate for the spaceframe. The predominant features of these joining techniques are:

Joining Method	**Advantages**	**Drawbacks**
Arc Welding	Joint Strength Familiar Technology	Casting Weldability Deformation at HAZ[1]

Adhesive Bonding	Joins Different Materials Sealant	Surface Treatment Required Demanding Assembly Practices
Spot Welding	Industry Standard Process Automated Compatible w/ Adh. Bonding	Surface Control Required Fatigue Performance Weld Tip Life
Riveting, Bolting	Good Fatigue Performance Dissimilar Material Joining	Material Consumables Added Joint Thickness
Clinching	Strong as Spot Welding Fixturing for Bonded Parts	Low Energy Absorption Joint Loosening

[1] Heat Affected Zones

Table 1. Joining Methods [Automotive Engineer, May 1993]

The most important aspect of the advantages and drawbacks of the selected joining method, or combination of thereof, is the ultimate mix of the production processes employed for the manufacture of this innovative vehicle. The conflicting philosophies of designers have led to interestingly distinct results. For instance, the utilisation of cast nodes for stress management at crucial areas is debatable. Some designers, especially in Europe, consider that these nodes should be abolished. Instead, they claim that extruded profiles should be welded together. [Krajtwick, 1995][Brobak, 1994] These conflicting solutions stem from the attributes of the joining technique as well as from the production volume of the vehicle. The latter parameter is of paramount importance. Inherently it determines whether each process, be it a forming operation for a component or a joining technique, is cost effective. Given that several design options are feasible and meet the requirements set, the production volume dictates which one should be selected on a cost minimising basis.

The availability of part forming operations and joining methods creates numerous viable combinations that would lead to feasible all aluminum spaceframe designs. This study will examine a few of these designs in an attempt to identify the significant parameters, and how these affect the attributes examined. The design specifications for three spaceframes have been provided by experts in the aluminum and automotive industries. [Krajtwick, 1995][Wasson, 1995][Mangin, 1995] These designs capture the entire range of philosophies behind the spaceframe concept. They come from both the United States and Europe and they are proxies to prototype or commercially available vehicles, such as the Ethos and the Audi A8. The most important features of these designs are as follows :

Design SF-1

Forming/Limiting Design Parameter	Part Count Percentage
Stamping (Class A) - Dent Resistance	8%
Stamping (Class A) - Stiffness	4%
Stamping (Non-Class A) - Dent Resistance	0%
Stamping (Non-Class A) - Stiffness	16%
Extrusion - Yield Strength	60%
Casting - Stiffness	0%

Forming/Limiting Design Parameter	Total Weight Percentage
Stamping (Class A) - Dent Resistance	8%
Stamping (Class A) - Stiffness	6%
Stamping (Non-Class A) - Dent Resistance	0%
Stamping (Non-Class A) - Stiffness	31%
Extrusion - Yield Strength	55%
Casting - Stiffness	0%

Finishing Operations	
Cutting	Yes

CNC-Milling	Yes
Punching	No
Drilling	Yes
Bending	Yes

Joining Techniques	
Spot Welding	Yes
Arc Welding - Metal Inert Gas	Yes
Adhesive Bonding	Yes
Riveting	Yes
Bolting	Yes
Clinching	Yes
Flanging	Yes

Process	**Alloy**	**Total Part Count**	**Total Part Weight** [lb.]	**Metal Price** [$/lb]
Stamping	5754-SSF	11	46	$1.64
Stamping	5754	6	33	$1.55
Stamping	5754-PREP	14	77	$2.05
Extrusion	6063	45	200	$0.95
Casting		0	0	
Total		76	356	

Table 2. SF-1 Spaceframe Design Parameters.

Design SF-2

Forming/Limiting Design Parameter	**Part Count Percentage**
Stamping (Class A) - Dent Resistance	8%
Stamping (Class A) - Stiffness	7%
Stamping (Non-Class A) - Dent Resistance	0%
Stamping (Non-Class A) - Stiffness	31%
Extrusion - Yield Strength	46%
Casting - Stiffness	8%

Forming/Limiting Design Parameter	Total Weight Percentage
Stamping (Class A) - Dent Resistance	7%
Stamping (Class A) - Stiffness	5%
Stamping (Non-Class A) - Dent Resistance	0%
Stamping (Non-Class A) - Stiffness	35%
Extrusion - Yield Strength	42%
Casting - Stiffness	11%

Finishing Operations	
Cutting	Yes
CNC-Milling	Yes
Punching	No
Drilling	Yes
Bending	Yes

Joining Techniques	
Spot Welding	Yes
Arc Welding - Metal Inert Gas	Yes
Adhesive Bonding	Yes
Riveting	Yes
Bolting	Yes
Clinching	Yes
Flanging	Yes

Process	Alloy	Total Part Count	Total Part Weight [lb.]	Metal Price [$/lb]
Stamping	5754-SSF	11	46	$1.64
Stamping	5754	6	33	$1.55
Stamping	5754-PREP	17	67	$2.05
Extrusion	6063	34	149	$0.95
Casting		6	40	$0.95
Total		74	335	

Table 3. SF-2 Spaceframe Design Parameters.

Design SF-3

Forming/Limiting Design Parameter	Part Count Percentage
Stamping (Class A) - Dent Resistance	9%
Stamping (Class A) - Stiffness	0%
Stamping (Non-Class A) - Dent Resistance	48%
Stamping (Non-Class A) - Stiffness	0%
Extrusion - Yield Strength	28%
Casting - Stiffness	15%

Forming/Limiting Design Parameter	Total Weight Percentage
Stamping (Class A) - Dent Resistance	8%
Stamping (Class A) - Stiffness	0%
Stamping (Non-Class A) - Dent Resistance	25%
Stamping (Non-Class A) - Stiffness	0%
Extrusion - Yield Strength	44%
Casting - Stiffness	23%

Finishing Operations	
Cutting	Yes
CNC-Milling	Yes
Punching	No
Drilling	No
Bending	Yes

Joining Techniques	
Spot Welding	No
Arc Welding - Metal Inert Gas	Yes
Adhesive Bonding	No
Riveting	Yes
Bolting	No
Clinching	No
Flanging	No

Process	**Alloy**	**Total Part Count**	**Total Part Weight** [lb.]	**Metal Price** [$/lb]
Stamping	6xxx	62	112	$1.60
Extrusion	6xxx	31	145	$0.95
Casting	4xxx	17	75	$0.95
Total		110	332	

Table 4. SF-3 Spaceframe Design Parameters.

The objective behind analysing more than one aluminum spaceframe designs is not to identify the optimal one. The most meaningful conclusion one may reach is the ranges of parameters, such as the production volume or material cost, which render one of the designs more desirable than the others. Once more, desirability is a function of the attributes associated to each of the models. At this point it is worth noting once more that the three designs have been put forward by experts currently involved in the aluminum and automotive industries. The designs meet the structural requirements required by automobile producers and, therefore, they are solely judged on their comparative competitive advantage, on a basis of monetary cost and adverse impact to the environment.

4. Methodology

In order to assess the repercussions of innovative designs and of new materials, it is necessary to use an analytical method which achieves a comprehensive and fair evaluation. The initial requirement for this tool is that it should take into account the pre-eminent elements that affect the measurable results. In the field of production processes, one has, therefore, to relate the engineering aspects of the operations, such as feasibility, to their economic or environmental consequences. Furthermore, the tool has to be devoid of judgement on the results. Judgement, at least in this case, entails the introduction of subjectivity and narrows the amount of information that can be communicated. The Materials Systems Laboratory has devised a framework which manages to capture the relevant features of operations and to quantify their impacts. [Poggiali, 1985][Busch, 1987]

4.1. Technical Cost Modelling

The Technical Cost Models (TCM) simulate production processes, such as stamping, extrusion and die casting, in order to obtain the inclusive cost of manufacturing a specific component. Recognising the interdependencies between design and material choices and the effects on cost of different production patterns and other economic factors, leads to broadening the boundaries of this simulation. As shown in Figure 8, simply analysing the part forming step disregards crucial information. Essentially, this quite limiting approach does not allow for the flexible implementation of the concept into the product.

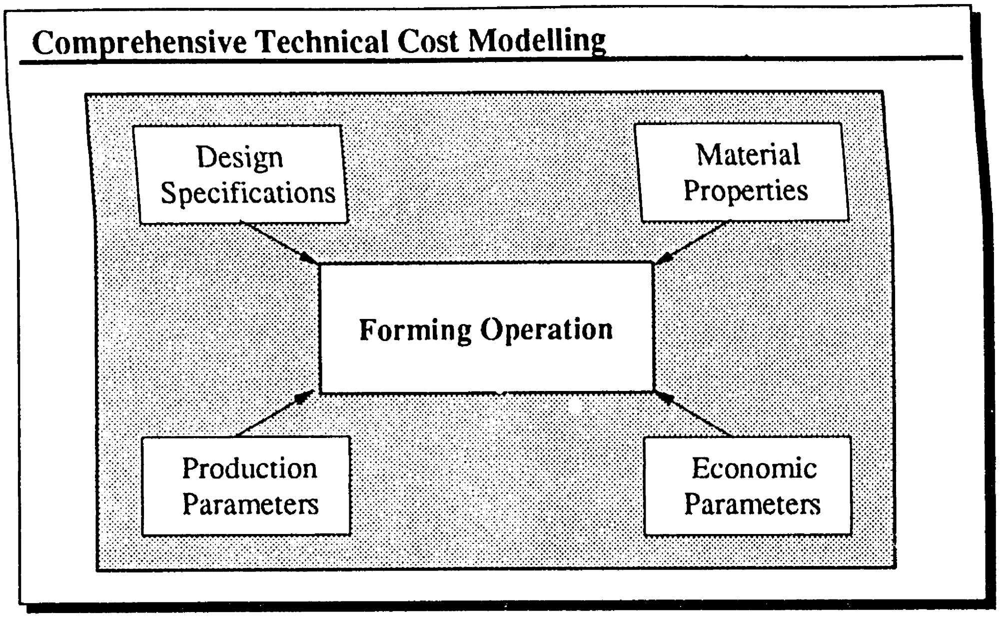
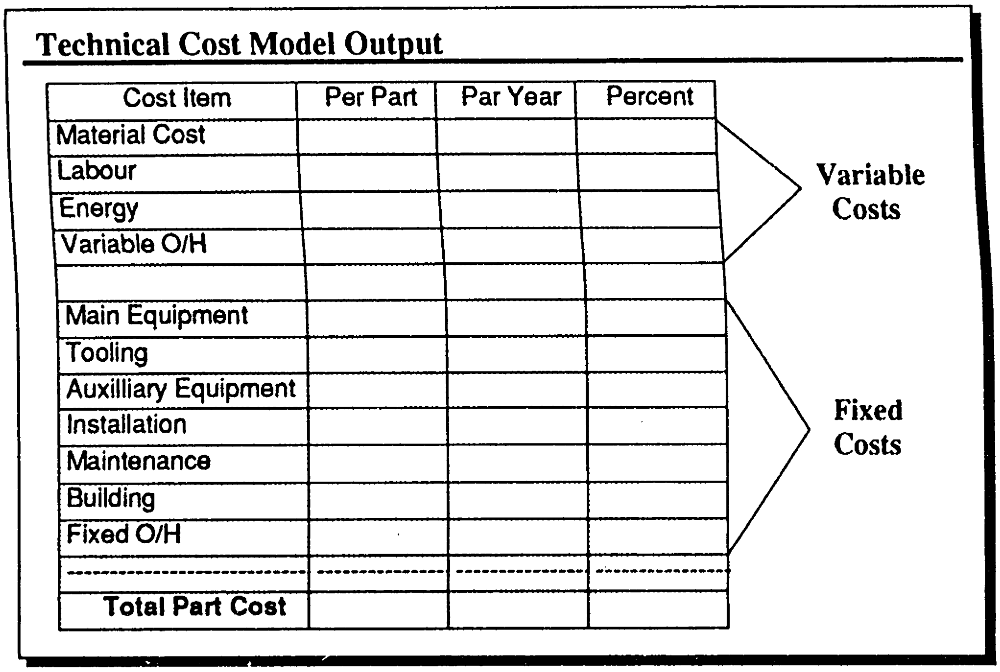


Figure 8.

TCMs require four basic sets of inputs. [Chen, 1992] They are:

1. Design specifications, e.g. part dimensions.
2. Material properties, e.g. Young's modulus, density and material price.
3. Production parameters, e.g. production volume, scrap rate, down time.
4. Economic parameters, e.g. wages, benefits, electricity cost.

These four sets of inputs are then integrated in a spreadsheet which simulates the production process. The output of the TCM is the production cost for the specified part, broken down as shown in Figure 9. This enables the user to identify which aspects of the operation have the greatest impact on the part cost. Furthermore, this framework facilitates the quick and easy modification of the tool to take account of technological advancements. Merely altering the parameters that are affected by innovation produces a new result -- the new component cost -- which reflects the material, design or process transformation.



Technical Cost Model Output

Cost Item	Per Part	Par Year	Percent
Material Cost			
Labour			
Energy			
Variable O/H			
Main Equipment			
Tooling			
Auxilliary Equipment			
Installation			
Maintenance			
Building			
Fixed O/H			
Total Part Cost			

Variable Costs

Fixed Costs

Figure 9.

4.2. Lifecycle Analysis

The three designs, i.e. the steel and aluminum unibodies and the aluminum spaceframe, will be assessed on the basis of their most important attributes. These include cost and emissions for the complete life cycle of the automobile. Therefore, each stage, from cradle to grave, has to be examined because of the dissimilar contributions to each stage by the three designs. This study includes:

1. The material mining and refining stage,
2. The vehicle production stage,

3. The use stage,

4. The post-use (disposal) stage.

The lifecycle cost modelling step combines the individual costs of every stage in the lifetime of the product to a single attribute, the lifetime cost. Since the monetary expenses do not occur at a single point in time, standard financial instruments, such as the discount rate, have to be used to convert the cash flows to an equivalent, single number. In this final part of the cost modelling, the results from each phase come together. However, the costs arising during each stage in the lifetime of the product are not incurred equally, if at all, by every interest group. Distributional effects have to taken into account, as shown in Figure 10.

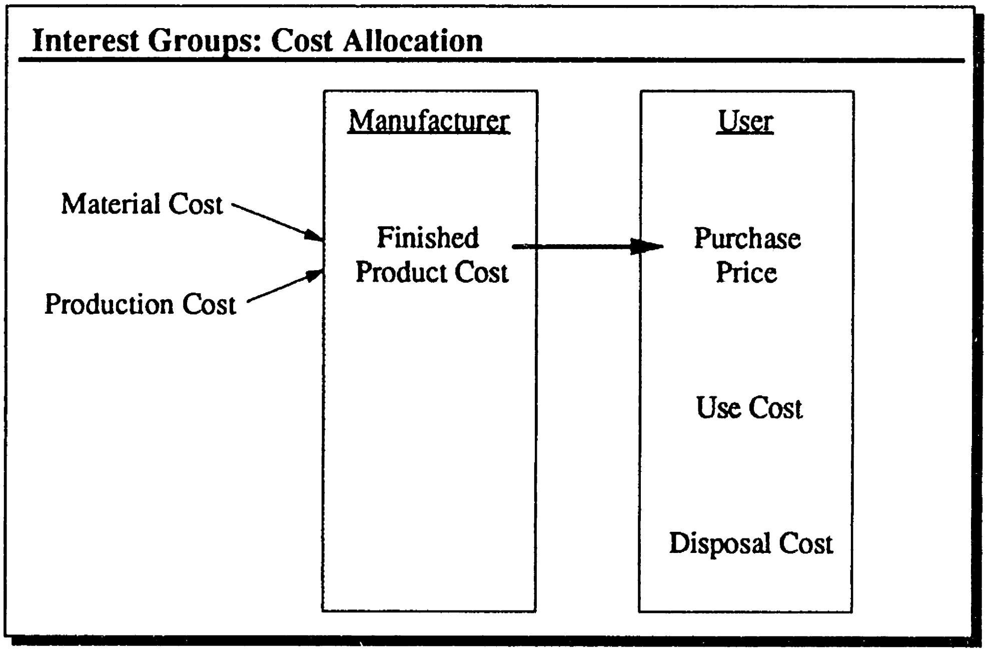


Figure 10.

The second group of parameters calculated is the group of emissions. This includes carbon dioxide (CO_2), carbon monoxide (CO), particulates, nitrogen oxides (NO_x), sulphur dioxide (SO_2) and other hydrocarbons (HC). Although other pollutants are also emitted during the lifetime of the BIW, these six airborne pollutants seem to be the most consequential for the case of the automotive BIW. [IKP, 1994] The emissions arise, firstly, from the energy required in each of the stages in the lifetime of the product. In general, energy production leads to the exhaust of undesirable substances, except for the case of hydroelectric power. The power mix, i.e. the combination of combustion fuels, determines the magnitude and composition of the effluents for each energy unit consumed. In addition, emissions arise from chemical reactions, mainly during the material mining and refining process. These are strictly related to the material chosen for the production of the components. Finally, emissions arise during the use phase due to the combustion of gasoline. These are related to the energy required to transport the automobile and its passengers.

The lifecycle emissions for a specific design can be calculated if the individual contributions from each stage are combined. The distinction that should be made is that adverse environmental impacts cannot be handled similarly to economic costs. They ought to be classified as externalities in the social sector and, hence, they do not apply to a specific interest group. Furthermore, although they are spread over time, discounting is a debatable method for reducing this "flow" into an equivalent quantity. The reason is that the scientific community has failed to reach consensus even on the range of values that would make discounting acceptable. [de Neufville, 1990] The main reason is that discounting is associated with the notion of intertemporal equity and there has yet to be a conclusive result on the short-term and long-term effects of pollutants. In this study it has been selected to perform the reduction by summing the individual contributions from each stage. There is a stronger point behind this action than the simplistic assumption of a zero discount rate in the absence of better information. If a stable state is reached, i.e. if one moves ahead in time so that the first vehicle has become obsolete, the sum of lifecycle emissions from a single vehicle is proportional to the annual emissions of the fleet of vehicles examined. Consequently, the quantity used retains its value as a measure of social efficiency of the design, except for the initial, transitive period.

5. Production Technical Cost Modelling

The models devised for the production processes have been designed as to simulate these processes as sharply as possible. A major concern has been to accommodate two relatively contradicting features. Firstly, the models have to be specific enough for a certain company to use them with confidence. Fundamentally, they have to yield results that reflect the true manufacturing cost of the component modelled. This is the ultimate benchmarking test of any technical cost model. Secondly, they should be able to depict the general situation in the industry. This aspect is more informative if a general comparison between designs is to be carried out. The models discussed below successfully compromise these two requirements by allowing the user to input the production characteristics one considers appropriate.

5.1. Conventional Hot Extrusion

Hot extrusion is the process by which heated material flows through the shaped opening of a die. The temperature ranges vary and they are strictly dependent upon the material extruded. The process is predominantly used to manufacture long, straight metal products of constant cross section. Typical applications include bars, hollow tubes, wires and strips. [Lyman, 1969] Aluminum alloys are considered the ideal material for the extrusion process, due to their formability and flow characteristics. Indeed, sections can be extruded even from heat-treatable high-strength aluminum alloys. However, until recently, the most common application of these extruded profiles, in the automotive industry, has been in the area of trim. [Ostermann, 1993]

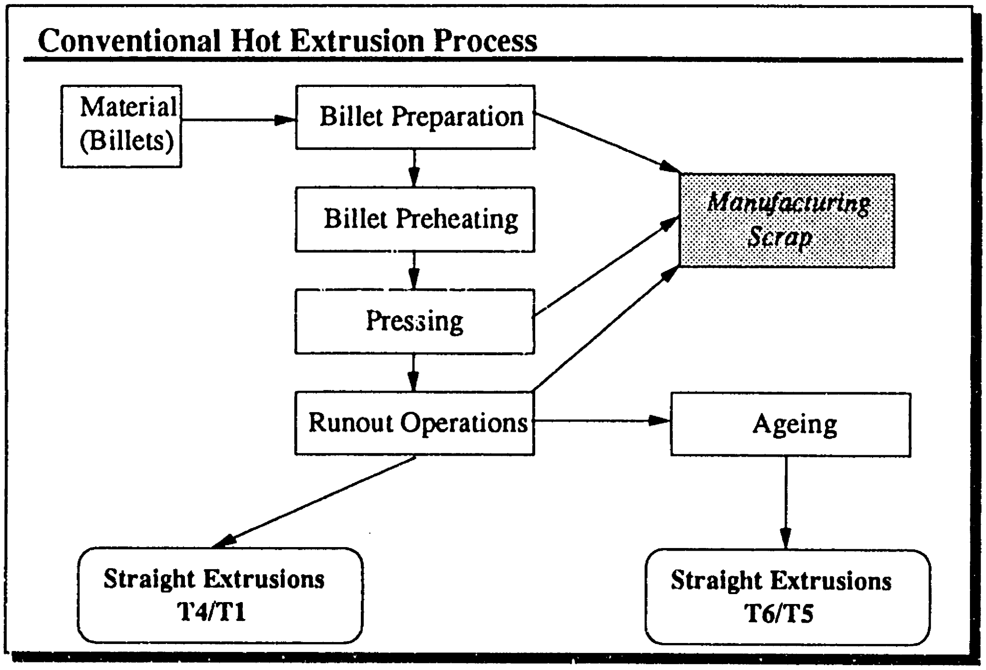


Figure 11.

The flow properties of aluminum qualify the material for direct, hot, non-lubricated extrusion. In general, this type of process is the least expensive and most easy to perform. A flow chart describing the process is included in Figure 11. A typical sequence of pressing operations includes:

- Loading the hot billet into the container,
- Allowing the ram to push the billet through the die by means of plastic deformation,
- Ending this operation when just a thin disc of material remains in the container,
- Discarding all excess material from the container,
- Repositioning all apparatus to the loading position for the following billet.

The most common equipment utilised for direct extrusion are direct-drive, oil-hydraulic presses. They can maintain a constant force throughout the entire extrusion stroke (cycle), thus minimising any potential defects from non-homogeneous portions in the profile. Their major drawback, which is a relatively low ram speed, is of no consequence for structural automotive applications. The low tolerances that can be accepted set a ceiling to the extrusion speeds which is, definitely, lower than the intrinsic limits of this class of presses. [Blazynski, 1986][Doyle, 1969]

The most significant parameters included in this Technical Cost Model are the following (see also Appendix I) :

Material Choice: Selecting the material determines, primarily, the material cost content of the extruded part. Furthermore, it decides the salvage value for any scrap generated during the manufacturing process and during the inspection (quality control) step. Given the significance of material cost for the total part cost [DiGuiseppe, 1994] it is wise to keep tract of any material losses. Furthermore, selecting the extruded material sets the range of speeds that can be achieved. [Altan, 1983] The feasible speeds for extrusion span two orders of magnitude, simply for aluminum alloys. For instance, the harder 2xxx series are in the low end of approximately 1 m/min and the softer 1xxx and 6xxx series can be processed at much higher speeds, even reaching 100 m/min. [Ackeret, 1987]

Geometry Specifications: These design parameters provide the information for the size and the complexity of the extruded piece. The inputs required include the length, cross sectional area, circumscribing circle diameter[3] (CCD) and perimeter of the profile. Material which is at a greater distance from the axis of the billet tends to flow slower than material close to it. The CCD is a criterion which portrays the degree of process control demanded for maintaining the dimensions of the shape. Another production parameter calculated from the inputs is the shape factor, defined as the ratio of the perimeter to the weight per unit length of the part. This factor is a normalised measure of the amount of surface generated. It relates to the complexity of the dies and to their fabrication and maintenance cost.

Equipment Specifications: This category contains all the pertinent information for extrusion presses and auxiliary equipment. The majority of the entries concern engineering parameters such as the maximum billet weight the press can accommodate, the maximum billet diameter and the maximum pressing force the press can exert. In addition, the current purchase price of the equipment has been included. An equipment database allows the user to select amongst several press models. These cover press sizes ranging from 16 to 35 MN.

Tooling: Arguably, the most crucial pieces of equipment utilised during the extrusion forming process are the dies. Die design embodies both art and science. In order to achieve the optimal design one has to consider the geometrical specifications of the manufactured part, the individual operational characteristics of the press and the properties of the metal. [Lang, 1981] Computer-aided design methods are often

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[3] The minimum diameter of the circle circumscribing the cross section of the shape.

employed to select the process variables such as extrusion speed and billet temperature. However, the acquired skill of designers also allows a trial and error approach. There exist two features that complicate die design. Firstly, all metals shrink after hot extrusion and, secondly, under high pressures and temperatures, the dies deform. Therefore, the dies have to be designed in anticipation of both the shrinkage and the shape deformation. By and large, there exist two approaches to die design. Their difference lies not in the quality of the final die aperture, but rather in the use of auxiliary components which minimise the stress and wear of the die. [DiGuiseppe, 1994] The first one promotes the production of less complex, cheaper and more often replaced die sets. However, the tolerances required for automotive applications probably prohibit this approach. The second one encourages larger, more gradual dies, where the auxiliary equipment at the front and back of the bearing surface face the highest stresses. Since the specifications for these parts are less strict than for the final die aperture, producers prefer to replace these parts more often if it ensures the quality of their product.

Special Equipment: Special equipment refers to automating apparatuses that potentially lead to savings by eliminating process inefficiencies. For example, the moving saw can reduce the overall pressing time. [Krajtwick, 1995] During the pressing cycle, the limiting condition for the size of the billet is either the capacity of the press, or the length of the runout table. If the latter is true, there exists an inefficiency, as the extruder has to resort to more, smaller billets. Consequently, it is necessary to undergo the load-unload cycle more times, thus increasing dead time and cost. The moving saw can cut extrusions as they move along the runout table, hence permitting the most efficient use of the press.

Of course, the extruder has to weigh the benefits of utilising such a piece of equipment to the cost of acquiring it.

Production Parameters: In this category all the entries are related to manufacturing issues. The ones standing out are the production volume, the down time (scheduled and unscheduled) and the rejection rate. The first factor determines the amount of dedicated equipment cost allocated to each part produced. The remaining two quantify the amount of resources, time and value added[4] respectively, that are lost due to imperfect production methods or human error.

5.2. Finishing Operations

Extrusion, as most other manufacturing processes, does not deliver products that are always ready for their applications. Very often several finishing operations, such as CNC-milling, angular cutting, drilling, punching and bending, are required to bring the straight, orthogonal extrusions up to design specifications. These operations are decoupled from the extrusion line, due to their independent standing. As not all extruded profiles require the same degree or mix of finishing operations, it is more appropriate to perform them separately.

In cost modelling each of these operations, it is necessary to know the exact process characteristics. For instance, in cutting, one has to acquire information for the depth of

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[4] In terms of time, material value, labour and equipment wear.

the cut, the angle at which the saw is set, the speed at which it moves and the scrap generated for every part. [Mills, 1983] Unfortunately, this vast amount of data is not openly available for all spaceframe designs considered in this study. Especially for the designs still at the prototype stage, the data gathered would also be somewhat incorrect, because, upon production, some of the design specifications would change. Therefore, the finishing operations cost model attempts a rather generic simulation of the processes. Some of the production characteristics are considered universal for every part undergoing the specific operation. Despite the apparent loss of accuracy through this simplification, the error introduced on the part cost and, most certainly, on the production and lifecycle cost of the BIW has been found to be within tolerable limits. [Dhillon, 1989]

The consequential variables for the finishing operations are the part geometry, the equipment utilised and the scrap generated. The first variable determines the cycle time of the operation, given the state of the machinery used. As expected, more massive profiles require more time, because more material has to be either cut or deformed. The second variable is a measure of automation. In general, there exists a correlation between equipment cost and cycle time, with more expensive, more automated equipment achieving higher productivity. The final variable accounts for the material downgraded due to the finishing operation. Although the virgin material was purchased at a high price, scrap has a much lower salvage value.

6. Analysis of Part Manufacturing Methods

6.1. Extrusion Process

For informed choices to be made, it is necessary to comprehend the behaviour of the part cost as important parameters vary. An enlightening analysis consists of setting a group of production parameters and then varying each of these separately, in a sensitivity analysis, to obtain the magnitude of the individual effects. For the extrusion process, the initial parameters are the following.

Production Volume:		100,000 per year
Material Price:		$0.95 per lb.
Offal Recovery:		Yes
Scrap Rate:		15%
Rejection Rate (Quality Control):		1%
Tooling Cost:		$7,500 per die set
Special Equipment:		Moving Saw
Part Specifications:	Aluminum Alloy	6063
	Cross Section	615 mm^2
	Length	1515 mm

The initial observation one can make is that a substantial part of the part cost is due to the cost of the material used. (Figure 12) This fact is important in the sense that it directs the efforts of the manufacturers towards minimising material losses. Also, it demonstrates the effects of material prices on the total part cost.

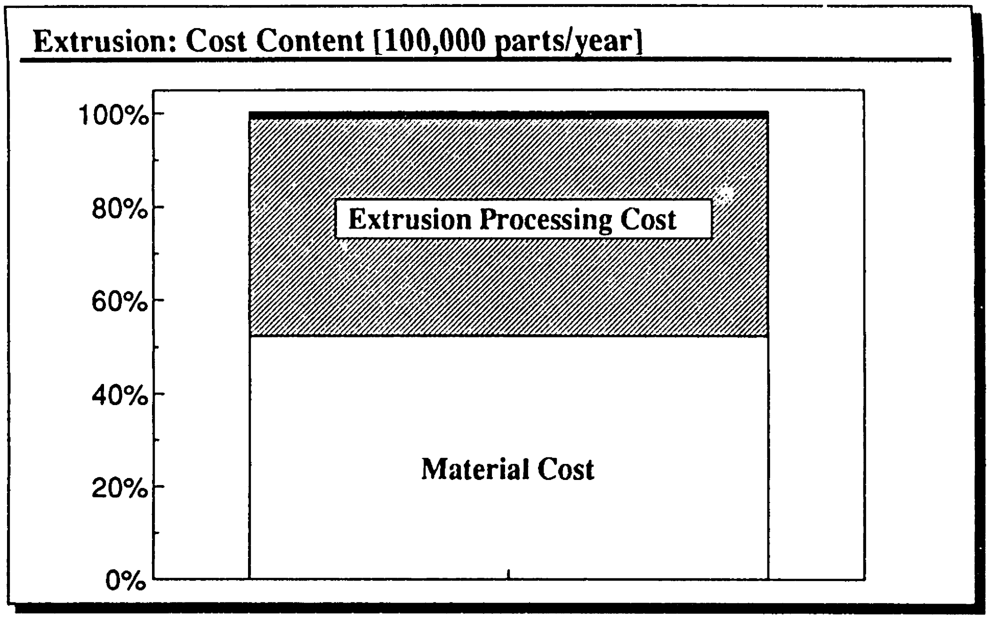

Figure 12.

Production Volume

The production volume affects the part cost by altering the portion of the dedicated equipment cost born by each of the parts. Extrusion does not involve high investments for dedicated tooling. The only pieces of equipment in this category are the die sets along with any auxiliary equipment. Their cost lies in the order of thousands of dollars and the lifetime of these tools is long enough for them not to be a major cost burden. (Appendix I) Varying the production volume, thus, reveals a steep reduction in part cost for the first few thousands of pieces. (Figure 13) The minimum efficiency scale is reached at production volumes of the order of 35,000 parts per year. For structural automotive applications such production ranges are characteristic of luxury class vehicles, the low end of automotive production.

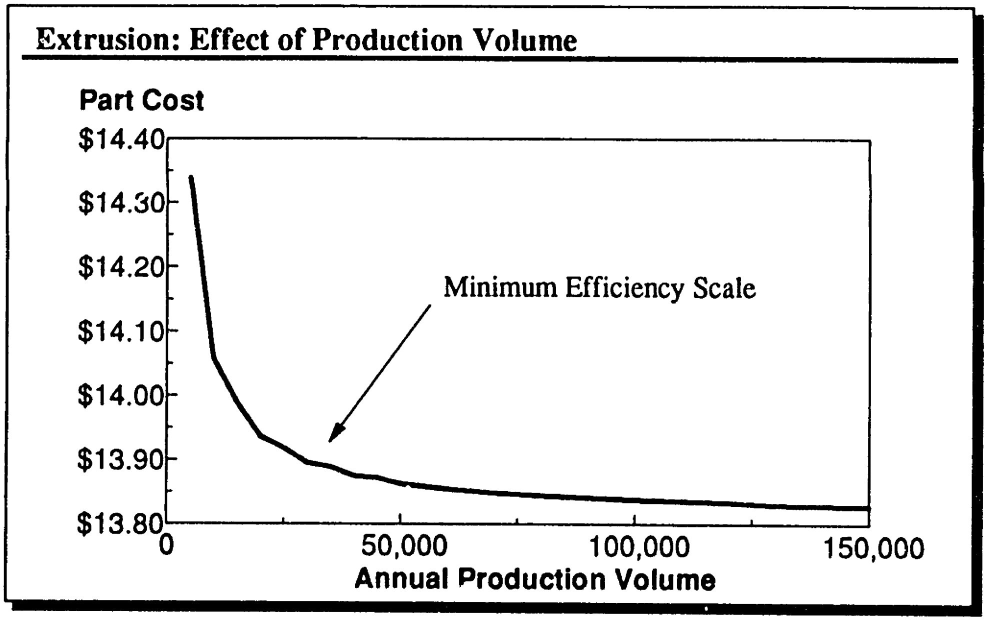

Figure 13.

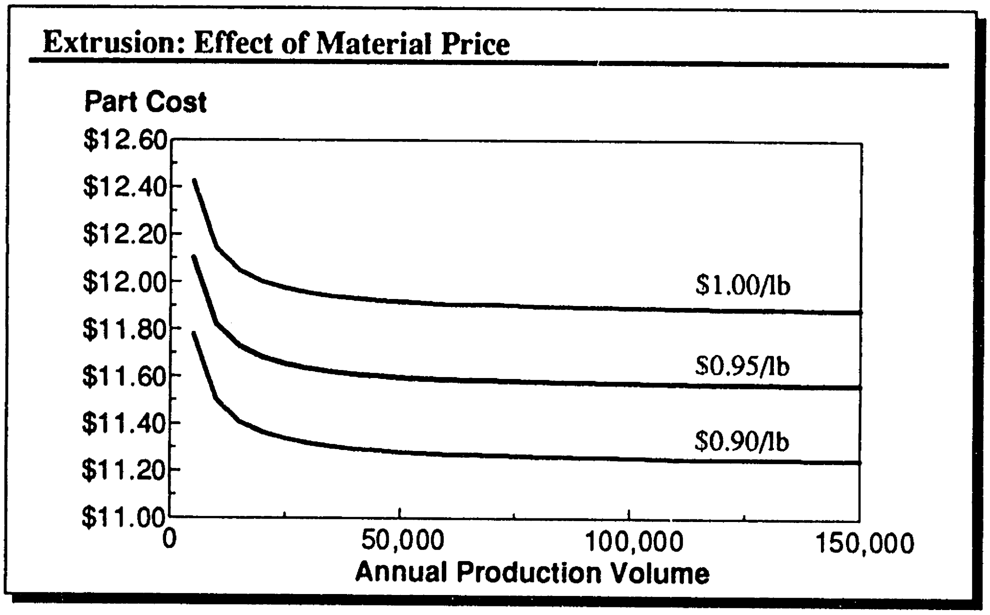

Figure 14.

Material Related Variables

The material cost content of the extruded materials draws attention to all material related variables. Firstly, the material price is a key factor. (Figure 14) As expected due to contribution of material cost, any increase in the purchase price of the alloy is significantly reflected in the cost of the extruded part. Furthermore, since the effects of the production volume are limited to the first few tens of thousands of parts, the gravity of this parameter persists throughout the entire production range.

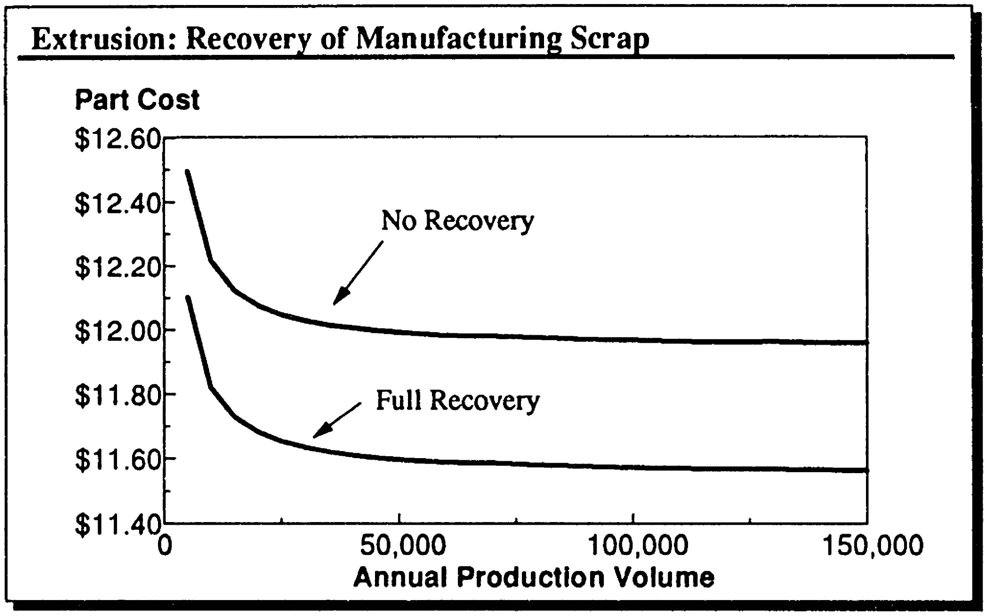

Figure 15.

The second factor, scrap recovery, is related to production management practices. The value of manufacturing scrap for aluminum is high, approximately $0.45 per pound. This creates an incentive to recover any material lost, either during the pressing cycle, or during quality control inspections. As shown in Figure 15, full recovery of production scrap leads to cost benefits that are equivalent to a 8% decrease in virgin material price. Although the scenarios depicted in the figure are, strictly speaking, the most optimistic and pessimistic ones, salvaging manufacturing scrap, often termed offal, is a relatively simple task with efficiencies possibly reaching perfection. Problems arise when the extrusion material changes. Mixing aluminum alloys results to downgrading the material, because properties vary significantly even with small changes in the alloy constituents. [Lyman, 1969] Again, simple practices create benefits. When the material changes, the press has to be cleaned before the new production run commences. It is standard practice to scrap the first few parts pressed because they do not meet specifications. These parts are usually out of tolerance because the flow of the material is not stable and because the die is still deforming. The time taken for extruding these pieces can be used to change the offal receptacles and to ensure the homogeneity of the scraped material. Furthermore, recovery does not entail any kind of investment. It is sufficient to have the already employed labourers keep the scraped material in designated places. In general, the time and effort required for this task does not necessitate any extra personnel.

Finally, the manufacturers should consider equipment that minimise material losses. The effect of the moving saw is depicted in Figure 16. The benefits from such machinery are related to the specifications of the part manufactured and one should not generalise on account of a single part. Also, it is not necessary that special equipment will produce any cost savings; as explained before the moving saw is applicable only if the production constraint is the length of the runout table. Therefore, the product mix of the press should be considered before deciding upon the purchase of such equipment. The extruder has to balance the material cost savings from efficiency enhancing equipment to the cost burden their purchase imposes.

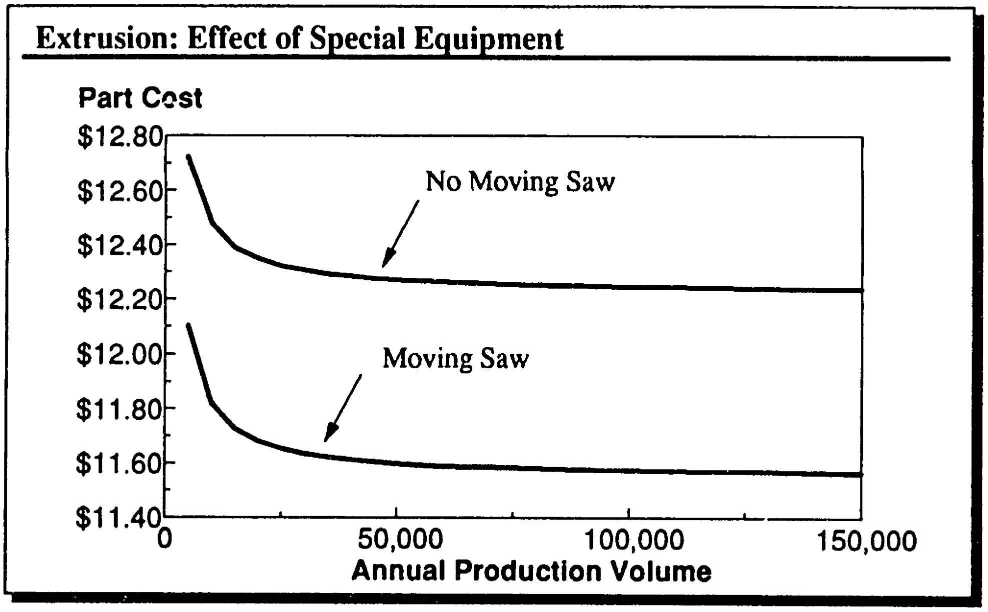

Figure 16.

Geometry Related Variables

The geometry of the extruded part defines some of the process variables and, thus, the total manufacturing cost. Firstly, the cross sectional area of the profile sets the maximum extrusion speed that can be achieved without an increase in defective parts. Although Figure 17 shows that varying the extrusion speed affects the part cost, the majority of the extrusions for structural automotive applications have to be pressed at, approximately, the same rate. On average, simulating the process with a fixed extrusion speed for all parts models effectively the pressing cycle and calculates accurately the part cost, for the mix of components produced.

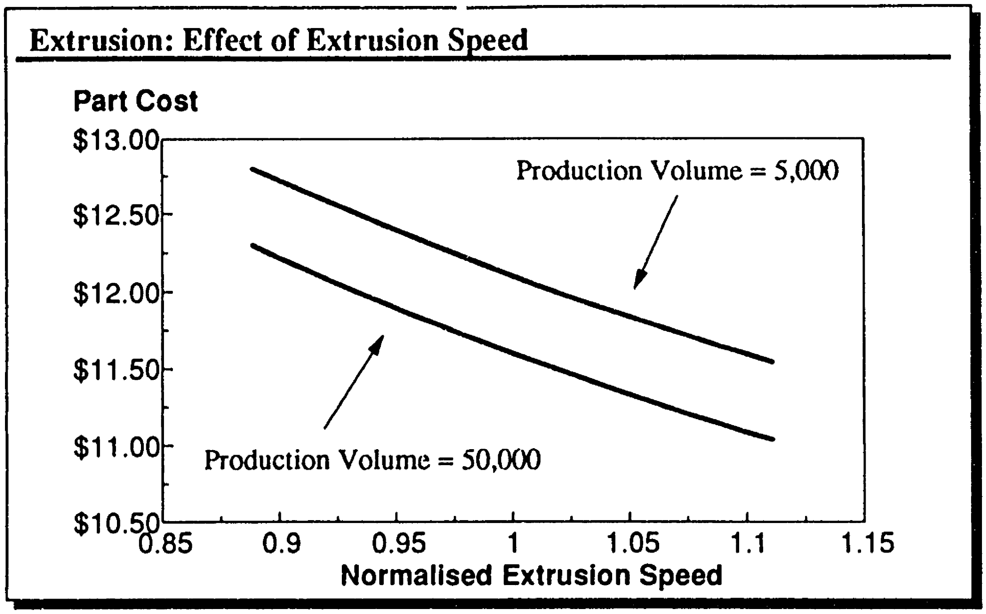

Figure 17.

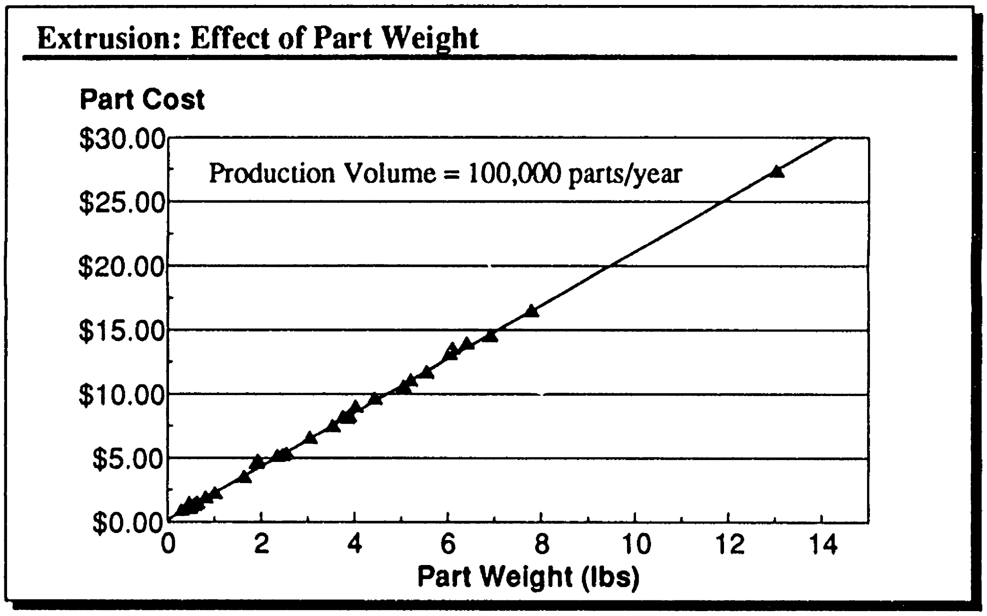

Figure 18.

Assuming a fixed extrusion rate leads to a linear correlation between part cost and part weight. The reason is that an overwhelming percentage of the piece cost accounts to non-dedicated elements. These elements increase linearly with size of the part. For a production volume of 100,000 parts per year, when the tooling cost is minimal, the fit to a line is satisfactory, yielding a cost of $2.15 per pound of extruded profile. (Figure 18)

The sensitivity analysis shows the volatility of the total part manufacturing cost as important parameters vary. It is therefore essential for reasons of accuracy to select these parameters wisely in order to simulate, as correctly as possible, the general extrusion practices. This will become even more apparent when the complete spaceframe design is cost modelled, because the weight of extruded components can exceed half of the total spaceframe weight.

6.2. Finishing Operations

The nature of finishing operations inherently renders the task of cost modelling difficult. There exist numerous methods of performing each of these operations and the main variable is the degree of automation employed. [Dhillon, 1989] More automated systems enhance the line productivity while imposing a higher initial investment burden. It has not been the intention of this study to examine which combination of equipment makes each finishing operation line more cost-effective. The contribution of these operations to the complete spaceframe cost are low, therefore, information on general practices suffice for a satisfactory cost assessment.

The most important parameters for this section are as follows:

Operation	No.	Variable	Equipment Cost	Tooling Cost	Rate[1] [per hr]
CNC-Milling	N/A	Milling Volume[2]	$250,000	$150	22
Drilling	1	No. of Drills	$90,000	$0	500
Punching	1	No. of Punches	$50,000	$10,000	350
Angular Cutting	1	Cross Sectional Area	$50,000	$1,000	1,210
Bending	1	Cross Sectional Area	$390,000	$4,000	261
Scrap Recovery	N/A	Material Recovered	N/A	N/A	N/A

[1] The rates included are for the part specified.

[2] In this case the milling volume is 10,000 mm^3.

Table 5. Finishing Operations' Equipment.

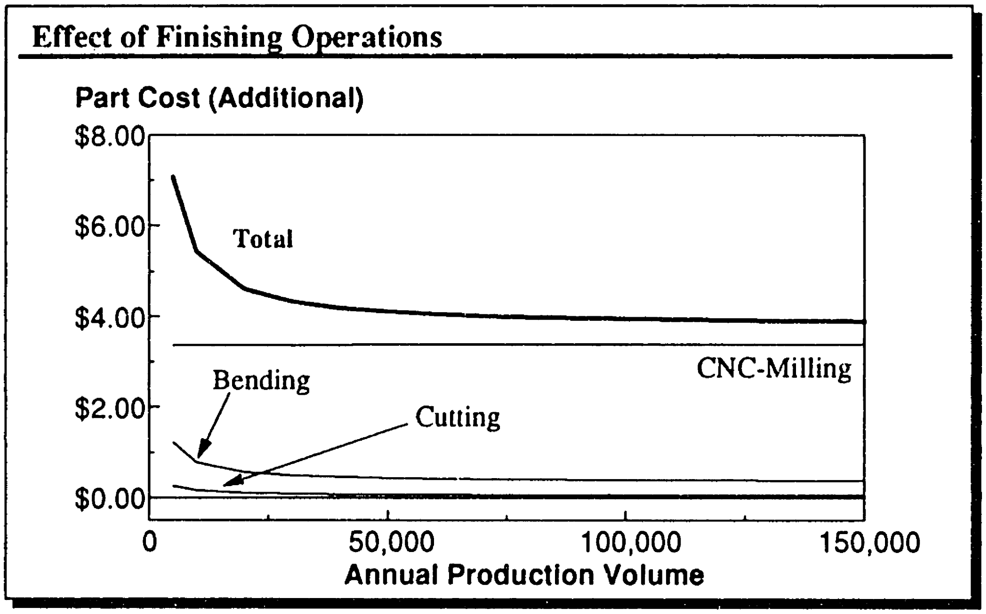

Figure 19.

Cutting, bending and CNC-milling are three finishing operations whose rates depend upon the geometrical characteristics of the part. Varying the production volume affects bending and cutting more than CNC-milling, because the tooling equipment for CNC-milling is proportional to the area milled and, therefore, independent of the parts produced. [Kalpakjian, 1989] (Figure 19).

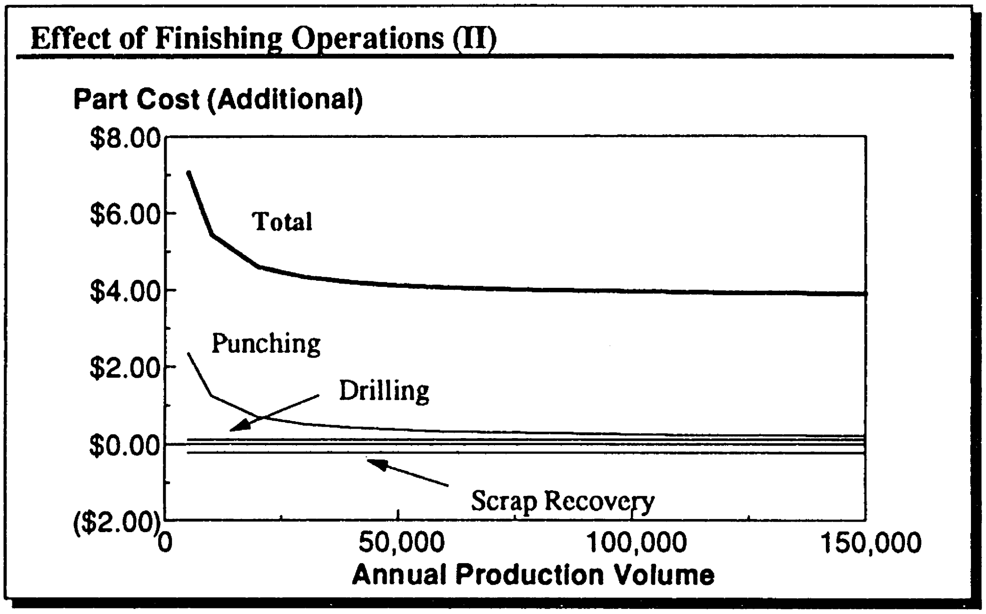

Figure 20.

Drilling and punching depend upon the number of such operations performed on the specific part manufactured. Clearly, this is an approximation, as the depth of the hole drilled or the size of the punch will affect the cost of the operation. The effect of the production volume is depicted in Figure 20, with punching being more sensitive than drilling.

The final important parameter is scrap recovery. The gravity of this parameter lies in the cost savings from retrieving and reselling the aluminum alloy, but also in the fact that the material has to be included in the preceding extrusion process. Hence, the cost of the finishing operations is not limited in themselves. They have repercussions to the extrusion process, since larger or longer parts have to be pressed. The technical cost models take account of this interdependence by including the percentage of the material scraped during the finishing operations into the weight of the extruded profile.

7. Part Production Cost Comparison

A preliminary assessment of designs can be carried out on the basis of their cumulative costs for part production. The results of such a comparison can lead one to drawing conclusions in a very limited scope, as not even the assembly cost for each design has been included, yet. However, some features of the cost components can reveal directions which should be pursued by automotive BIW designers.

7.1. Spaceframe Designs

This study has opted for examining three spaceframe designs in order to show the effects of different conceptual approaches to the same problem. In general, all spaceframe designs combine three available part forming operations, i.e. stamping, extrusion and die casting. The latter could, sometimes, be omitted. The quality of all extruded profiles and all die cast members is consistent for the entity of the parts manufactured. On the other hand, the quality of the stampings varies, depending upon the requirement these parts have to meet. As examined in other studies, [Han, 1994] stamped members of the BIW can be classified in four categories with the distinctive parameter being the complexity of their shape, the forming operation and the quality of their finish. Therefore, the cost structure for the stretched outer quarter panel with class-A finish is significantly different from the cost structure of the deep drawn floor panel with non class-A finish. The results included in this section of the study describe a representative mix of stampings applicable for the spaceframe design. More information concerning this stamping mix is included in Chapter 3.

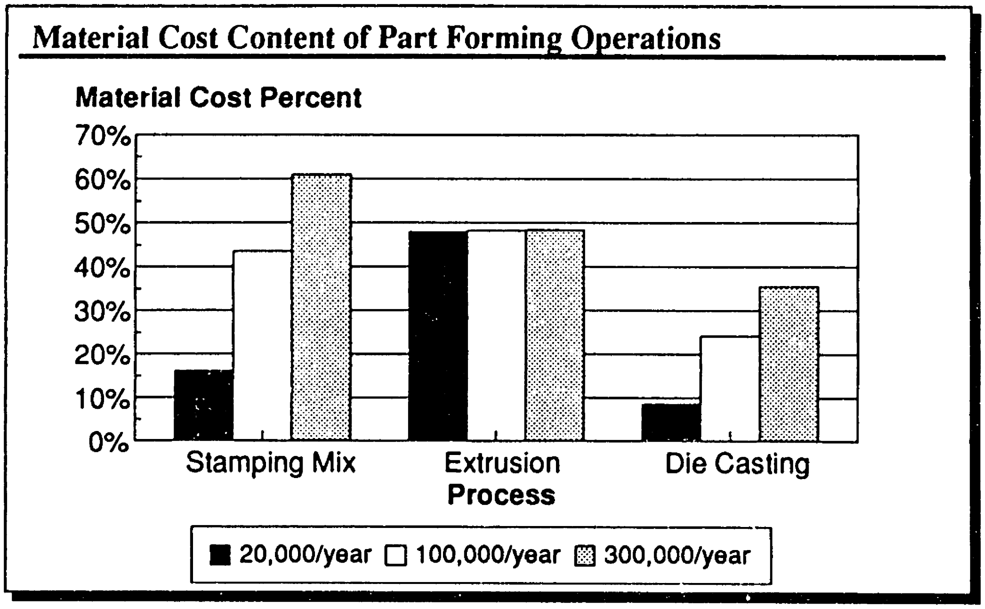

Figure 21.

The three manufacturing methods (stamping, extrusion, die casting) are extremely dissimilar, firstly in the way they exploit the formability characteristics of the material. [Kalpakjian, 1985] Consequently, the sensitivity of each process to the material cost shows inherently distinct patterns. (Figure 21) Stamping is the most sensitive process at high production volumes, however at low production volumes the material cost content of stampings is low. The same pattern is followed by die casting. On the other hand, extrusion portrays a fairly constant material cost content throughout the range of production volumes. This consistency in material cost content by the extrusion process is interpretable by the low degree of dedicated equipment. Figure 21 directs designers[5]

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[5] In this context, the term designer surpasses the notion of engineering design. The

towards the processes with larger fluctuations in material content. The benefits of these processes can be exploited at higher production volumes, although material price fluctuations can be more pronounced at the same high production volumes.

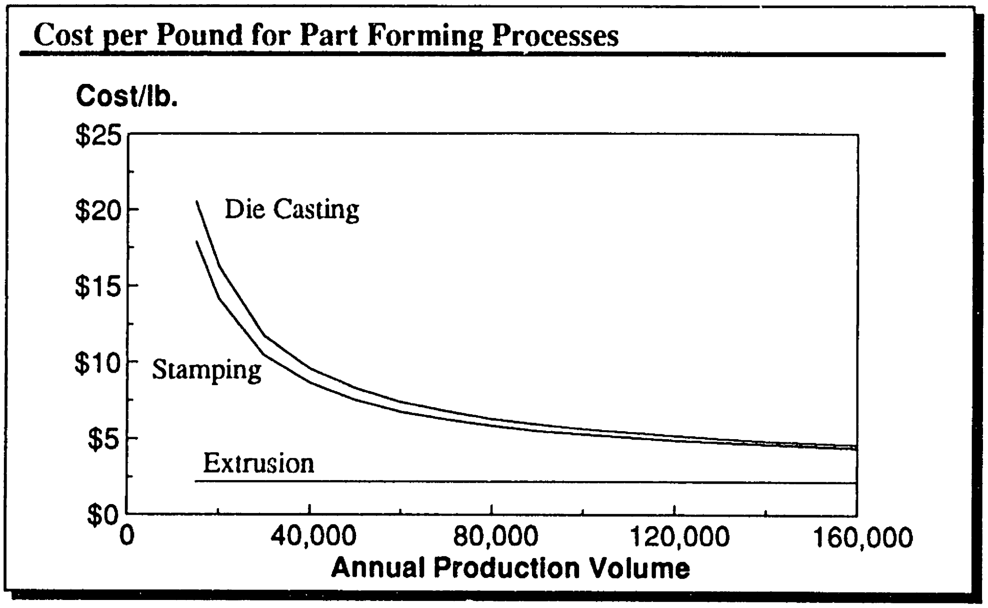

Figure 22.

A second feature which might interest designers is the variation with respect to production volume of cost per unit weight of the part manufactured. Figure 22 delineates the pattern for stamping, extrusion and die casting. As expected, the normalised cost shows a significant variation for stamping and die casting and is almost constant for extrusion. The importance of this figure is that it, firstly, enables designers to easily calculate the effects, on part cost, of alterations in the design specifications of the spaceframe. Secondly, it clearly drives them to implement designs with high weight

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evaluation is not limited to aspects of feasibility, performance, durability, etc. but is also extended to include the cost of manufacturing the product.

percentages of extruded profiles, at low production volumes. Essentially, Figure 22 provides all the cost-related information a designer might need, if one wanted to examine the interchangeability between parts manufactured using the three part forming operations. Although interchangeability cannot be completely grasped without accounting for assembly practices and because it is impossible to perform one-to-one process substitutions for a specific part[6], the cost-per-pound data yield a rough first-order approximation to the benefit or the burden associated with an alternative spaceframe design.

The disparity in design approaches is reflected on the part forming cost for each of the spaceframe designs. The following table gives a cost breakdown for each forming operation employed, for an annual production volume of 100,000 vehicles.

Forming Process	SF-1	SF-2	SF-3
Extrusion	$437	$325	$317
Finishing	$68	$50	$48
Stamping	$549	$522	$617
Die Casting	$0	$224	$530
--------------------	----------------	----------------	----------------
Total Part Cost	$1054	$1121	$1512

Table 6. Spaceframe Cost Content by Forming Process.

The respective weights of the parts for each forming operation are included in Table 7.

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[6] The three forming techniques yield products with completely different functional forms and aesthetic appeal.

Forming Process	SF-1 [lb.]	SF-2 [lb.]	SF-3 [lb.]
Extrusion	200	149	145
Stamping	105	95	112
Die Casting	0	40	75
--------------------	---------------	--------------	--------------
Total Part Weight	305	284	332

Table 7. Spaceframe Weight Content by Forming Process.

These results show that even at production volumes of the order of 100,000 vehicles per year, it pays to include as many extruded parts as possible. The second design, even though lighter than the first one, faces a part fabrication cost burden, because it utilises 30 lb. more of stamped and die cast members. The 51 lb. reduction in extruded profiles does not suffice to balance the additional cost of the stamped and die cast parts.

The results also point to a certain conclusion on the functional role of each of the metal mix components. At low production volumes, i.e. in the range below 100,000 parts per year, it is significantly cost-effective to minimise the amount of stampings in the spaceframe BIW. Therefore, stampings should be limited to strictly the parts that cannot, by any means, be substituted by extruded members. These are the floor panels and the outer panels. Furthermore, the outer panels should not be designed as load bearing members. The preceding analysis has revealed that it is far less expensive to integrate extrusions in the structural frame and to implement stampings solely as hang-on, exterior panels. This approach is the one of the SF-1 design. Unfortunately, even in this case, the cost of the stamped members is significant. The main reason is that the exterior panels, i.e. the roof, fenders and mostly the outer quarter panels, require many stamping operations each, because of aerodynamic, styling and aesthetic requirements. [Han, 1994]

7.2. Comparison Between Unibody and Spaceframe Designs

It is of interest to compare the part production costs of the three spaceframe designs to the ones of the steel and the aluminum unibodies. Although this comparison cannot be conclusive because assembly and use costs of the BIWs have not been evaluated, it is again a first order approximation. Hence, the five designs are compared for three arbitrarily chosen production volumes. (Table 8)

Annual Production Volume	**Steel Unibody**	**Aluminum Unibody**	**SF-1**	**SF-2**	**SF-3**
20,000	$3,345	$3,984	$1,995	$2,473	$3,820
100,000	$1,160	$1,591	$1,054	$1,121	$1,512
300,000	$745	$1,192	$901	$898	$1,129

Table 8. Part Production Cost Comparison.

The results reveal that there exists a production volume range where the all aluminum spaceframe can be cheaper than the steel unibody, as far as part production cost is concerned. The break-even production volume between SF-1 (or SF-2) and the steel unibody lies beyond 50,000 vehicles per year. (Figure 23) This is because at low production volumes the steel design is burdened by high capital investment requirements for the stamping process.

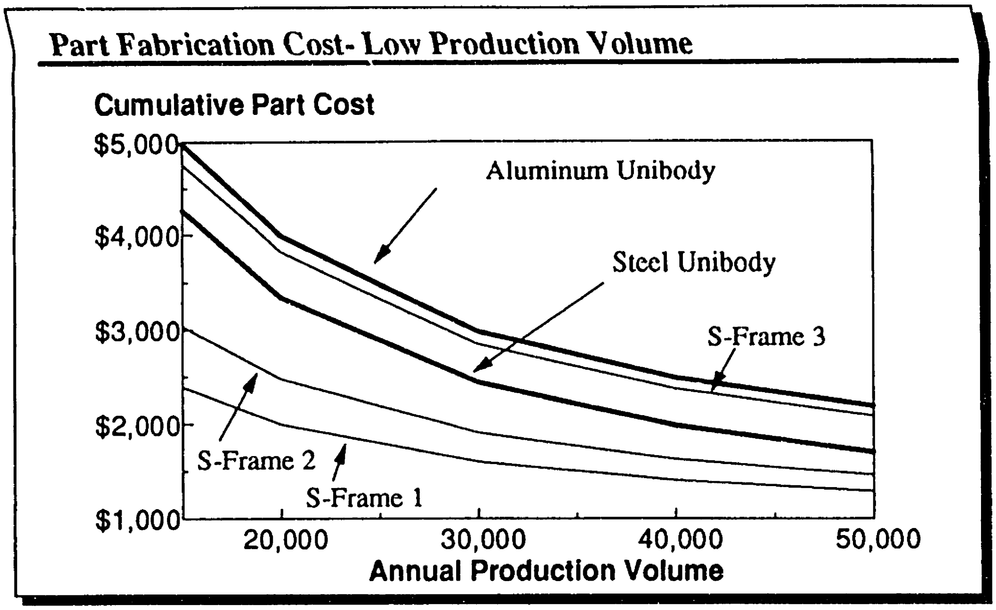

Figure 23.

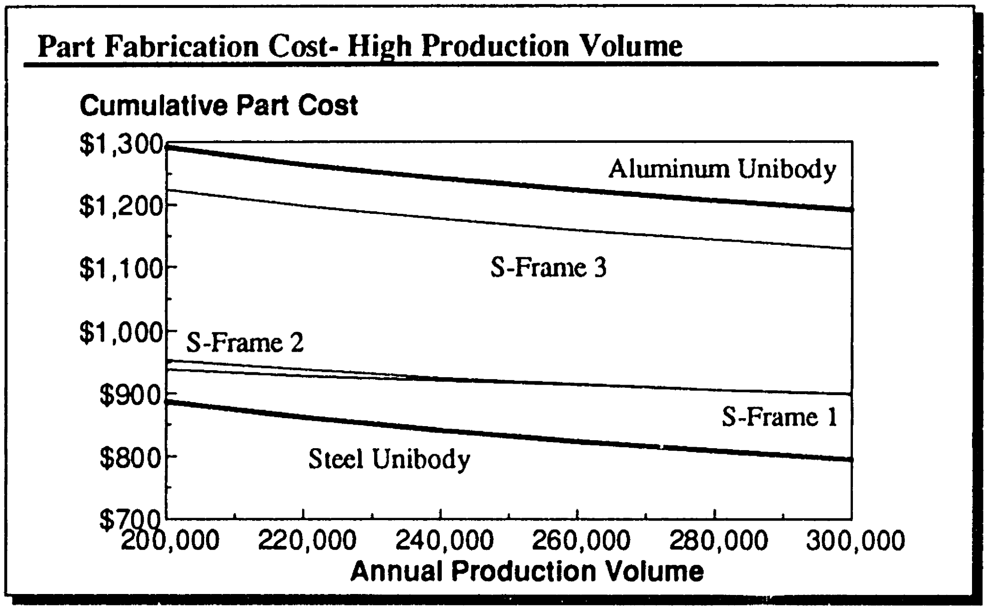

Figure 24.

Furthermore, there exists even a broader range of production volumes and spaceframe design approaches which render spaceframes less expensive than their aluminum unibody counterpart. Figures 23 and 24 show that all spaceframe designs fall below the aluminum unibody cost level throughout the production volume range of 20,000 to 300,000 vehicles per year.

The cost analysis of the five BIW designs establishes the importance of a holistic approach, even if the level of this analysis is limited to the part production cost. The material and design choices are reflected in the cost of the final product, in this case the BIW. Even if the designer has determined the material, both the general[7] and the specific[8] elements of the design can lead to substantial cost differences. Furthermore, the desired production volume affects the rank of the possible configurations. All other attributes being the same between the five designs, one would probably choose SF-1 for production at very low production volumes and the steel unibody at high ones. However, one should examine the entity of costs associated with the BIW before any valid conclusions are to be drawn.

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[7] E.g. unibody versus spaceframe design strategies.

[8] E.g. metal component mix in the spaceframe design, or the use of castings.

8. Assembly of the Body-In-White

The assembly stage is the point in the vehicle manufacturing process where the individual components of the BIW are integrated into a single structure. Ideally, the connecting points between parts, i.e. the joints, have to be inobtrusive. Furthermore, they have to retain the mechanical properties of the materials joined and they should not create any physical discontinuities. In practice, no joining technique can meet these elusive quality specifications. Instead, the effects of the joining methods are factored into the design of the specific BIW.

In the case of the steel unibody, it seems that resistance spot welding has been proven to be the most effective joining method. Almost all designs advancing into production employ resistance spot welding as their sole joining technique. However, the introduction of alternative materials forces the designers to reconsider their choices for the joining methods. The material properties of the new material combined with the structural and economic shortcomings of resistance spot welding pave the way for alternative joining processes. For the aluminum spaceframe, multiple joining methods, such as arc welding, adhesive bonding and mechanical fastening, seem to satisfy the structural and manufacturing requirements. [Automotive Engineering, May 1992]

The pertinent features in the selection of joining methods lie, primarily, in the structural requirements the joints have to meet. Because the automotive body structure is mainly designed for stiffness, the loads structural parts have to sustain are relatively light.

Therefore, the joints have to be able to effectively transmit only these light loads. [Nordmark, 1993] There exist, also, some areas where the limiting condition is strength, e.g. the suspension and the engine mounts. In these areas, designers need to focus in the fatigue characteristics of the BIW structure. [Seeds, 1989]

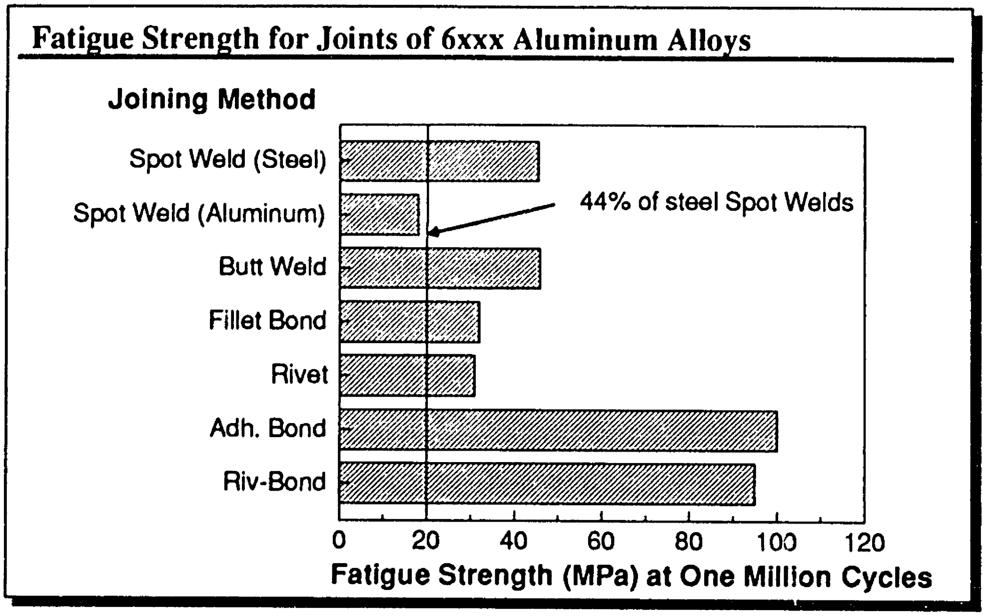

Figure 25.

The rationale behind the potential utilisation of new joining methods is based on the reduced performance needed by the joints in a BIW with lightweight materials. For example, in an aluminum unibody there exists the potential of a 40% weight reduction in the BIW compared to the steel unibody. [Han, 1994] The average thickness of the stamped aluminum panels is approximately 1.72 times that of the steel panels. If secondary weight savings are realised, the reduction in the curb weight of the vehicle is of the order of 25%. Basing the analysis on these two last generalisations, one can calculate that the aluminum BIW has to accommodate stresses that are only 44% of the stresses in the steel unibody. [Automotive Engineer, May 1993] Even if this simplistic approach may not be entirely correct, the ballpark result reveals that more joining techniques can meet the lower loading requirement for the aluminum unibody. (Figure 25)

However, the alternative joining methods are not devoid of issues. Especially, if the production volume is high, there might exist problems in achieving the process rates required without overly degrading the quality of the joint. The following paragraphs describe the important features of the potential joining methods.

Spot Welding: The main issues concerning resistance spot welding have been discussed in other essays. [Han, 1994][Automotive Engineering, August 1993] The predominant shortcoming of this technique is that the properties of aluminum do not allow for a cost-effective application. The sheer number of spot welds, the low weld tip life and the high energy requirement for this process render it increasingly more costly.

Arc Welding: Arc welding, in the form of metal inert gas (MIG) welding, has the advantage of maintaining the strength of the parent material by 80 to 90%. [Aluminum Association, 1977] It is a fairly familiar process which can be automated if mass production is envisaged. However, the fatigue performance of the joint is strongly influenced by the local design configuration and by any discontinuities in the weld line. In some cases, the heat affected zones [Nordmark, 1993] might require post-weld heat treatment to enhance the properties of the joint. Alternatively, the joint design has to accommodate the deteriorated performance, i.e. the weak link, by reducing the direct and shear stresses born by the heat affected zones. Finally, the weldability of castings is questionable. [Automotive Engineer, May 1993] The dissimilar alloys joined may lead to excessive losses in the mechanical properties of the joint.

Adhesive Bonding: Adhesive bonding has the major advantage of joining dissimilar materials without affecting the quality of the individual components. This type of joining is more suitable for thin parts, as the failure load of the joint is strongly influenced by the gauge of the parts. [Automotive Engineering, August 1994] Furthermore, the adhesive always acts a sealant. However, adhesive bonding suffers from quality assurance issues. The strength of the joint depends predominantly upon the size and uniformity of the fillet[9]. Studies have shown that a perfect fillet has the same effectiveness as one with four times its size, if the latter one has certain defects[10]. [Automotive Engineering, August 1994] In addition, adhesive bonding for automotive applications imposes further constraints on the type of resin used. This resin should be "tough", i.e. it should deform in a ductile manner to avoid catastrophic failure with minimal energy absorption. The same resin should have adequate wetting characteristics [Kewley, 1987], good slump resistance and the dispensing equipment should incorporate preventive means for excess application. The requirements described above lead to increased costs for the adhesive material and the equipment employed to perform the joining.

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[9] The fillet is defined as the adhesive joining the two metal parts.

[10] These are mainly undersized bead diameter, misaligned flanges and flanges without adhesive.

Mechanical Fastening: Mechanical fastening encompasses riveting, bolting and clinching. These processes tend to be easier and more effective if the parts to be joined are thin. Moreover, these processes can join dissimilar materials. However, they all suffer in the area of joint stiffness. Riveting, as well as bolting, demands material consumables and increases the joint thickness. [Nordmark, 1993]

The advantages of more than one joining techniques can be exploited, if compatible combinations of the processes described above are implemented. For instance, if the joint experiences high stresses, then it could more appropriate to employ both bonding and riveting. Clearly, the individual characteristics of each of the joining techniques dictate the order in which the operations must be performed. In the bond-rivet case, it is more appropriate to commence with the riveting as this would also act as a means of fixturing. If the adhesive were cured first, riveting would introduce cracks in the fillet, thus greatly reducing the ability of the fillet to withstand direct stresses. In a weld-bond case, the welding can only be performed when the adhesive is uncured, because overcuring the adhesive during welding deteriorates the strength of the bond.

Technical cost modelling for the assembly of the BIW has to incorporate the flexibility of selecting whichever combination of joining techniques. The TCM used for the spaceframe design is the same as the one introduced in Reference [Han, 1994]. The modular form of this model allows the user to choose between the joining techniques quite easily and to combine any of them at will.

The most significant parameter in the TCM remains the joint length. Appendix II includes all the pertinent information for the three feasible spaceframe designs examined in this study. This information reflects the variety of interleaving approaches from experts in the aluminum and automotive industries. Another important manufacturing parameter is the number of subassemblies. Figure 26 depicts the standard manufacturing process for the aluminum spaceframe. The cumulative cost of the assembly operation depends upon the number of subassembly stations, as the amount of dedicated and non-dedicated equipment varies between a single and a multiple stage assembly process.

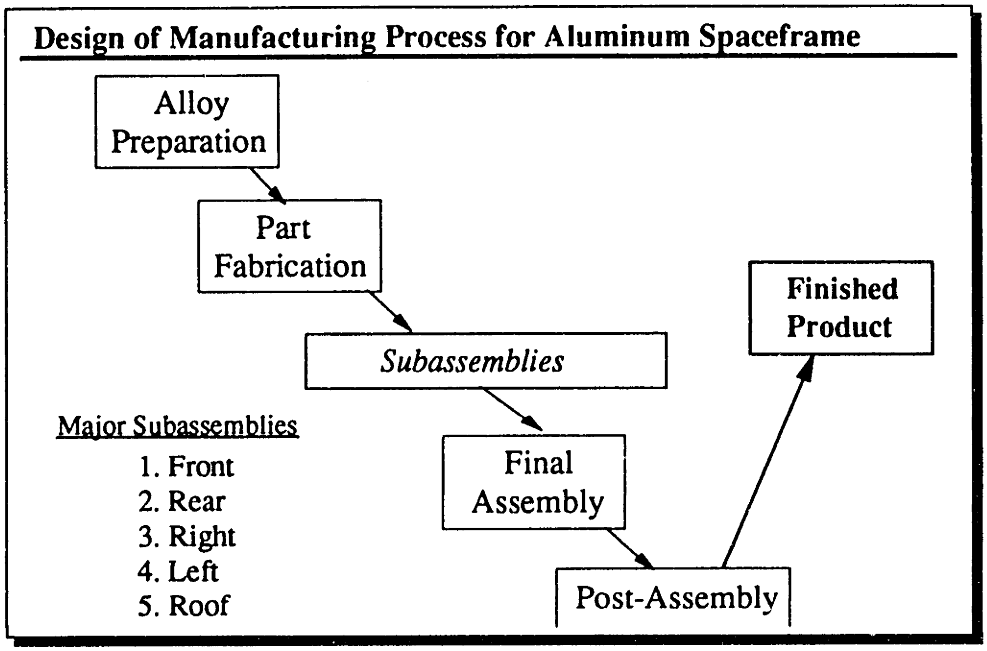

Figure 26.

9. Assembly Cost Results

The assembly process becomes of interest because of its high contribution to the total Body-In-White manufacturing cost. For the base case of the steel unibody, the joining method is standard spot welding, as is the case for the aluminum unibody design. For the three spaceframe designs, the joining technique is a combination of spot welding, adhesive bonding, arc welding and mechanical fastening. The exact mix of these operations is detailed in Chapter 3.

In the process of modelling the assembly stage, it is important to keep in mind the versatility in the available operation set-ups. For instance, it is standard practice to increase the degree of automation as the production volume for the BIW increases. Therefore, one should expect more labour-intensive procedures at relatively low production volumes and high equipment costs for larger ones. This study has attempted to capture this feature by assuming different configurations for each of the assembly lines. At certain production volumes, the model has been adjusted to alter the line set-up from a labour-intensive one to one with a higher degree of automation. Although this change leads to artificial steps in the assembly cost per BIW, examining the assembly cost at ranges that are not very close to the step should yield results with acceptable accuracy.

The three spaceframe designs have been proposed for certain production volume ranges. Given the large number of combinations in part forming operations and joining methods, the proposed designs portray the experts' opinions on the implementable designs for the specified production volume. It would therefore be somewhat irrelevant if the assembly set-ups for each of the three spaceframe designs were assessed at volumes for which they were not meant. However, the three spaceframe designs collectively span the 5 to 300 thousand bracket for the annual BIW production volume.

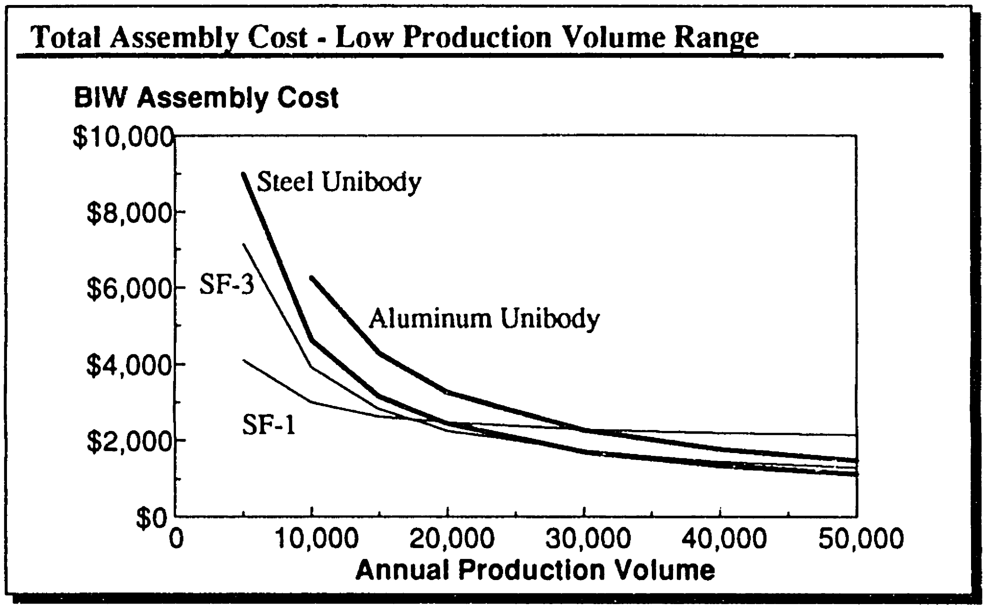

Figure 27.

Despite the vast number of variable parameters for each joining operation, there are a few general points that can be made. Spot welding is the most sensitive joining technique to the production volume. Arc welding, adhesive bonding and mechanical fastening, in the form of either riveting or bolting, require consumables which render them inherently more stable. In the spaceframe configurations examined, it was found that the costs of each of the joining methods were of the same order of magnitude. This result means that the decrease in assembly cost cannot be expected to be radical with increasing production volumes. On the other hand, for the two unibodies, significant cost savings are realised as the production increases. (Figures 27, 28, 29) The total assembly costs for each of the designs were as follows:

Annual Production Volume	Steel Unibody	Aluminum Unibody	SF-1	SF-2	SF-3
20,000	$2,429	$3,265	$2,467		$2,253
100,000	$1,385	$2,011		$1,804	$1,279
300,000	$622	$866			$1,275

Table 9. Assembly Cost Comparison.

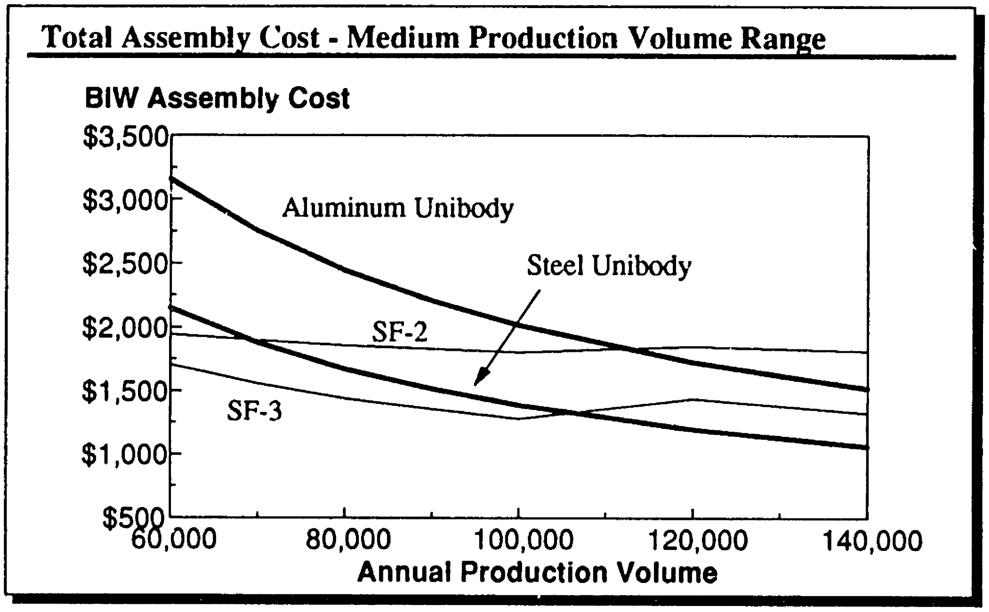

Figure 28.

A considerable cost contributor to the assembly cost of the three spaceframe designs is the extent of rework the assembled BIWs require. The information on Audi's A8 is that the amount of rework is substantial. [Roth, 1994] Although this cost has not been included in the results of this section, it is most improbable that it will exceed $100 per BIW assembled. [The cost of $100 approximately corresponds to 3 labourers reworking for a full hour on each BIW.]

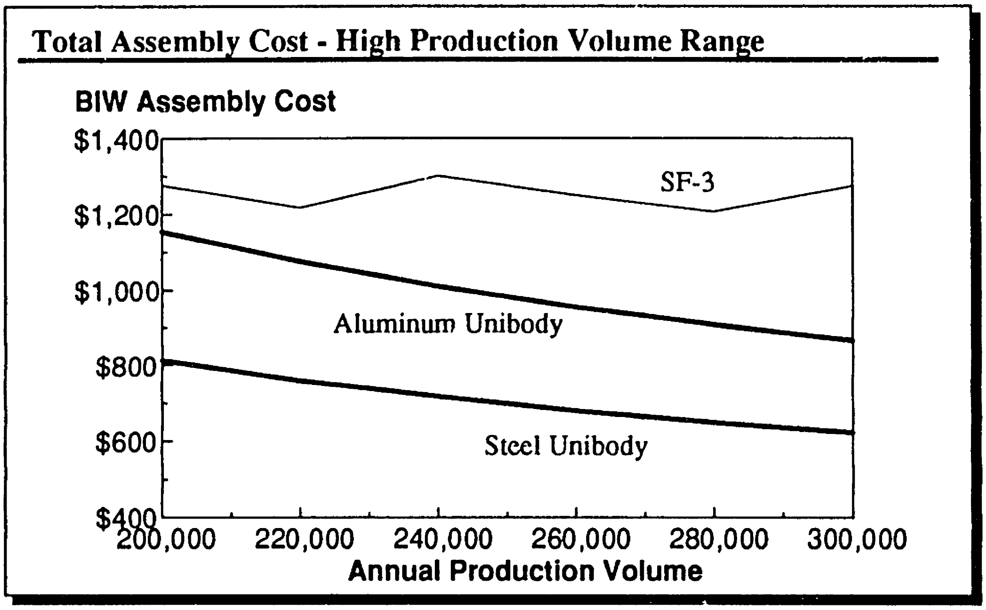

Figure 29.

The first conclusion that can be drawn from the assembly cost results is that the mixture of joining techniques for SF-1 can compete in cost with the spot welded steel unibody. (Figure 27) The low production volume assigned to SF-1 permit the exploitation of the cost benefits associated with the labour-intensive assembly methods. To the contrary, spot welding becomes extremely cost-effective at the high end of production, where even the aluminum unibody BIW assembly turns up to be cheaper than the SF-3 spaceframe design one. (Figure 29) In the middle range of 60 to 140 thousand BIWs per year, the spaceframe designs compete with both the steel and aluminum monocoques. (Figure 28)

10. Production Costs

This section combines the individual costs of producing the parts which form the automotive BIW for the five designs and the cost of integrating these parts into a single structure. Essentially, this is the cost that automotive producers face if they select to manufacture each of these designs. Furthermore, these costs are a measure of the price that automobile users will be asked to pay for purchasing the respective BIWs. The total production costs for the designs were found to be as follows:

Annual Production Volume	**Steel Unibody**	**Aluminum Unibody**	**SF-1**	**SF-2**	**SF-3**
20,000	$5,774	$7,249	$4,471		$6,073
100,000	$2,545	$3,602		$2,926	$2,792
300,000	$1,417	$2,056			$2,404

Table 10. Total BIW Production Cost Comparison.

In low production volumes, one can observe that the aluminum spaceframe could hold a cost advantage towards the steel unibody. (Figure 30) SF-1 proves to be cheaper to produce up to volumes of approximately 34,000 vehicles per year. Furthermore, in the same range, both the aluminum spaceframe designs, i.e. SF-1 and SF-3 are less expensive than the aluminum unibody.

In the middle range of production volumes, the steel unibody becomes the least expensive option. (Figure 31) The spaceframe designs SF-2 and SF-3 compete with each other and become almost equally expensive to the aluminum unibody around the 150,000 vehicles-per-year mark.

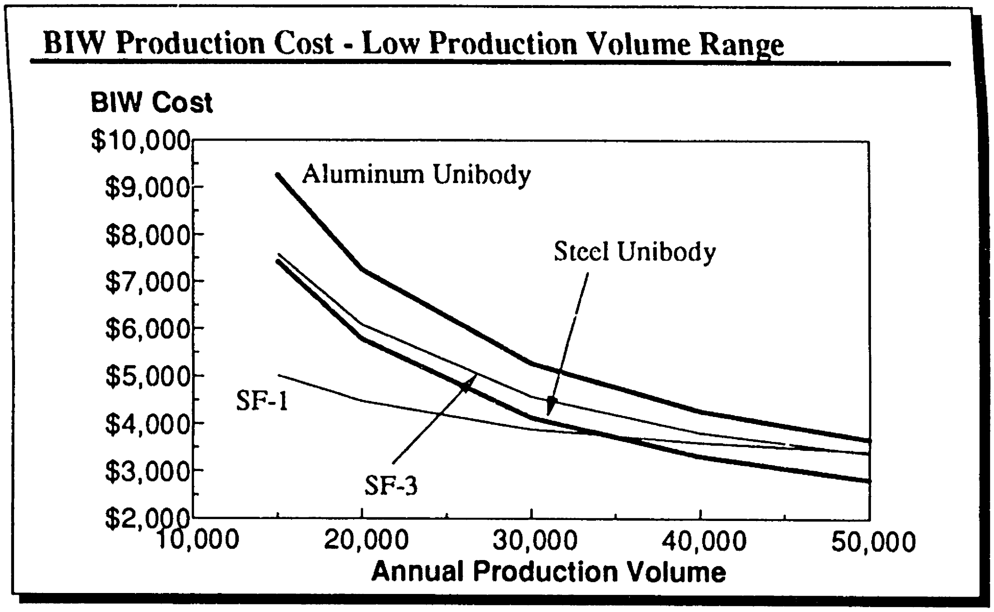

Figure 30.

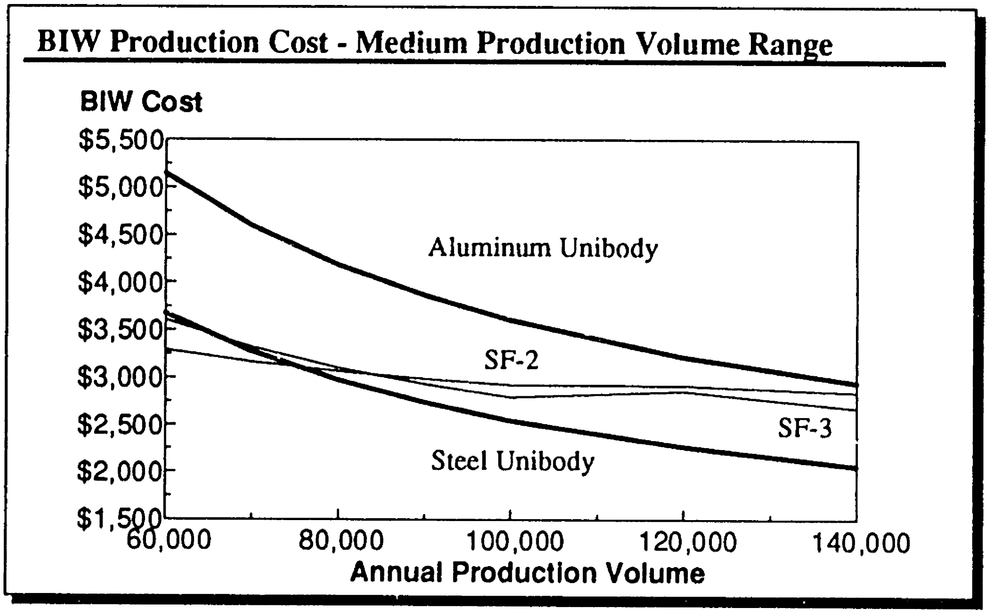

Figure 31.

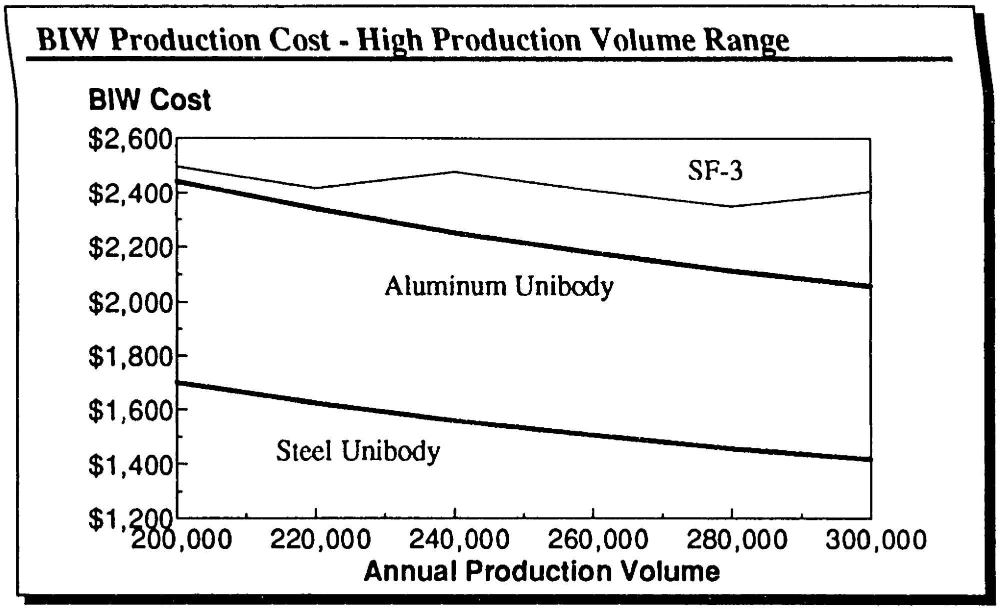

Figure 32.

In the high range of production volumes, the spaceframe does not seem to be able to compete, on cost, with any of the unibody designs. (Figure 32) The two monocoques are manufactured using stamping and spot welding. These two processes require expensive dedicated equipment which render the unibody designs cost effective in the high end of production. On the other hand, the production methods for the spaceframe cease to exhibit any economies of scale at large production volumes.

11. Use and Post-Use Cost Calculation

During the useful lifetime of a vehicle, the owner needs to allocate some funds in order to keep the vehicle in working condition. These expenses consist of repair and maintenance costs, insurance premiums and the cost of purchasing gasoline. Altering the material of the BIW affects the magnitude of these costs, depending upon the specific design characteristics of the BIW.

The costs of repairing and insuring the aluminum BIWs are the hardest to quantify. Previous studies have shown that it is probable for aluminum vehicles to be more expensive. [Automotive Industries, Feb. 1992] However, none of the currently available studies has managed to juxtapose vehicles in the class of the base case Ford Taurus, as aluminum has only been employed for the luxury vehicle market. Furthermore, the number of all aluminum vehicles is relatively small and therefore this small sample size could result in non-representative conclusions on the repair, maintenance and insurance costs for the aluminum BIWs. [Tversky, 1974] For the reasons stated above, this study assumes that all costs other than fuel costs are equal between the five designs examined.

Applying the assumptions which are included in Figure 33, it is quite straightforward to evaluate the annual cost of powering the steel vehicle. [MVMA, 1991][DOE, 1988] [Bush, 1994][Aut. News, 1992][Han, 1994] Discounting to the present value renders the annual cash flows into an equivalent single quantity. The discount rate is calculated by subtracting the current inflation rate from the relevant interest rate. [Hausman, 1979]

Vehicle Use Cost Assumptions

■ Vehicle Average Useful Life	12.5 years
■ Vehicle Average Annual Mileage	10,250 miles/year
■ Vehicle Average Fuel Economy	
– Base Case	Ford Taurus
– City Cycle	18.0 miles per gallon
– Highway Cycle	26.0 miles per gallon
– EPA 55/45 cycle	21.6 miles per gallon
■ Unleaded Gasoline Price	$1.20/gallon (inflation-adjusted)
■ Annual Discount Rate	10%

Figure 33.

In contrast to the previous section of this study, one has to mention that it is impossible to assess the cost of powering the automotive BIW. The comparison must be based on the complete vehicle, because weight savings do not correspond to linear reductions in gasoline consumption. However, the differences in use cost still remain meaningful, as they reflect the cost savings arising from weight reductions in the BIW structure.

The effects of lightweighing on fuel consumption have been studied extensively. [Ibis, 1992][DeLuchi, 1993][OECD, 1980][SRI International, 1991][Martchek, 1995] Although these studies do not yield exactly the same results, they provide a useful working framework. As Figure 34 shows, the varying results form a bounded region of possible gains in miles-per-gallon travelled, for each value of BIW weight. The average value of the studies is included as the most probable scenario. The mpg for each design and the present value of the lifetime use costs for the five BIW designs are portrayed in Tables 11, 12.

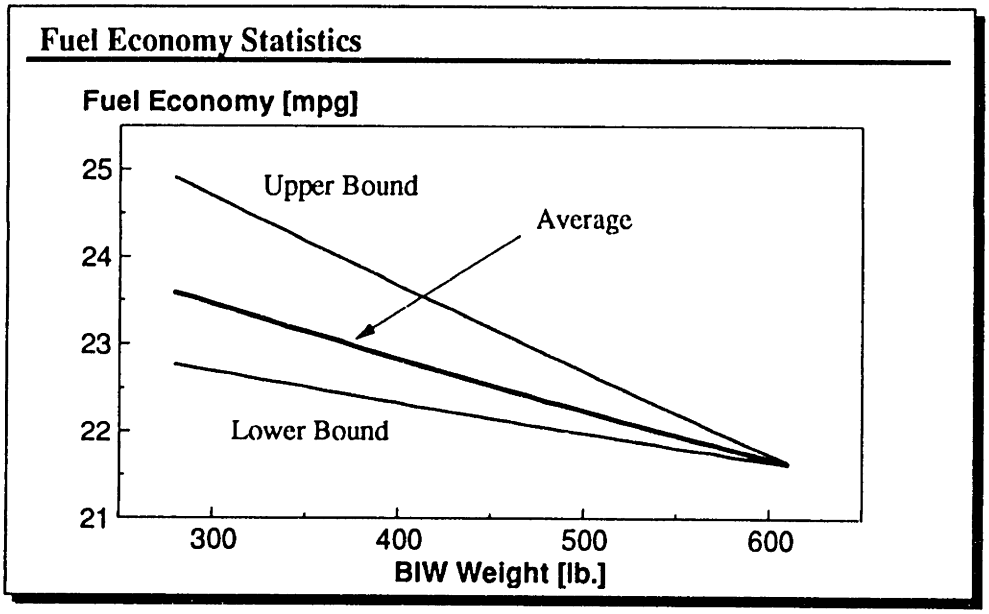

Figure 34.

Miles Per Gallon	Steel Unibody	Aluminum Unibody	SF-1	SF-2	SF-3
Lower Bound	21.6	22.66	22.68	22.76	22.58
Average	21.6	23.4	23.43	23.57	23.26
Upper Bound	21.6	24.6	24.65	24.87	24.37

Table 11. Vehicle Fuel Efficiency.

Lifetime Fuel Cost	Steel Unibody	Aluminum Unibody	SF-1	SF-2	SF-3
Upper Bound	$3,961	$3,776	$3,773	$3,760	$3,789
Average	$3,961	$3,656	$3,651	$3,630	$3,679
Lower Bound	$3,961	$3,478	$3,471	$3,440	$3,511

Table 12. Vehicle Lifetime Fuel Cost.

The final stage in the life of the automobile is the disposal stage. At this point, the vehicle has no more transportation value to the owner and has to be discarded. The monetary effects of this stage are restricted to the salvage value of the metallic BIW. Discounting the value of the hulk to the present day, using the same discount rate as before, yields the following cost benefits from the disposal phase. The salvage value for the two metals has been assumed to be \$0.05 for steel and \$0.30 for aluminum per pound.

Salvage Value	**Steel Unibody**	**Aluminum Unibody**	**SF-1**	**SF-2**	**SF-3**
Cost Benefit	\$7	\$20	\$20	\$18	\$22

Table 13. Vehicle Salvage Value.

Although the spaceframe designs are comprised of a mixture of aluminum alloys, the salvage value of the spaceframe material is assumed constant on a per pound basis. The magnitude of the disposal stage costs, when compared to the other lifetime costs, allows for this simplification. As can be seen from the preceding analysis, disposal cost differences are merely in the order of ten dollars, whereas production and use cost differences can be in the order of thousands of dollars.

12. Interest Group Lifecycle Costs

In examining the benefits of any new automotive design, one has to assess how these benefits are allocated between the relevant interest groups. If the sole attribute for each BIW is considered to be its monetary cost, then it is possible to assess the desirability of any new design. The base case constitutes the benchmark by which every other BIW is evaluated. If the new design proves to be cheaper than the steel base case, then one may safely conclude that this design proves to be of higher merit than the base case. In this section, the sole attribute examined is the monetary cost; all other attributes are assumed to be equal between the five designs.

The automotive manufacturers have the liberty of setting the selling price of the vehicle. However, the price set by automobile producers for each vehicle also determines its acceptability by the market, because the consumer interest group can dictate its preferences by choosing amongst the available alternatives. If the only attribute is monetary cost, then the latter group will opt for any of the new designs, if they prove to be less expensive than the base case steel unibody. Therefore, a higher price than the steel unibody will most probably lead to lower sales for the specific model. It is, hence, relevant to establish the additional profits (or losses), for manufacturers, which are associated with attempting to sell the new designs at the same price as the base case steel unibody. Since all attributes at the selling point are equal, this would ensure at least the same acceptance by the market. The additional profits or losses calculated this way mark the lowest benefit achievable by the automobile manufacturers. The highest ones can be deduced if the savings arising in the use stage are also captured by the manufacturers. In essence, the assumption underlying this calculation is that the producers set such a price as to render the life time costs born by the users equal to the one of the steel unibody design.

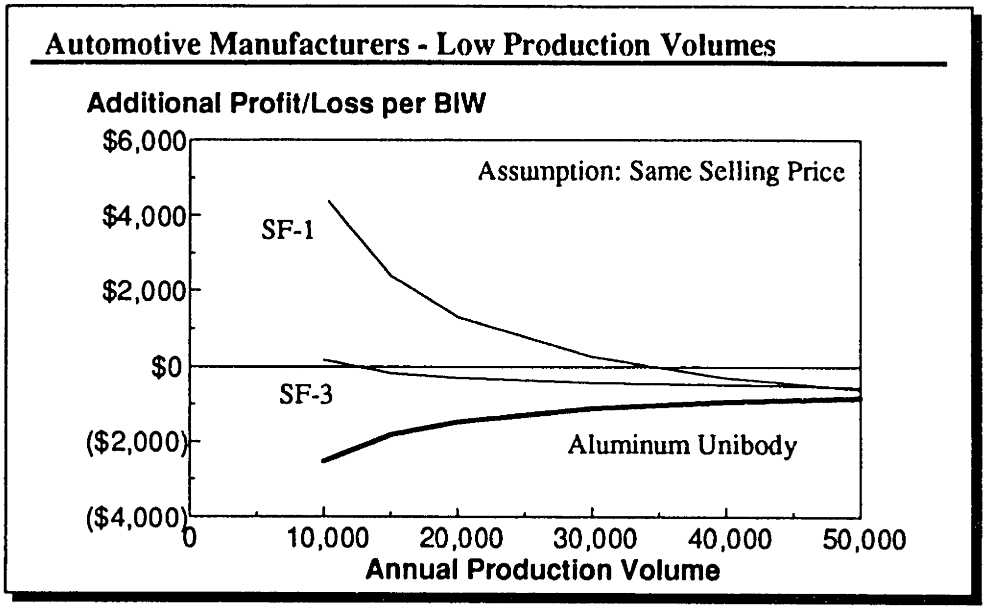

Figure 35.

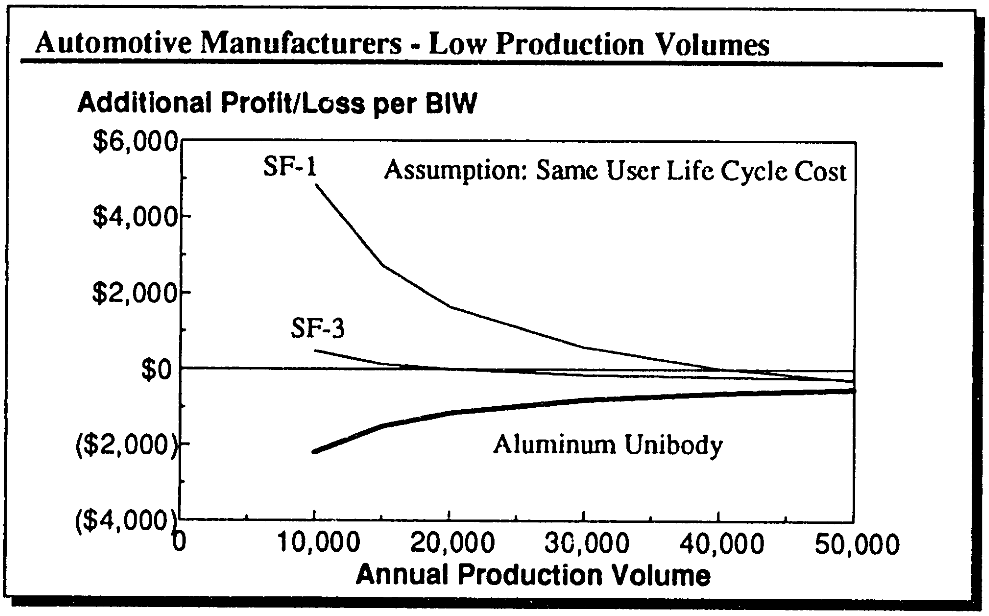

Figure 36.

In low production volumes, under the assumption of the same selling price, SF-1 proves to be more desirable than the steel unibody for production volumes lower than approximately 34,000 vehicles per year. (Figure 35) If the use cost savings are included, this range extends to a production volume of approximately 40,000 vehicles per year. (Figure 36) Note that the aluminum unibody design cannot contest the steel design, even if the use cost savings are based on the optimistic upper bound results. Finally, both SF-1 and SF-3 are at least equally as desirable as the aluminum monocoque.

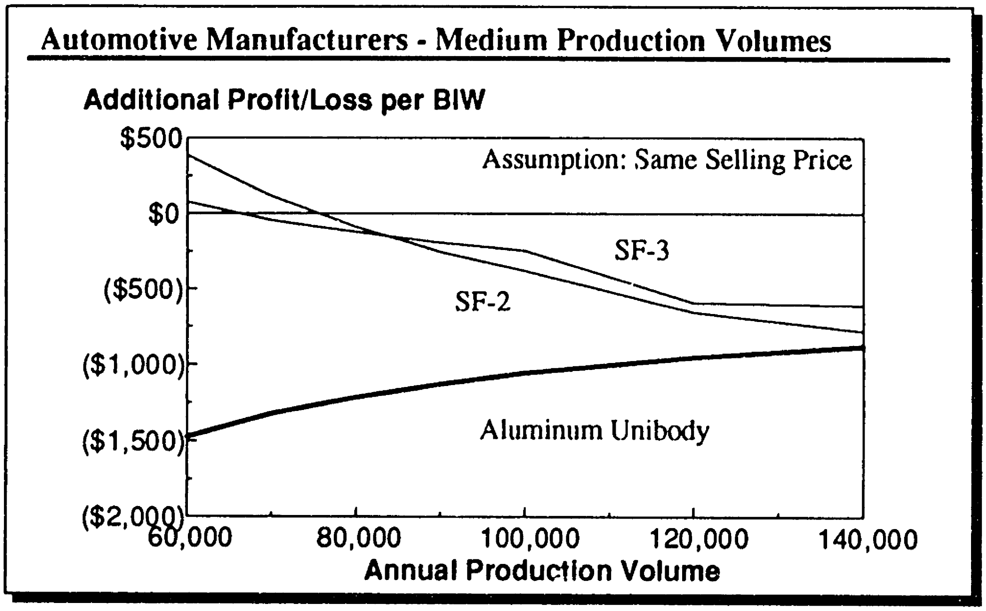

Figure 37.

In medium production volumes, all aluminum designs fall short of their steel counterpart. (Figures 37, 38) If one examines the costs not adjacent to the 50,000 production volume mark[11], the two spaceframes and the aluminum unibody lead to losses of, at least, $200

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[11] The 50,000 production volume mark portrays an artificial burden on the unibody designs. (See Chapter Assembly)

per BIW sold. If the assumption of same user lifecycle cost is applied, SF-2 and SF-3 prove profitable below approximately 100,000 BIWs per year.

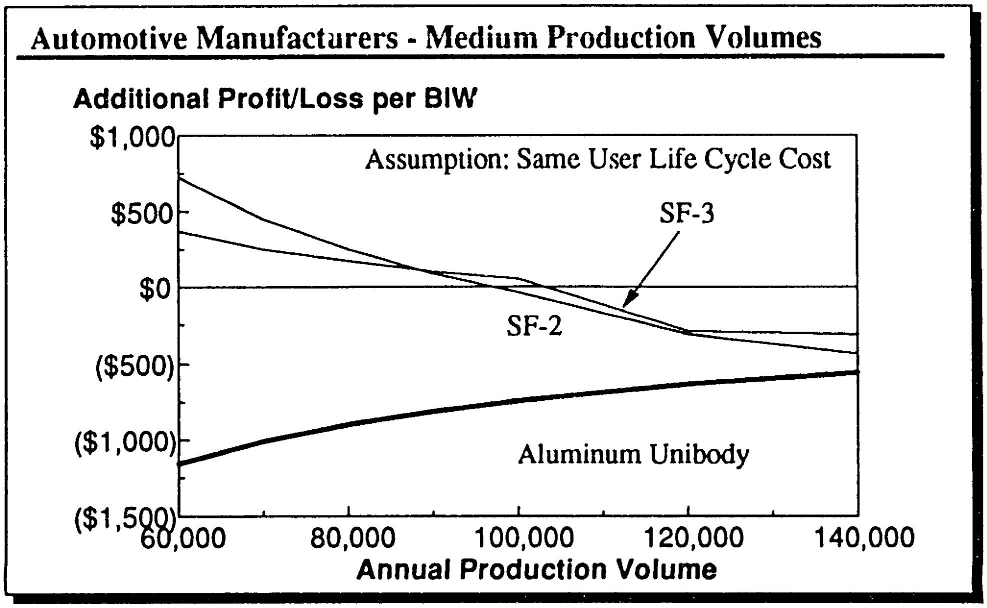

Figure 38.

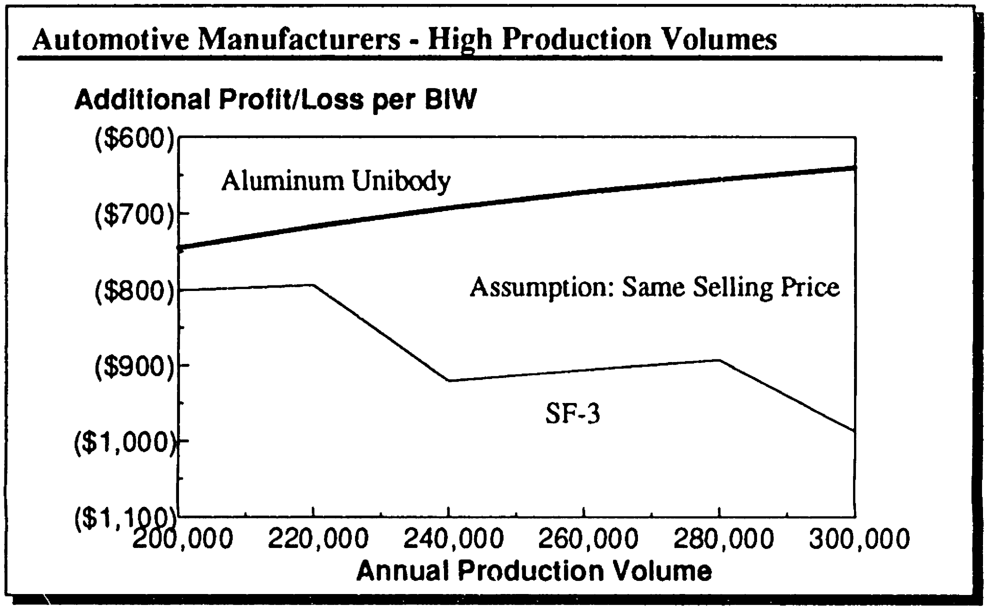

Figure 39.

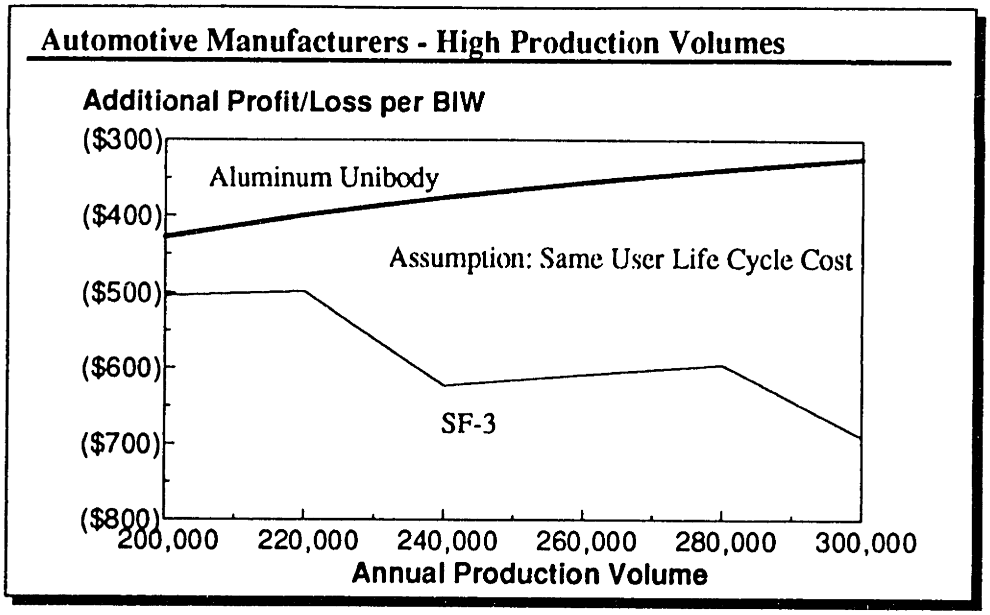

Figure 40.

In high production volumes, the steel unibody is favoured by the automotive producers. (Figures 39, 40) In this case, the cost benefits from the use stage cannot compensate for the additional costs from the manufacturing stage, because the discrepancies in cost between the designs are more pronounced in these high production volumes than at lower ones.

13. Airborne Emissions

In recent years the issue of air quality has been in the forefront of publicity. In general, there exists the perception that mankind has been involved in practices that irreversibly affect the environment. Just to mention a few examples, there has been extensive discussion on the specific issues of inner city pollution, global warming and water or land pollution. The Federal Government has attempted to abate these problems by promulgating regulations that set standards for industrial practices and their products. Hence, for the automotive industry, one can observe the tailpipe emission standards for light duty passenger vehicles and the stack emission limits for the production sites. [Sel. Env. Law Statutes, 1993]

The emissions associated with the automobile can be classified into two distinct categories, the direct and indirect emissions. Direct emissions refer to those airborne pollutants that arise during the processes transforming the input components to the desired output form and composition. On the other hand, indirect emissions are due to the energy consumption during the transformation processes. The production of energy usually requires the combustion of fuel, such as coal or oil. The combustion process leads to the emission of airborne post-combustion pollutants. Evidently, the magnitude of these pollutants depends upon the type of fuel. Conversely, there exist energy production methods that do not use combustion and lead to minimal emissions, such as is the case with hydroelectric power. Furthermore, on the subject of energy consumption, one has to note that another significant element is the efficiency in transporting the electric power from the generator site to the use point.

The predominant difficulty in evaluating the effects of automobile associated emissions is that these emissions constitute simply the initial step in the biological impact pathway. [Evaluating Chem. Reg., 1980] Therefore, in the schematic in Figure 41, emissions would be classified as a discharge, signalling their exit from effective commercial control. As a result, the pollutants discussed in this study would lead to higher air concentrations ("presence"). The population distribution at the area examined will consequently be exposed to these higher pollutant concentration levels. Finally, the responsiveness of the exposed organisms to the specific pollutants, combined with the exposure period, will determine the biological impacts. These impacts include human health effects, adversely affected vegetation or animal health effects.

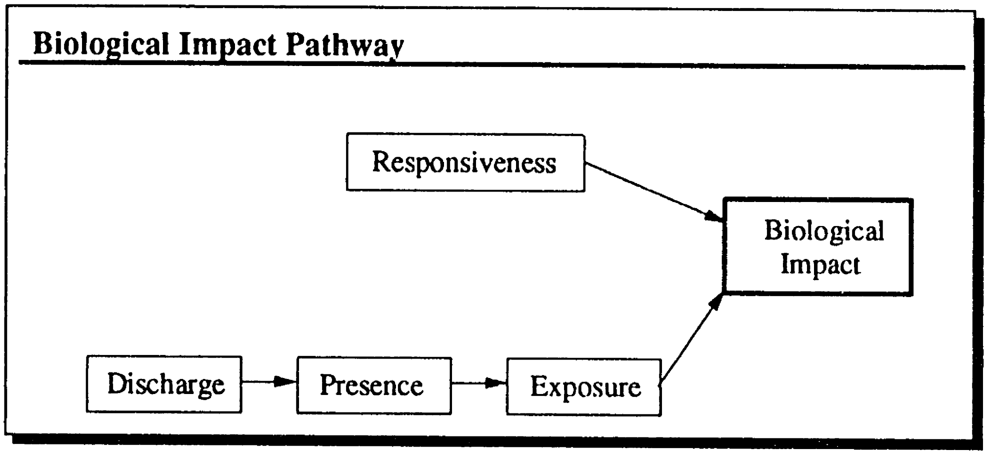

Figure 41.

Despite the clearly specified process leading to adverse effects, there exist two parameters that inhibit the implementation of such a study. Firstly, the amount of detail required to perform the assessment is enormous, as emissions and concentrations can only be examined on local basis. [Seinfeld, 1986] This means that the repercussions of an emission reducing strategy have to be assessed using a fine geographic and demographic grid. Furthermore, the assessor has to accumulate information concerning all other sources of pollutants in the region.

The second parameter is related to the uncertainty of the effects of certain pollutants. Although laboratory experiments have demonstrated that exposure to some substances for prolonged periods of time can lead to severe health problems, the dose-response relations for pollutants has not yet been completely documented. Moreover, the combinatorial influence of more than one pollutants still remains uncertain. [Ashford, 1976]

The conclusion one may draw is that emissions arising during the lifetime of an automobile are related to social welfare. However, the exact relationship eludes the scientific community. This study has chosen to avoid dealing with this problem and to simply assemble an emissions inventory, for each airborne pollutant tracked. The methodology is different for direct and indirect emissions:

1. *Direct Emissions*: Since these emissions are strictly related to the amount of material produced by each process, the calculation consists of estimating the

pollutants using emission factors. These factors have been compiled to inform on the emissions per unit weight of material. [Habersatter, 1991][Tillman, 1991]

2. *Indirect Emissions*: This class of emissions has been calculated by assuming a power generator mix and a set of efficiencies for transporting the electricity generated. The energy requirements for each stage in the life cycle have been either calculated in the previous sections, or entered, as is the case for the mining and refining stage. It is important to note that use stage emissions are included in this category, although their calculation is somewhat different. Use stage emissions are estimated by assuming emission factors for each gallon of gasoline burnt. These factors include precombustion burdens and emissions released during the refining of petroleum to produce commercially available gasoline.

14. Results of Airborne Emissions

The initial category of results concerning airborne emissions is the one including the mining and refining, part production and disposal stages. These stages can be examined on a BIW basis, because the emissions inventory is structured on emission factors per unit weight of material. In order to narrow the amount of information portrayed in this section, all results, unless otherwise stated, refer to a steel design weighing 615 lb. and an aluminum design weighing 332 lb. If any other steel or aluminum design needs to be modelled, simple linear scaling of the emissions to the required weight yields the correct result.

The direct emissions for the two designs were found to be as shown in Table 14. Transport related emissions are shown in Table 15, by applying the same assumptions as in Reference [Han, 1994]. All values are in kg per BIW.

Design	CO_2	HC	NO_x	CO	Particulates	SO_x
Steel	563.40	0.00	0.15	0.00	0.34	0.75
Aluminum	251.69	0.06	0.46	1.90	34.68	1.29

Table 14. BIW Direct Emissions.

Design	CO_2	HC	NO_x	CO	Particulates	SO_x
Steel	9.96	0.03	0.17	0.04	0.01	0.02
Aluminum	5.09	0.01	0.05	0.01	0.01	0.08

Table 15. BIW Transport Related Emissions.

The indirect emissions depend significantly upon the power generation mix. For this reason, it has been chosen to examine several power generation mixes which might be relevant for the material production, part fabrication and post-use stages. [IPAI, 1993] [DeLuchi, 1993] The results for steel are shown in Fig. 42 and for aluminum in Fig. 43.

Energy Related Emissions: Steel Design

kg/BIW	Carbon Dioxide	HC	NOx	CO	Particulates	SOx
USA	2,567.05	0.25	9.11	0.44	2.36	18.70
USA/2000	1,854.97	0.68	6.65	0.35	1.57	12.53
Oil	2,124.44	1.60	5.52	0.56	1.04	11.94
IPAI	915.35	0.10	3.26	0.16	0.84	6.66
France	316.44	0.34	1.21	0.07	0.22	1.71
Germany	1,576.75	0.46	5.63	0.29	1.37	10.89
Norway	103.29	0.38	0.50	0.04	0.02	0.05

Figure 42.

Energy Related Emissions: Aluminum Design

kg/BIW	Carbon Dioxide	HC	NOx	CO	Particulates	SOx
USA	9,516.31	0.94	33.78	1.62	8.74	69.34
USA/2000	6,876.55	2.52	24.67	1.30	5.83	46.45
Oil	7,875.53	5.93	20.46	2.07	3.86	44.25
IPAI	3,393.30	0.36	12.10	0.58	3.12	24.69
France	1,173.09	1.26	4.47	0.27	0.81	6.33
Germany	5,845.18	1.69	20.86	1.07	5.06	40.36
Norway	382.90	1.41	1.86	0.15	0.06	0.17

Figure 43.

In the use phase, lightweighing provides an advantage for the aluminum design. The emission values are calculated with average gains in fuel efficiency being achieved through lightweighing (see Chapter: Use Cost). The emission factors are not limited to the combustion of gasoline. These values include emissions for exploration, transport, refining and distribution of currently available gasoline. [Agnetun, 1993] The emission results in Table 16 reflect the total values for the specific pollutants, for the complete vehicle. Although the emission values for the two designs do not constitute a basis for comparison, as they are attributable to the complete passenger vehicle, their difference is ascribed to lightweighing of the BIW.

Design	CO_2	HC	NO_x	CO	Particulates	SO_x
Steel	50,000.48	129.10	77.87	209.02	6.15	36.89
Aluminum	46,461.11	119.19	71.89	192.97	5.18	34.05

Table 16. Vehicle Use Emissions.

14.1. Comparison of Designs on Specific Scenario

The complexity of parameters affecting the total, lifetime emissions for the BIW renders the complete examination of all outcomes a considerable task. Instead, one may attempt to simulate the most probable scenario for the steel and aluminum designs. The scenario depicted in this section is based on the following assumptions:

1. Five designs, including three spaceframe BIWs and the steel and aluminum unibodies. The details for these designs are included in Chapter 3.

2. Steel power generation mix is the USA/2000 mix. [DeLuchi, 1993]
3. Aluminum power generation mix is the IPAI mix.
4. Use differentials are based on the average fuel efficiency - weight relationship.

The results show that all the aluminum designs perform better in the pollutant categories that dominate during the use phase. These are the first four (CO_2, Hydrocarbons, NO_x, and CO) in Figure 44. However, the heavier burden, for particulates and sulphur oxides, carried by aluminum in the mining and refining stage cannot be balanced by the use phase.

Lifecycle Emission Differentials from Steel Unibody Base Case

kg/BIW	Carbon Dioxide	HC	NOx	CO	Particulates	SOx
Aluminum Unibody	(2,859.50)	(10.21)	(1.16)	(14.12)	32.90	8.21
Space Frame 1	(2,914.47)	(10.22)	(1.35)	(14.16)	32.33	7.82
Space Frame 2	(3,145.35)	(10.25)	(2.15)	(14.31)	29.94	6.17
Space Frame 3	(2,617.62)	(10.19)	(0.33)	(13.95)	35.41	9.94

Figure 44.

Upon closer examination it was found that the magnitude of pollutant increases (or reductions) are mostly of the same order of magnitude for the material production stage and the use phase. Taking Spaceframe SF-1 as an example, it is clear that all emission reductions, except for hydrocarbons, are in the use phase. Despite the cleaner energy mix of aluminum related plants, the additional energy required to process the material proves a burden for aluminum. [IKP, 1994] (Table 17)

	CO_2	HC	NO_x	CO	Particulates	SO_x
Non-Use	923.90	(0.31)	4.62	1.89	32.81	10.65
Use	(3,839.37)	(9.91)	(5.98)	(16.05)	(0.47)	(2.83)
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Total	(2,914.47)	(10.22)	(1.35)	(14.16)	32.33	7.82

Table 17. Lifecycle Emission Differential between Steel and Aluminum Designs.

The general tendency in recent years has been towards cleaner sources of electricity production. [Deluchi, 1993] This dynamic improvement of powerplant emission characteristics will favour the steel design. The reason is that the already clean power generation mix for aluminum related processes cannot improve as much as the one for steel related processes, and the contribution of energy production emissions is quite high. Furthermore, the areas where aluminum is at deficit, especially the airborne particulates, are direct emissions. Hence, power mix improvements will not lead to significant changes in this class of pollutants. Only new processes or more efficient pollutant trapping devices can yield better results.

15. Discussion

The main objective of this study has been to inform the predominant interest groups on the benefits and attributes associated with new alternative BIW designs. Therefore, the results have been portrayed in tabular form, for both the monetary and environmental attributes. This section intends to discuss the opportunities arising from the new designs.

The main advantage of all lightweight aluminum designs is the reduction of effluent emissions during the use stage through the enhancement of fuel efficiency. A significant distinction in treating the results is whether this pollution reduction is considered a competitive advantage or merely a means of meeting future regulatory restrictions. In the case that pollution reduction is perceived as a competitive edge over other models, one must assess the desirability of each design based on two attributes, namely cost and emissions. The condition of optimality will depend upon certain combinations of these two sets of attributes. [de Neufville, 1990] This study will explicitly avoid establishing this optimality condition, as the trade-off between monetary cost and externalities has been found to be ambiguous and controversial. [MSL, 1993]

However, this study will attempt to incorporate the effects of future regulatory action, since it is possible that future regulations will render lightweighing, through the use of lighter materials, necessary. Essentially, it is assumed that the regulations will be targeted towards minimising fuel consumption and emissions during the use stages of passenger vehicles. The current tendencies in the automotive industry seem to justify this approach.

[U. Michigan] However, there exist a number of implementable solutions that can address the same problem. To name a few, more fuel efficient internal combustion engines, enhanced tailpipe emission control devices and mandatory car pooling.

Corporate Strategy

The implementation of the aluminum designs requires forethought in order to choose paths which yield the highest expected gains. The business plan examined in this section concentrates on two consecutive four-year periods. In the first period, the decisions made by the automotive manufacturers are the following:

1. The class of vehicles in which the new design, if any, is to be introduced. This decision specifies the production volume of the BIW. The available choices are 20,000, 100,000 and 300,000 vehicles per year. The pricing strategy of the manufacturer, for aluminum designs, is to capture the additional cost benefits from the use stage. If this strategy is implemented, the user faces the same lifetime cost as for the steel unibody design.
2. The regional market in which the new design will be introduced. The available options are the United States or Europe. The varying parameter is the purchase price of gasoline, it being $1.20 per gallon in the US and approximately $4.00 in Europe.
3. The BIW design to be implemented. For simplicity, the number of designs considered is limited to two, in each case. These designs include the base case

steel unibody and the least expensive of the aluminum designs, for each vehicle class.

The uncertainty over the success of marketing these new designs is quantified by setting probabilities for the random events. All the numeric values of probabilities are in respect to an infallibly successful steel design. Hence, one does not have to quantify uncertainty equally affecting both the steel and aluminum designs.

1. Market Acceptance: The aluminum designs will be as desirable to the consumers as their attributes prove them to be. Although probably a conservative assumption, the only distinctive attribute is cost to the user[12]. All other attributes are considered to be equal and emissions are treated as a constraint, rather than as a competitive advantage. The probability of high acceptance for the second period is assumed to be "locked" to the outcome of the first period. Therefore, if any aluminum design is successful in the first period, it is assumed that it will most probably (95% certain) be successful in the second one. In the case where market acceptance is low, it is assumed that the automotive manufacturers will lower the price of the vehicle to the price of the competing steel design. Hence, the manufacturers will not capture any cost benefits arising in the use phase.
2. Regulatory Action: A possible outcome of severe regulation is that the stringent tailpipe emission standards will, implicitly, render the use of aluminum for the automotive BIW mandatory. Regulatory action is assumed independent of market acceptance and its effects come to play only in the second period.

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[12] Aluminum designs could potentially prove to have better handling characteristics and to be more flexible in the design stage.

3. Material Price: The material cost content for aluminum designs has been found to be substantial, thus warranting the examination of the effects of material price changes. Furthermore, aluminum producing firms have explicitly stated that the adoption of an all-aluminum design from any automotive manufacturer will lead them to invest into new casting technology. This technology is expected to reduce the cost of the material by approximately 30%. [Marstrander, 1995] It is assumed that if the aluminum design is implemented in the first period, material prices will drop in the second one. Any benefits from material price decreases will be captured by automotive manufacturers.

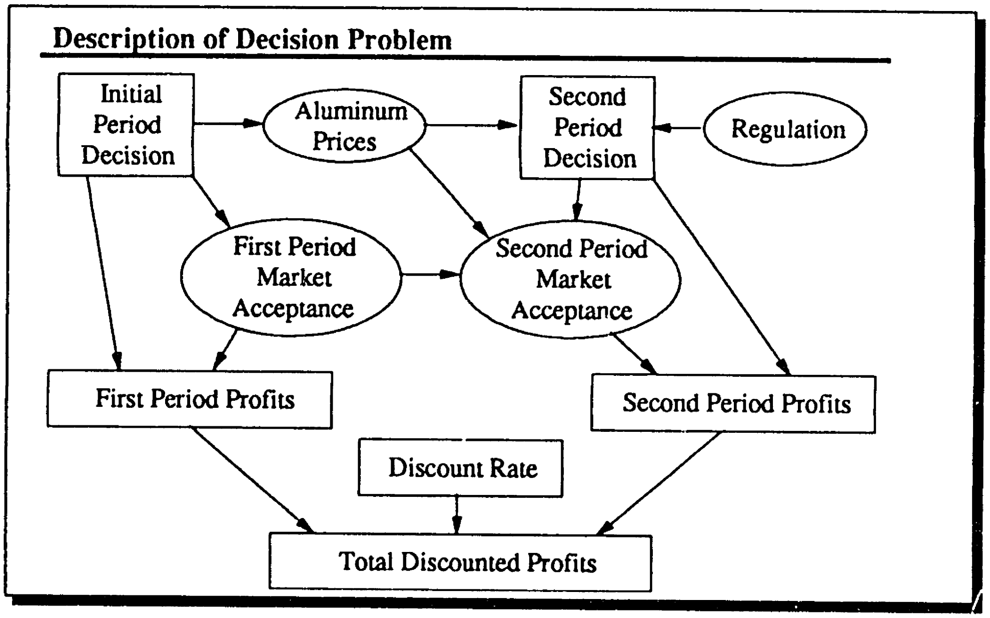

Figure 45.

The metric used to identify the most preferable solution will be the expected difference in profits of each of the designs as compared to the steel base case. Therefore, the steel design will be assigned zero additional profits in each instance. It is also assumed that automotive manufacturers are seeking to maximise their profits. A schematic representation of the decision problem is included in Figure 45, with oval shaped nodes denoting random events. More details are included in Appendix III.

The probability elicitation for the chance nodes is a difficult process [Clemen, 1991] which requires the enlightening assistance of experts. This study has not assumed any base case probabilities for market acceptance or regulatory action. Instead, it has been selected to perform a thorough sensitivity analysis throughout the range of possible values for both these variables.

Low Production Volume

For a production volume on the order of 20,000 vehicles per year it has been found that the aluminum spaceframe SF-1 should be implemented by the automotive industries. (Chapter: Production Costs) In essence, this design is superior in all respects to its steel counterpart. SF-1 costs less to produce, it uses less fuel in its lifetime and it has the probability of achieving even further cost gains if aluminum prices drop in the future. The sensitivity analysis on the probability of market acceptance reveals that even if the probability of high market acceptance for the specified price is extremely low, SF-1 would be preferred to the steel unibody. (Figure 46) Furthermore, if SF-1 seems to be the preferable design for the US, it will also be the one for Europe. The additional cost savings from the use stage increase the profits of automotive producers even more so.

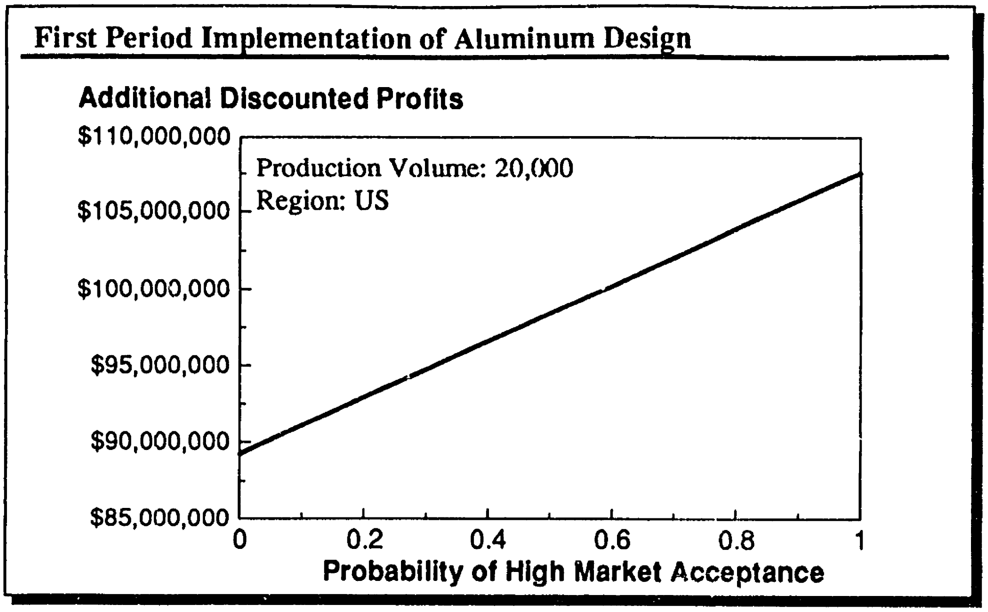

Figure 46.

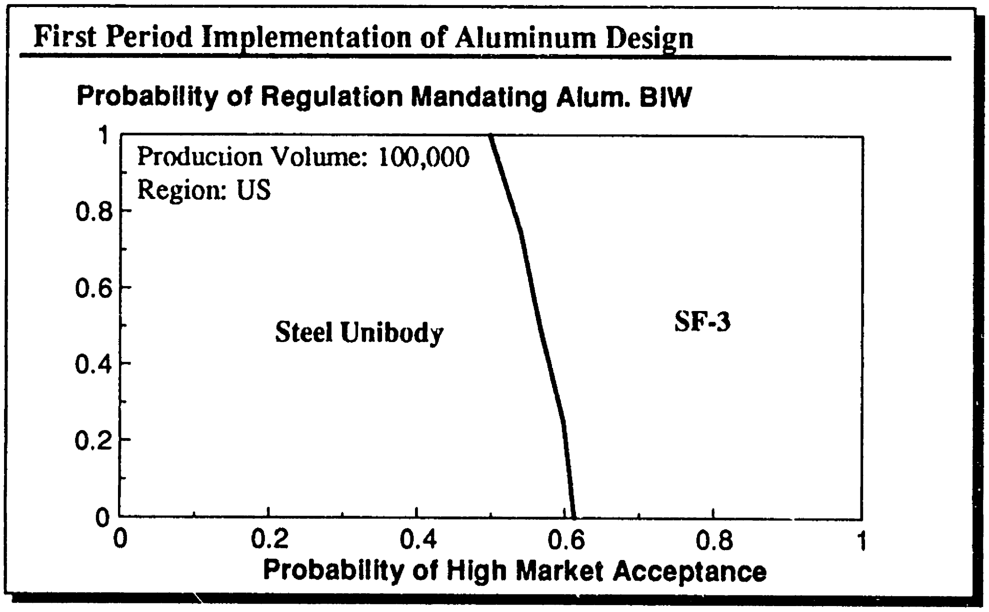

Figure 47.

Medium Production Volume

For production volumes on the order of 100,000 bodies-in-white per year, the aluminum spaceframe design SF-3 has the potential to compete on a cost basis with the steel unibody. A simple graphic representation of all the possible outcomes is offered in Figure 47. The horizontal and vertical axes span the entire range of values for the two independent chance nodes, i.e. the probability of high market acceptance and the probability of stringent regulatory action. The line drawn marks the combinations of these variables which make the automobile manufacturer indifferent between the steel and aluminum designs. Hence, along this line, carmakers do not capture any additional profits by introducing an aluminum design. On either side of this line, one of the two designs is preferred. The results, as depicted in Figures 47 and 48, reveal that there exist combinations of the probabilistic variables which render the aluminum design more profitable than the steel one. As expected, the regional disparities in gasoline prices render the possibility of success of the aluminum design higher in Europe than in the United States. Hence, the probability of high market acceptance required for additional profits in Europe is on the order of 15% compared to 55% for the United States.

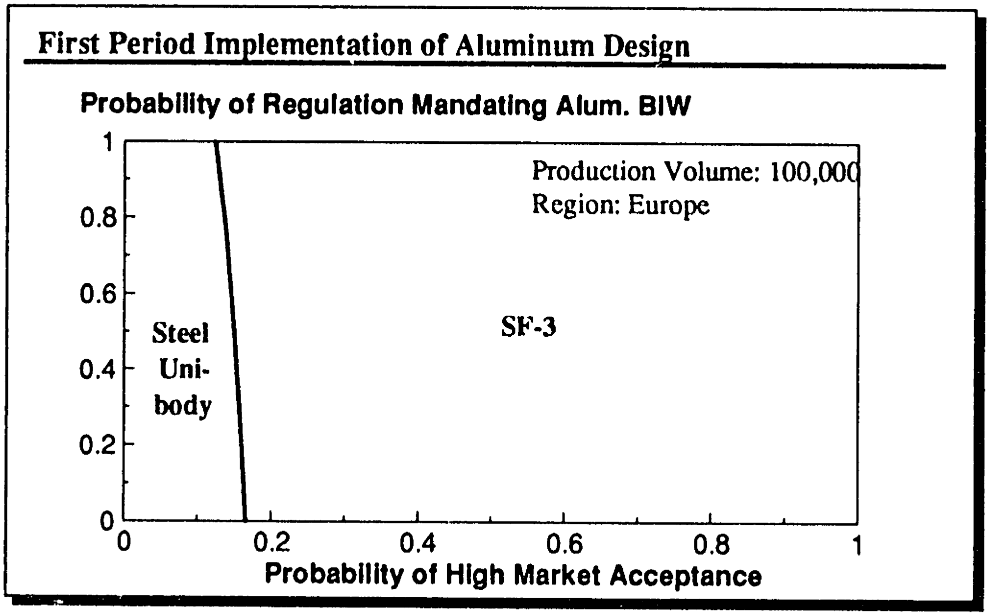

Figure 48.

High Production Volume

For production volumes on the order of 300,000 BIWs per year, the aluminum unibody design cannot compete with the steel unibody, if one considers the US as the marketable region for the vehicles. No matter what the values of probabilistic variables are, the steel unibody yields higher profits than its aluminum counterpart. However, if Europe is considered, there exist combinations of the probabilistic outcomes that make the aluminum unibody the preferred design. Figure 49 shows the dependence of the initial stage BIW choice upon the estimates of market acceptance and stringent regulation. The figure reveals the significance of determining correctly the initial market acceptance probability.

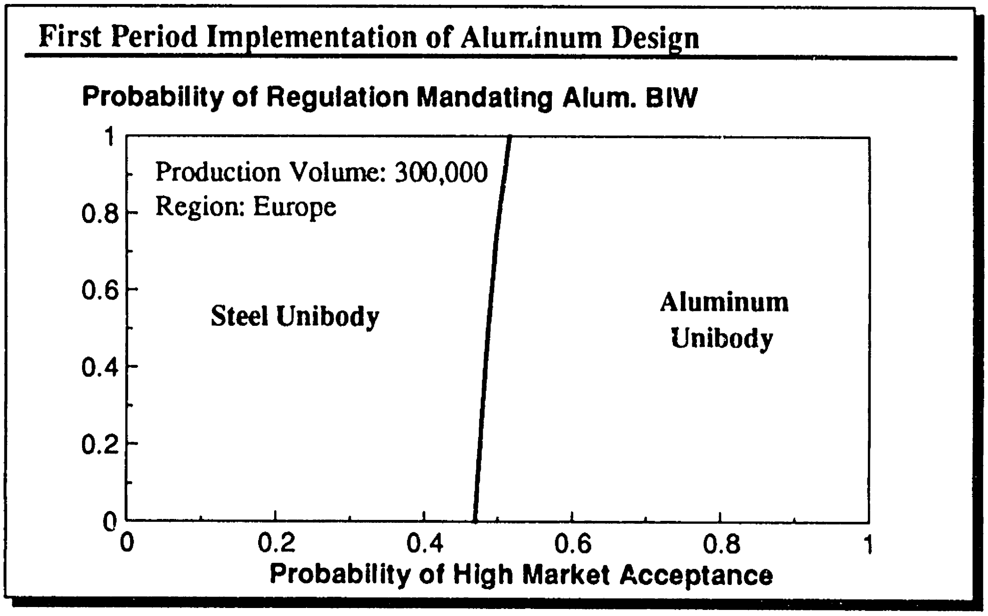

Figure 49.

Recommendation

The results of the previous sections can, thus, be summarised as a recommendation for corporate strategy:

Annual Production Volume	**United States**	**Europe**
20,000	Spaceframe Design SF-1	Spaceframe Design SF-1
100,000	Steel Unibody *or* Spaceframe Design SF-3[1]	Steel Unibody *or* Spaceframe Design SF-3[1]
300,000	Steel Unibody	Steel Unibody *or* Aluminum Unibody[1]

[1] Depending upon uncertain variables (market acceptance, regulation).

Table 18. Recommendation for Corporate Strategy.

It should be noted that the preceding recommendation is valid only if the assumptions stated in the beginning of this section hold true. It is worth pointing out once more that the analysis leading to this corporate strategy recommendation is based on one consequential assumption: the airborne pollutant reductions in the use phase for the lighter aluminum vehicles do not constitute a competitive advantage over the rival steel unibody.

16. Conclusions

The objective of this study has been to inform on the repercussions on traditional (monetary) and non-traditional (externalities) costs of innovative design and material choices for the automotive BIW. The study examined four such designs, comprising of three all-aluminum spaceframe designs and one aluminum unibody BIW. These designs were compared amongst themselves and with the base case steel unibody BIW.

The results concerning monetary costs reveal a strong dependence upon the selected annual production volume for each of these five designs. Due to dissimilarities in economies of scale for the different part production and joining methods, certain BIWs prove to be the least expensive at low production volumes while being more expensive than others as the annual production volume increases. For instance, the SF-1 spaceframe design has been shown to be the most inexpensive BIW for production volumes lower than 34,000 vehicles per year.

Another important parameter affecting the cost of any aluminum design is the part production mix, or, otherwise, the metal mix. Spaceframe BIWs exploit three part forming operations, namely extrusion, stamping and die casting. The equipment necessary to perform each of these operations varies in terms of capital investment and utilisation. This study has concluded that there exist significant cost benefits associated with implementing spaceframe BIWs with high weight contents of extruded parts at low production volumes. The reason is that the minimum efficiency scale for the extrusion process lies in the region of 30,000 parts per year, as compared with the one for stamping which lies above 100,000 parts per year.

All aluminum designs prove to be lighter than their steel counterpart. The weight savings achieved through the introduction of the lighter material range from 46% to 53% of the steel unibody weight. Despite this reduction in the need for material, the aluminum designs are usually more expensive to produce than the steel monocoque. The reason is that the material price for virgin aluminum is substantially higher than the price of steel. However, lightweighing proves beneficial in the use stage. The reduced curb weight of the BIW leads to a decreased fuel requirement during the useful life of the automobile, thus achieving better fuel efficiency. The repercussions of lightweighing are more pronounced in Europe, where the price of unleaded gasoline is, approximately, 230% higher than in the United States.

As far as airborne emissions are concerned, this study has identified the two most consequential stages in the lifetime of the BIW. The first one is the mining and refining stage for each of the metallic materials. In general, aluminum is plagued with higher process related emissions from this stage. Furthermore, despite the cleaner power generation mix assumed for aluminum, the increased processing energy required for this material proves to burden its energy related emissions as well[13].

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[13] Except for the hydrocarbon category.

However, the lighter aluminum designs are redeemed in the use stage, which is the second important stage in the life of the BIW. In four out of six pollutant categories, the use stage emission reductions outweigh the burden imposed in the mining and refining stage. Thus, the lifecycle emissions for aluminum designs prove favourable for carbon dioxide, carbon monoxide, nitrogen oxides and other hydrocarbons. It should also be noted that the emission profiles for steel and aluminum designs are not limited to emission reduction. In addition, one notices the effects of pollution displacement. The enhancements in the use stage could alleviate inner city pollution problems, although adversely affecting emissions at mining and refining sites.

Finally, this study attempted to assess the potential advantages of lighter aluminum BIW designs, strictly in terms of monetary costs. The analysis has shown that there exists at least one class of vehicles, the luxury class[14], where the implementation of the aluminum BIW design will yield higher profits to automotive manufacturers. For other vehicle classes, associated with higher production volumes, the aluminum designs could potentially be successful, especially in Europe due to the discrepancy in gasoline prices. Their success is predominantly conditional on the market acceptance of the new aluminum vehicles. Even extremely stringent regulatory action does not seem to severely affect the decision of automotive manufacturers on whether or not to move the aluminum design into production. Hence, automotive manufacturers should concentrate their efforts on capturing the additional cost savings arising during the use of lighter aluminum designs. This is clearly a proactive approach as the successful marketing of the

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[14] Production volumes for this vehicle class are assumed to be of the order of 20,000 vehicles per year.

innovative aluminum bodies-in-white eliminates the uncertainty of future regulatory action. Furthermore, if more stringent emission controls are anticipated, the aluminum designs offer an option which has the potential for increased profits. Thus, introducing aluminum designs is a flexible and potentially profitable solution, not depending upon the uncertainty of regulatory action.

It should be noted that these results depend upon the framing of the problem and the quantification of uncertainty. Although this description of the problem captures the whole range of possible outcomes, the results are critically contingent upon the explicitly stated assumptions.

17. Future Work

This thesis has addressed some of the topics associated with aluminum designs for the automotive body-in-white. The analytical techniques used have managed to portray the significance of each stage in the useful life of the BIW, from cradle to grave. However, there still remain some issues where more light ought to be shed.

One such issue is recycling. Recycling reduces the amount of virgin material required for any design. Therefore, the mining and refining stages will produce quite different results for both cost and airborne emissions. The recycling loop will decrease the energy needed to produce wrought or sheet material, for both aluminum and steel. The effects for both materials have, therefore, to be quantified. The analysis for such a task should not be considered as a simple addition to the current analysis. Recognising that recycling starts at the design point directs the effort towards the notion of "design for recycling" or "green design".

Another issue not addressed in this thesis is the potential competitive advantage of lightweight designs in emissions reduction. It seems plausible that automobile buyers will be willing to pay a higher price for a cleaner vehicle. The apparent trade-off between cost and pollution reduction has to be analytically quantified.

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Appendix I

Technical Cost Model: Extrusion Process

Equipment Data Table

Input Page

*Company:*__________

*Site:*__________

*Part:*__________

Process	Equipment Cost	Dedication (%)	Workers per Shift	Down Time	Time to process	Batch size	Space Req'ment	Power Req'ment
1. Billet Preparation								
Log Storage	$0.00	0.00%	0	0.00%	0	0	0	0
Log Transport	$0.00	0.00%	0	0.00%	0	0	0	0
Log Stacking/Shearing	$0.00	0.00%	0	0.00%	0	0	0	0
Total Billet Preparation	$0.00	0.00%	0	0.00%	0	0	0	0
2. Billet Preheating								
Oven	$100,000.00		0				0	0
3. Extrusion								
Extrusion Press	$1,400,000.00	0.00%	4	0.00%	0	0	0	0
Dies	$7,500.00	100.00%	0	0.00%	0	0	0	0
4. Runout								
Runout Table	$0.00		0				0	0
Puller	$0.00		0				0	0
Belt System	$0.00		0				0	0
Stretcher	$0.00		0				0	0
Quenching Units	$0.00		0				0	0
Saw & Saw Gauge	$0.00		0				0	0
Other	$0.00		0				0	0
Total Runout	$500,000.00		0				0	0
Total Steps 2-3-4	$0.00	0.00%	0	0.00%	0	0	50000	0
5. Aging								
Oven	$100,000.00	0.00%	0	0.00%	0	0	6000	0
7. Surface Treatment								
Chem-milling	$0.00	0.00%	0	0.00%	0	0	0	0
8. Inspection								
Inspection	$0.00	0.00%	0	0.00%	0	0	0	0
Total	$0.00	0.00%	0	5.20%	0	0	0	0

ALUMINUM EXTRUSION COST MODEL

=======> Material Selection

Choose material by number ========> 4

	Selection #	Alloy	Price	Scrap Rate	[/lb]
Aluminium Alloys:	1	3003			
	2	3103			
	3	6060			
	4	6063	**$0.95**	**$0.45**	
	5	6061			
	6	6082			
	7	6351			
	8	7020			

Selected Material Data

Alloy	Price	Scrap Price	
6063	$2.09	$0.99	per kg

=======> Extrusion Geometry

Cross Sectional Area	**0.001181**	[m^2]
Length of Each Piece (m)	**0.74**	m
Density	**2700**	kg/m^3
Circumscribed Diam for this geometry	**159.24**	[mm]
Final (machined) Part Weight	**2.360**	kg
Enter your choice for Press Size [MN]:	**35**	P_Size
Enter number of holes in die :	1	n_holes

Weight/meter of Extrusion - G1:	3.339	[kg/m]
Part Weight	2.360	kg
Circumscribed Diam for this geometry [mm]	159.24	

=======> 1. Billet Preparation

	Storage	Transport	Cutting	Total
Equipment Cost	$0.00	$0.00	$0.00	$0.00
Dedication (annual)	0.00%	0.00%	0.00%	0.00%
Workers per Shift	0	0	0	0
Down Time	5.20%	5.20%	5.20%	5.20%
Time to Process (min)	0	0	0	0
Batch Size (billets)	0	0	0	0
Space Req'ment	0	0	0	0
Power Req'ment	0	0	0	0

Line Utilisation	0.00%	0.00%	0.00%	0.00%

Cutting Lubricant Reqd(liter/billet)	**0.000**	LUB1
Cutting Lubricant Cost ($/liter)	**$2.00**	LUB1$

=======> 2. Billet Preheat

Specific heat (Al alloy)	900	J/kg C	
Temperature	**940**	F	
Room T	80	F	
dT	478	C	
Energy req	18.67083	KWh	per billet, ideal
Efficiency	**20.00%**		
Energy req (total)	32580.59	KWh	
Cost	$2,606.45		

Equipment Cost	$100,000
Dedication	//////////////////.
Workers per Shift	0
Down Time	//////////////////.
Time to Process (min)	//////////////////.
Batch Size (billets)	//////////////////.
Space Req'ment	0
Power Req'ment	32580.59
Line Utilisation	1.03%

=======> 3. Extrusion

Selected Press Size:	35	[MN]
Closest Lower Listed Press Size :	35	[MN]

Regression Results [f(press size)]

Container Diameter	0.313	[m]
Maximum Billet Length	0.759	[m]

Corresponding Press Characteristics:

Container Diameter	0.315	[m]
Press Container X-Section Area	0.07793	[mm]
Maximum Billet Length	0.750	[m]
Specific Pressure	449	[MPa]
Extrusion Weight / m: Go	210.4	[kg/m]
Maximum Billet Weight	157.8	[kg]
Runout Table Length [m]	35	RUNOUT_L
Press Cost	$1,400,000	

Moving Saw Equipment: 1 (1=Yes, 0=No)

	Scrap Inp	Calculated	Used
Max number pieces by Runout Table length	44	44	44

Max number pieces by Max billet weight	56	58	58
Actual Max Allowable Number of Pieces /Billet	56	58	58
Actual Billet Weight	157.25	156.31	156.31
Actual Billet Length	0.747	0.743	0.743
Ram Displacement [m]	0.717	0.713	0.713
Required Number Profiles	20203	20203	20203
Material Req by Scrap Percentage Input	47,669		0
Calculated Number Billets	360.77	348.33	348.33
Required Number Billets	361	349	349
Total Order Weight for Billets	56767.54	54553.55	54553.55
Number Profiles Produced	20216	20242	20242
Profile Surplus Production	13	39	39

Length of Discarded Billet [m]	**0.03**	SCRP_BLL
Length of Discard/Runout Length [m]	**2.00**	SCRP_RUN

Productivity

Extrusion Speed (m/min)		**14**	SPEED
e.g., AA6060/6063 20-60 m/min			
and AA6082/6061 10-35 m/min			
Effective Extrusion Time	[sec/billet]	183.3	
Time to Load Billet	[sec/billet]	**6**	BILOAD
Time to Upset Billet	[sec/billet]	**3**	UPSET
Time for Burb Cycle	[sec/billet]	**2**	BURB
Time to Withdraw Ram	[sec/billet]	**4**	RAM_OUT
Time to Shear Discard	[sec/billet]	**7**	SHER_BUT
Total Dead Time	[sec]	22	DEAD_T
Dead Time Override (If =0, above value used)		**0**	
Extrusion Cycle Time (optimum)	[sec/billet]	205.3	
Time to Change Die	[min]	**2.0**	DICHNG
Die Change Frequency	[#/shift]	**4**	DIEFREQ
Billets Extruded per Shift	[#/shift]	137.0	BLLT_SHIF
Avg. Die Change Time	[sec/billet]	3.50	AVGDICHN
Total Cycle Time for Extrusion		208.8	TCYCTM
Total Cycle Time for Extrusion (per profile)		0.060	min

Extrusion Press

Equipment Cost	$1,400,000	
Dedication	0.00%	
Workers per Shift	4	
Down Time	5.20%	
Time to Process (min)	0.060	
Batch Size (profiles)	1	
Space Req'ment	0	
Power Req'ment	0	
Line Utilisation	1.03%	
Line Utilisation	8.06%	Default

Die Set

Equipment Cost	$7,500.00	*Die cost*	*$2,500.00*
Dedication	100.00%		
Workers per Shift	0		
Down Time	5.20%		
Time to Process (min)	0		
Batch Size (profiles)	0		
Space Req'ment	0		
Power Req'ment	0		
Line Utilisation	100.00%		

=======> **4. Runout**

	R/out Table	Puller	Belt System	Stretcher
Equipment Cost	$0.00	$0.00	$0.00	$0.00
Dedication	////////////////////	////////////////////	////////////////////	////////////////////
Workers per Shift	0	0	0	0
Down Time	////////////////////	////////////////////	////////////////////	////////////////////
Time to Process (min)	////////////////////	////////////////////	////////////////////	////////////////////
Batch Size (profiles)	////////////////////	////////////////////	////////////////////	////////////////////
Space Req'ment	0	0	0	0
Power Req'ment	0	0	0	0
Line Utilisation	1.03%	1.03%	1.03%	1.03%

	Quench	Saw	Other	*Total*
Equipment Cost	$0.00	$0.00	$0.00	*$500,000*
Dedication	////////////////////	////////////////////	////////////////////	////////////////////
Workers per Shift	0	0	0	*0*
Down Time	////////////////////	////////////////////	////////////////////	////////////////////
Time to Process (min)	////////////////////	////////////////////	////////////////////	////////////////////
Batch Size (profiles)	////////////////////	////////////////////	////////////////////	////////////////////
Space Req'ment	0	0	0	*0*
Power Req'ment	0	0	0	*0*
Line Utilisation	1.03%	1.03%	1.03%	1.03%

Cutting Lubricant Req'd (liter/cut)	**0.000**	LUB3
Cutting Lubricant Cost ($/liter)	**$0.00**	LUB3$
Quench Water Req'd (liter/min)	**0**	QUENCH

Combined Step : Billet Preheating - Extrusion - Runout

Equipment Cost	$2,000,000
Dedication	8.06%
Workers per Shift	4
Down Time	5.20%
Time to Process (min)	0

Batch Size (profiles)	0	
Space Req'ment	$50,000.00	
Power Req'ment	$32,580.59	kWh
Line Utilisation	8.06%	

======> 5. Aging

Heating	Specific heat (Al alloy)	900	J/kg C			
	Temperature	**375**	F			
	Room T	80	F			
	dT	164	C			
	Energy req	7.0E+09	J			
		1953.123	kWh			
Losses	Aging Duration	**10**	hrs			
	Oven Dimensions (ft)	Length	Width	Height	Thickness	Surf Area
		40	**12**	**10**	**1.5**	**2000**
	Oven Surface Area	188.68	m2			
	Coefficient k	**0.50**	W/mK	[0.2 - 1.0]		
	dQ/dt	33.50	kW			
	Energy Req	334.99	kWh			
	Efficiency	**15.00%**				
	Total Energy Req	15,254.11	kWh			
	Percent Losses	14.64%				
	Equipment Cost	$100,000				
	Dedication	0.00%				
	Workers per Shift	0				
	Down Time	5.20%				
	Time to Process (min)	0				
	Batch Size (profiles)	0				
	Space Req'ment	6000				
	Power Req'ment (total)	15,254.11	KWh			
	Line Utilisation	0.00%				
	Line Utilisation	1.84%		Default		

======> 7. Surface Treatment

Material Required for Each Part:	**0**	lb
Price of Material	**$25.00**	/lb

Equipment Cost	$0.00
Dedication	0.00%
Workers per Shift	0
Down Time	5.20%
Time to Process (min)	0
Batch Size (profiles)	0
Space Req'ment	0
Power Req'ment	0

Line Utilisation	0.00%

======> **8. Inspection - Quality Control**

Equipment Cost	$0.00	
Dedication	0.00%	
Workers per Shift	0	
Down Time	5.20%	
Time to Process (min)	0	
Batch Size (profiles)	0	
Space Req'ment	0	
Power Req'ment	0	
Line Utilisation	0.00%	
Line Utilisation	8.06%	from Extrusion

Data 4-28-93 S.Storen:
For Typical 6XXX Series

Press Size [MN]	16	22	35
Container Diameter [m]	0.178	0.212	0.315
Area[m^2]	0.02488	0.03530	0.07793
Max Billet Length [m]	0.58	0.68	0.75
Specific Pressure [MPa]	643	623	449
Weight/m; Go [kg/m]	67.2	95.3	210.4
Max Billet Wt [kg]	39.0	64.8	157.8
Runout Length [m]	35	42	35
Press Cost ($)	500,000	700,000	1,000,000

DATA TABLE
Circumscribed Diameter Range [mm]
e.g. between 25 and 50 - D-sigma
Minimum Wall Thickness - Sm
Min Wt/m, for extrusion - G1

Number of Run-Out Holes - n
for given D and Press Sizes

D-sigma [mm]	Sm [mm]	G1 [kg/m]	n	n	n
			16	22	35
0	1.0	0.08	10	0	0
25	1.2	0.26	4	6	0
50	1.5	0.34	3	4	0
75	1.7	0.54	2	3	6
100	2.0	0.97	1	2	4
150	2.5	1.62	0	1	2
200	3.0	2.63	0	0	1
250	4.0	4.21	0	0	1

ALUMINUM EXTRUSION COST MODEL

=======> Production Factors

Order Size	**20,000**	
Production Volume	20,000	NO_XTRUD
Order Weight per Year (Kg)	47,193	ORDERWT
Machine Down and/or Break Time	5.20%	
Rejection Rate (QC)	**1.00%**	
Actual Number of Extruded Profiles	20,202	per year
Weight of Extruded / Macined Profiles	47,669	kg

=======> Material Flow & Scrapage

	Input	*Rel. to Previous*
Total Scrap Percentage		15.97%
Extrusion Scrap Percentage	**12.00%**	12.00%
Fabrication Scrap Percentage	**4.51%**	4.51%

	Process	Mat'l In	Mat'l Out	Scrap
1	Billet Preparation	2.808		
2	Billet Preheating			
3	Extrusion	2.808	2.471	0.337
4	Runout			
5	Aging			
6	Fabrication	2.471	2.360	0.111
7	Surface Treatment			
8	Inspection			
9	Inventory			
10	Transportation		2.360	
	Total	2.808	2.360	0.448

=======> Exogenous Cost Factors

Working Days per Year	**240**	DAYS
Number of Shifts per Day	**1**	SHIFT
Working Hours per Shift	**8**	HRS
Working Hours per Month	**173.3**	
Total Working hours/year	2079.6	TOTHRS
Capital Recovery Rate (% of initl investment)	**12%**	CRR
Capital Recovery Period	**10**	CRP
Working Capital Period (years)	**0.25**	WORKCAP
Auxillary Equipment Costs (% of Cap Equip)	**5%**	AUX
Maintenance (% of Cap & Aux Costs)	**4%**	MAINT
Installation (% of Cap % Aux Costs)	**10%**	INSTALL
Building Lifetime (years)	**20**	BLIFE
Building Space Cost Factor ($/sq.ft)	**$75.00**	BCOST

Direct Labor Wage ($/hour)	**$32.00**	LAB
Electricity Price	**$0.08**	Kwh
Natural Gas Price	**$6.00**	MMBTU
Water Price	**$0.00**	per liter
Variable Overhead (% of Variable Costs)	**4%**	VOH
Fixed Overhead (% of Fixed Costs)	**10%**	OVHD

=======> **Default Calculations**

Default Data

Good kgs	900	kg/hr manned	
Recovery (scrap)	23.00%		
Extrusion scrap	15.00%		
Rejection Rate	2.00%		
Fabrication	60.00%		
Down Time	5.19%		
Die Cost	$0.106	/kg	
Aging Cost	$0.015	/lb	
Plant Surface Area	200,000	sq. ft.	
Plant Equipment Cost	$6,000,000		
Plant Aging Facilities	$100,000	for 20,000-30,000 lbs capacity	
Plant Aging Capacity (av)	25,000	lbs	
Aging Time	10	hrs	[= 1 day]
Plant Lines	3		
Part Weight	2.360	kg	

Cost		
Die	$0.25	per part
Aging	$0.08	per part
Surface Area Requirement	66,667	sq. ft.

ALUMINUM EXTRUSION COST MODEL **BILLET PREPARATION**

Variable Cost Elements	Per Piece	Annual	Percent
Material Cost	$5.70	$114,016.92	94.34%
Labor Cost	$0.00	$0.00	0.00%
Energy Cost	$0.00	$0.00	0.00%
Variable Overhead Cost	$0.23	$4,560.68	3.77%
Total Variable Cost	$5.93	$118,577.59	98.11%

Fixed Cost Elements	Per Piece	Annual	Percent	Investment
Equipment Cost	$0.00	$0.00	0.00%	$0.00
Auxillary Equipment Cost	$0.00	$0.00	0.00%	$0.00
Installation Cost	$0.00	$0.00	0.00%	$0.00
Maintenance Cost	$0.00	$0.00	0.00%	
Building Cost	$0.00	$0.00	0.00%	$0.00
Fixed Overhead	$0.00	$0.00	0.00%	
Cost of Working Capital	$0.11	$2,282.15	1.89%	$29,644.40
Total Fixed Cost	$0.11	$2,282.15	1.89%	$29,644.40
Total Operation Cost	$6.04	$120,859.74	100.0%	

Additional Information

Process		Utilisation	Int. # of Lines	% Int Lines	
	Storage	0.00%	0	ERR	
	Transport	0.00%	0	ERR	
	Cutting	0.00%	0	ERR	
	Total	0.00%	0	ERR	
	Average	0.00%	0		[Building]

ALUMINUM EXTRUSION COST MODEL PREHEAT / EXTRUSION / RUNOUT

Variable Cost Elements	Per Piece	Annual	Percent
Material Cost	($0.34)	($6,739.32)	-6.55%
Labor Cost	$1.07	$21,454.61	20.86%
Energy Cost	$0.13	$2,606.45	2.53%
Variable Overhead Cost	$0.03	$692.87	0.67%
Total Variable Cost	$0.90	$18,014.60	17.52%

Fixed Cost Elements	Per Piece	Annual	Percent	
Equipment Cost	$1.51	$30,299.41	29.46%	$2,007,500.00
Auxillary Equipment Cost	$0.07	$1,492.85	1.45%	$100,375.00
Installation Cost	$0.16	$3,134.98	3.05%	$210,787.50
Maintenance Cost	$0.06	$1,271.69	1.24%	
Building Cost	$2.02	$40,464.46	39.35%	$3,750,000.00
Fixed Overhead	$0.38	$7,666.34	7.45%	
Cost of Working Capital	$0.02	$494.26	0.48%	$6,420.24
Total Fixed Cost	$4.24	$84,823.99	82.48%	$6,075,082.74
Total Operation Cost	$5.14	$102,838.59	100.00%	

Additional Information

	General	Die
Utilisation	8.06%	100.00%
Integer Number of Lines	100.00%	100.00%
Percentage of Integer Lines	8.06%	100.00%

ALUMINUM EXTRUSION COST MODEL **AGING**

Variable Cost Elements	Per Piece	Annual	Percent	
Material Cost	$0.00	$0.00	0.00%	
Labor Cost	$0.00	$0.00	0.00%	
Energy Cost	$0.06	$1,220.33	41.40%	
Variable Overhead Cost	$0.00	$48.81	1.66%	
Total Variable Cost	$0.06	$1,269.14	43.05%	
Fixed Cost Elements	**Per Piece**	**Annual**	**Percent**	**Investment**
Equipment Cost	$0.02	$326.32	11.07%	$100,000.00
Auxillary Equipment Cost	$0.00	$16.32	0.55%	$5,000.00
Installation Cost	$0.00	$34.26	1.16%	$10,500.00
Maintenance Cost	$0.00	$13.71	0.46%	
Building Cost	$0.06	$1,110.78	37.68%	$450,000.00
Fixed Overhead	$0.01	$150.14	5.09%	
Cost of Working Capital	$0.00	$27.32	0.93%	$354.82
Total Fixed Cost	$0.08	$1,678.83	56.95%	$565,854.82
Total Operation Cost	$0.15	$2,947.97	100.0%	

Additional Information

Utilisation	1.84%
Integer Number of Lines	1
Percentage of Integer Lines	1.84%

ALUMINUM EXTRUSION COST MODEL **SURFACE TREATMENT**

Variable Cost Elements	Per Piece	Annual	Percent
Material Cost	$0.00	$0.00	ERR
Labor Cost	$0.00	$0.00	ERR
Energy Cost	$0.00	$0.00	ERR
Variable Overhead Cost	$0.00	$0.00	ERR
Total Variable Cost	$0.00	$0.00	ERR

Fixed Cost Elements	Per Piece	Annual	Percent	Investment
Equipment Cost	$0.00	$0.00	ERR	$0.00
Auxillary Equipment Cost	$0.00	$0.00	ERR	$0.00
Installation Cost	$0.00	$0.00	ERR	$0.00
Maintenance Cost	$0.00	$0.00	ERR	
Building Cost	$0.00	$0.00	ERR	$0.00
Fixed Overhead	$0.00	$0.00	ERR	
Cost of Working Capital	$0.00	$0.00	ERR	$0.00
Total Fixed Cost	$0.00	$0.00	ERR	$0.00
Total Operation Cost	$0.00	$0.00	ERR	

Additional Information

Utilisation	0.00%
Integer Number of Lines	0
Percentage of Integer Lines	0.00%

ALUMINUM EXTRUSION COST MODEL **INSPECTION**

Variable Cost Elements	Per Piece	Annual	Percent
Material Cost	($0.02)	($471.93)	94.34%
Labor Cost	$0.00	$0.00	0.00%
Energy Cost	$0.00	$0.00	0.00%
Variable Overhead Cost	($0.00)	($18.88)	3.77%
Total Variable Cost	($0.02)	($490.80)	98.11%

Fixed Cost Elements	Per Piece	Annual	Percent	Investment
Equipment Cost	$0.00	$0.00	0.00%	$0.00
Auxillary Equipment Cost	$0.00	$0.00	0.00%	$0.00
Installation Cost	$0.00	$0.00	0.00%	$0.00
Maintenance Cost	$0.00	$0.00	0.00%	
Building Cost	$0.00	$0.00	0.00%	$0.00
Fixed Overhead	$0.00	$0.00	0.00%	
Cost of Working Capital	($0.00)	($9.45)	1.89%	($122.70)
Total Fixed Cost	($0.00)	($9.45)	1.89%	($122.70)
Total Operation Cost	($0.03)	($500.25)	100.0%	

Additional Information

Utilisation	8.06%
Integer Number of Lines	1
Percentage of Integer Lines	8.06%

ALUMINUM EXTRUSION COST MODEL COST SUMMARY

Variable Cost Elements	Per Piece	Annual	Percent
Material Cost	**$5.34**	**$106,805.67**	**47.23%**
Labor Cost	**$1.07**	**$21,454.61**	**9.49%**
Energy Cost	**$0.19**	**$3,826.78**	**1.69%**
Variable Overhead Cost	**$0.26**	**$5,283.48**	**2.34%**
Total Variable Cost	**$6.87**	**$137,370.53**	**60.74%**

Fixed Cost Elements	Per Piece	Annual	Percent	Investment
Equipment Cost	**$1.53**	**$30,625.72**	**13.54%**	**$2,107,500.00**
Auxillary Equipment Cost	**$0.08**	**$1,509.16**	**0.67%**	**$105,375.00**
Installation Cost	**$0.16**	**$3,169.24**	**1.40%**	**$221,287.50**
Maintenance Cost	**$0.06**	**$1,285.40**	**0.57%**	
Building Cost	**$2.08**	**$41,575.24**	**18.38%**	**$4,200,000.00**
Fixed Overhead	**$0.39**	**$7,816.48**	**3.46%**	
Cost of Working Capital	**$0.14**	**$2,794.28**	**1.24%**	**$36,296.75**
Total Fixed Cost	**$4.44**	**$88,775.52**	**39.26%**	**$6,670,459.25**
Total Operation Cost	**$11.31**	**$226,146.05**	**100.0%**	

Production Parameters		
Production Volume	20,000	per year
Rejection Rate	1.00%	
Average Down Time	5.20%	
Scrap from Finishing	4.51%	

Extrusion Press		
Utilisation	8.06%	
Press Size	35	MN
Capital Cost	$2,000,000	including Preheat and Runout equipment
No. of workers	4	per shift
Die Set Cost	$7,500	

Appendix II

Body-In-White Assembly Parameters

Body-In-White Assembly Specifications

Steel Unibody

Production Volume	20,000	100,000	300,000
Variable Cost	$240	$240	$240
Fixed Cost	$2,184	$1,145	$382
Total Cost	$2,429	$1,385	$622
Investment	$125 Million	$327 Million	$327 Million

Aluminum Unibody

Production Volume	20,000	100,000	300,000
Variable Cost	$280	$280	$280
Fixed Cost	$2,985	$1,731	$586
Total Cost	$3,265	$2,011	$866
Investment	$170 Million	$446 Million	$446 Million

Spaceframe SF-1

Production Volume	20,000
Variable Cost	$2,364
Fixed Cost	$103
Total Cost	$2,467
Investment	$4.4 Million

Spaceframe SF-2

Production Volume	100,000
Variable Cost	$1,462
Fixed Cost	$342
Total Cost	$1,804
Investment	$118 Million

Spaceframe SF-3

Production Volume	100,000
Variable Cost	$733
Fixed Cost	$546
Total Cost	$1,279
Investment	$197 Million

Appendix III

Decision Analysis Parameters

Decision Analysis Parameters

Initial Period Decision

Options:
1. Steel Unibody
2. Aluminum Design[1]

Probabilistic Events - First Period

First Period Market Acceptance (p)	*Range:* $0<p<1$

Second Period Decision

Options:
1. Steel Unibody
2. Aluminum Design

Probabilistic Events - Second Period

Second Period Market Acceptance (p)	*Range:* $0<p<1$, if aluminum design was not implemented in first period. $p=0.95$ if aluminum design was successful in first period. $p=0.05$ if aluminum design was not successful in first period.
Regulatory Action (q)	*Range:* $0<q<1$
Aluminum Price Reduction (r)	$r=1$, if aluminum design was implemented in first period. $r=0$, if aluminum design was not implemented in first period.

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[1] The design chosen depends upon the production volume. The cheapest design amongst the three aluminum spaceframes and the aluminum unibody is selected.

Decision Analysis Problem

Initial Decision	Acceptance	Regulation	Alum. Cost	Second Decision	Acceptance
Steel	Standard	Preclusive	Low	Aluminum	High
Steel	Standard	Preclusive	Low	Aluminum	Low
Steel	Standard	Preclusive	High	Aluminum	High
Steel	Standard	Preclusive	High	Aluminum	Low
Steel	Standard	Mild	Low	Steel	Standard
Steel	Standard	Mild	Low	Aluminum	High
Steel	Standard	Mild	Low	Aluminum	Low
Steel	Standard	Mild	High	Steel	Standard
Steel	Standard	Mild	High	Aluminum	High
Steel	Standard	Mild	High	Aluminum	Low
Aluminum	High	Preclusive	Low	Aluminum	High
Aluminum	High	Preclusive	Low	Aluminum	Low
Aluminum	High	Preclusive	High	Aluminum	High
Aluminum	High	Preclusive	High	Aluminum	Low
Aluminum	High	Mild	Low	Steel	Standard
Aluminum	High	Mild	Low	Aluminum	High
Aluminum	High	Mild	Low	Aluminum	Low
Aluminum	High	Mild	High	Steel	Standard
Aluminum	High	Mild	High	Aluminum	High
Aluminum	High	Mild	High	Aluminum	Low
Aluminum	Low	Preclusive	Low	Aluminum	High
Aluminum	Low	Preclusive	Low	Aluminum	Low
Aluminum	Low	Preclusive	High	Aluminum	High
Aluminum	Low	Preclusive	High	Aluminum	Low
Aluminum	Low	Mild	Low	Steel	Standard
Aluminum	Low	Mild	Low	Aluminum	High
Aluminum	Low	Mild	Low	Aluminum	Low
Aluminum	Low	Mild	High	Steel	Standard
Aluminum	Low	Mild	High	Aluminum	High
Aluminum	Low	Mild	High	Aluminum	Low

Probabilities

Initial Decision	Acceptance	Regulation	Alum. Cost	Second Decision	Acceptance
Steel	1	1	0	Aluminum	0.9
Steel	1	1	0	Aluminum	0.1
Steel	1	1	1	Aluminum	0.9
Steel	1	1	1	Aluminum	0.1
Steel	1	0	0	Steel	1
Steel	1	0	0	Aluminum	0.9
Steel	1	0	0	Aluminum	0.1
Steel	1	0	1	Steel	1
Steel	1	0	1	Aluminum	0.9
Steel	1	0	1	Aluminum	0.1
Aluminum	0.9	1	1	Aluminum	0.95
Aluminum	0.9	1	1	Aluminum	0.05
Aluminum	0.9	1	0	Aluminum	0.95
Aluminum	0.9	1	0	Aluminum	0.05
Aluminum	0.9	0	1	Steel	1
Aluminum	0.9	0	1	Aluminum	0.95
Aluminum	0.9	0	1	Aluminum	0.05
Aluminum	0.9	0	0	Steel	1
Aluminum	0.9	0	0	Aluminum	0.95
Aluminum	0.9	0	0	Aluminum	0.05
Aluminum	0.1	1	1	Aluminum	0.05
Aluminum	0.1	1	1	Aluminum	0.95
Aluminum	0.1	1	0	Aluminum	0.05
Aluminum	0.1	1	0	Aluminum	0.95
Aluminum	0.1	0	1	Steel	1
Aluminum	0.1	0	1	Aluminum	0.05
Aluminum	0.1	0	1	Aluminum	0.95
Aluminum	0.1	0	0	Steel	1
Aluminum	0.1	0	0	Aluminum	0.05
Aluminum	0.1	0	0	Aluminum	0.95

Probability DataTable

Initial Decision	Pricing	Acceptance	Acceptance
	Steel		1
	Aluminum	High	**0.9**
		Low	0.1

Regulation	Regulation
Preclusive	1
Mild	0