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EXPERT SYSTEM BASED APPROACH FOR MATERIAL SELECTION OF AUTOMOBILE BODY-IN-WHITE STRUCTURAL PANELS USING NUMERICAL RANKING AND SUSTAINABILITY INDICES

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EXPERT SYSTEM BASED APPROACH FOR MATERIAL SELECTION OF AUTOMOBILE BODY-IN-WHITE STRUCTURAL PANELS USING NUMERICAL RANKING AND SUSTAINABILITY INDICES

A Dissertation
Presented to
The Graduate School of
Clemson University

In Partial Fulfillment
Of the Requirements for the Degree
Doctor of Philosophy
In Automotive Engineering

By
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ABSTRACT

The goal of this work is to establish a set of quantifiable measures for design for sustainability (DFS) that can be applied to automotive applications in terms of environmental, social, economic and technical aspects. In this study, a comprehensive analysis was made in order to develop a methodology that can evaluate different body-in-white designs in terms of major sustainability aspects. Besides the complete life cycle analysis, environmental impacts and cost factors will be analyzed over vehicle's entire life-cycle (fuel extraction and refining, Pre-manufacturing, Manufacturing, Use, and Post-use stages). The considered material options include: conventional steel, high strength steel, aluminum, magnesium, titanium and composites that are currently used in body-in-white (BIW) structures and exterior body panels. Sustainability scoring method was developed and used to decide on how using lighter materials in auto body applications is beneficial or not. The proposed major sustainable factors are categorized into four major groups: environmental, economical, social and technical groups. Also, each group has corresponding factors which were chosen by extensive search and screening, so only important sustainability aspects for auto body design have been selected in this study. Then the dissertation proceeds to show some sustainability scoring methods in order to get better understanding as well as relative ranking for different materials from sustainability point of view.

Moreover, this work discusses the role and application of some multi-criteria decision making methods in materials selection, namely quality function deployment (QFD) and analytical hierarchy process (AHP). However, multi-criteria decision making methods are efficient tools to choose alternative from large set of alternatives, especially when two or more conflicting goals are present. Besides that, knowledge based system (KBS) was established for eco-material selection for auto-body structural panels. The goal behind using KBS is to help designers in material selection process which usually needs experience, time and effort.

DEDICATION

This dissertation is dedicated to my late father and my mother who have supported me all the way since the beginning of my life.

Also, this work is dedicated to my wife Wasayef Altawafshih and my son Kenan who have been a great source of motivation and inspiration.

ACKNOWLEDGMENTS

I would like to first acknowledge the inspirational instruction and guidance of my advisor, Dr. Mohammed Omar; he has given me continuous support guidance throughout this work. I also would like to thank my committee members, Dr. Fadi Abu-Farha, Dr. Pisu Pierluigi, and Dr. Thomas Kurfess for their valuable suggestions and guidance to improve the quality of this work.

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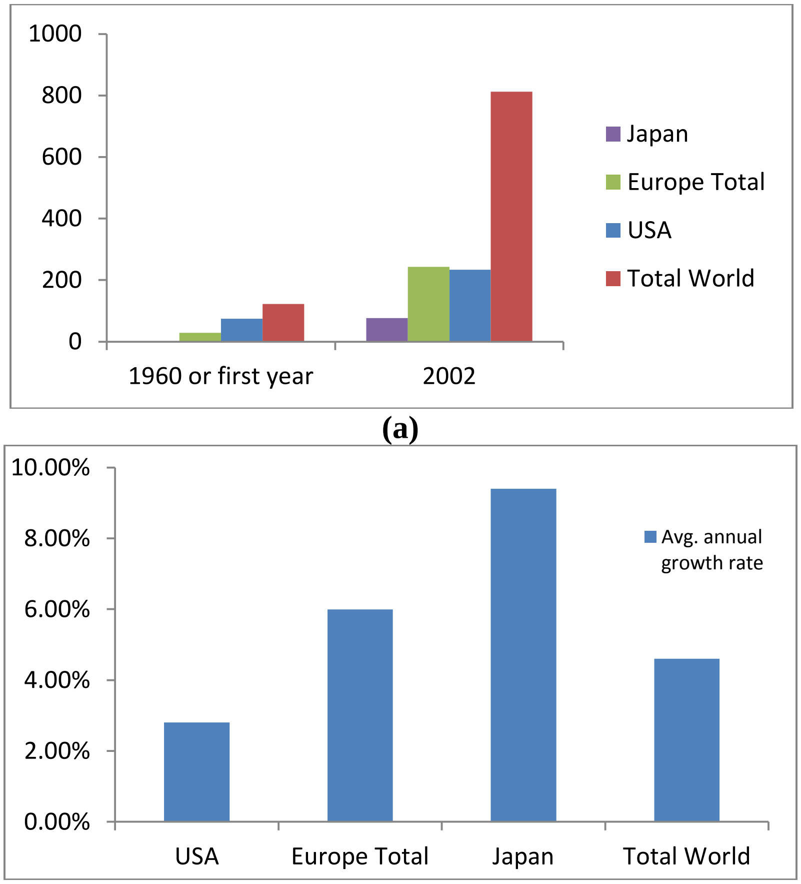
CHAPTER ONE

DESIGN FOR SUSTAINABILITY IN AUTOMOTIVE INDUSTRY: A COMPREHENSIVE REVIEW

1.1. INTRODUCTION

Nowadays, 96% of the world's transportation systems depend on petroleum-based fuels and products, with the global transportation systems accounting for about 40% of the world's oil consumption of nearly 75 million barrels of oil per day (Mcauley, 2003). Furthermore, since 1960 the vehicle ownership in the United States had grown from about 74.4 million to more than 239 million in 2002 with an average annual growth rate of 3%. However, the global growth trend is much faster than US, with ownerships outside the United States climbing from about 47.6 million to over 573 million over the same period (Dargay et al., 2007). This global growth of vehicles as shown in Fig. 1.1 will result in significant increases in global fuel demand, material requirements, and air emissions while Fig. 1.2 shows vehicle weight trends for model years 1975 to 2009 in United States where the a higher vehicle's weight trend has started from 1987. As a result, sustainability continues to become a critical issue for the automotive industry motivating more significant reductions to the overall environmental impact of vehicles worldwide, in order to ensure the automobile as a product is an environmentally sustainable one. At the same time, this trend adds more pressure on the Original Equipment Manufacturers (OEMs) to not only come up with new solutions to minimize the environmental impact through the usage of more efficient processes that preserve resources, but also to develop quantitative metrics to assess such impact and gauge improvement efforts.

According to Curtis and Walker (2001) the definition of designing for sustainability involves balancing social, ethical and environmental issues alongside economic factors within the product or service development process. It ensures that the needs of both the business customer and society are met whilst protecting the ecosystem. This definition highlights the inherent complexity in sustainability accounting and tracking efforts.



(a)

(b)

Figure 1.1: (a) Historical vehicle Ownership (millions), 1960-2002; and (b) average annual growth rate between 1960-2002.

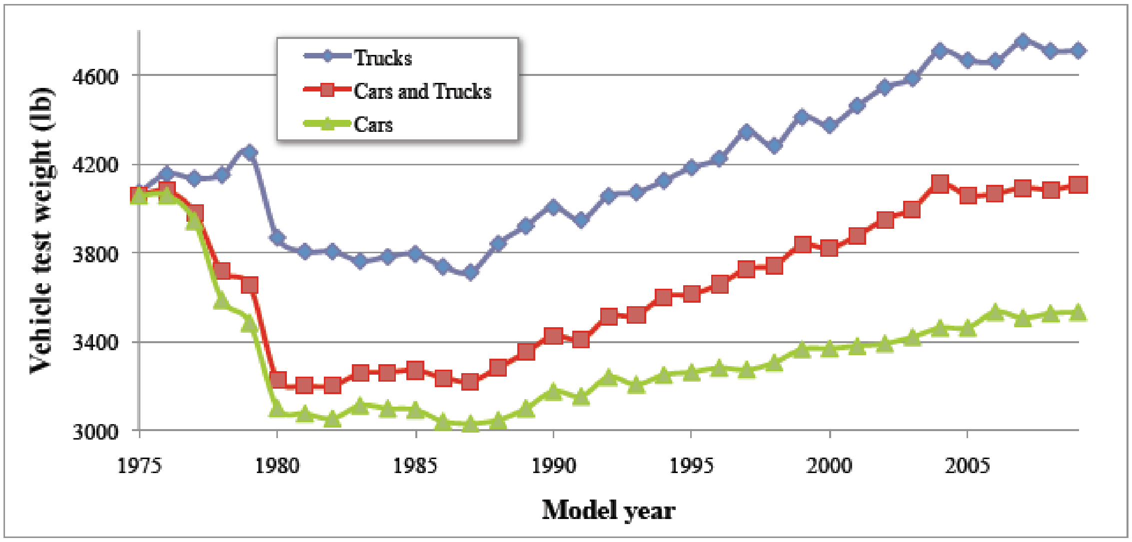


Figure1.2: Light duty vehicle weight trends for model years 1975 to 2009 (U.S. EPA, 2009)

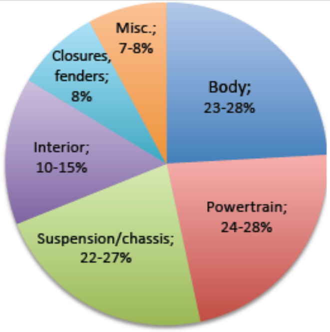
One of the main sources to achieve sustainability is to select lightweight materials like aluminum and magnesium in vehicle structures. However, the competition between alternative materials like high-strength steel, aluminum, magnesium, and plastic continues to result in a rich portfolio of options to reduce vehicle mass component-by-component (e.g., engine, beams, panels, etc). In addition, design approaches for the vehicle body structure that more heavily utilize higher strength steels and aluminum are beginning to be embraced by some manufacturing companies, and this could substantially reduce the mass of vehicle models. Several major studies, as well as some automakers' announced plans, indicate that mass-reduction technology with minimal additional manufacturing cost could achieve up to a 20% reduction in the mass of new vehicles in the 2015-2020 timeframe. This incremental mass reduction approach would, in turn, result in a 12% to 16% reduction in CO_2 emissions while maintaining constant vehicle size and performance (Lutsey , 2010).

Lutsey (2010) studied different automotive mass reduction technologies and he found that body-in-white (Fig. 1.3) might be the first choice to consider for two reasons:

- It accounts for the main part of vehicle's curb weight; where BIW and closures account ~30% of the vehicle's weight;

- It has the vast potential of weight savings if compared to other systems like powertrain or chassis due to the fact that external panels of BIW have flat or semi-flat shapes which make them attractive for re-design process (See Table 1.1). Actually, some OEMs already introduced lightweight BIW designs in their vehicles such as Audi (TT, A2, and A8), Jaguar (XJ), Lotus and Honda (NSX, Insight). See Table 1.2 for more details about OEMs and how they apply lightweight materials in their vehicles.

Table 1.1: Vehicle mass breakdown by system and components (Lutsey, 2010)

Approximate vehicle mass breakdown[a]	System	Major components in system
	Body-in-white	Passenger compartment frame, cross and side beams, roof structure, front-end structure, underbody floor structure, panels
	Powertrain	Engine, transmission, exhaust system, fuel tank
	Chassis	Chassis, suspension, tires, wheels, steering, brakes
	Interior	Seats, instrument panel, insulation, trim, airbags
	Closures	Front and rear doors, hood, lift gate
	Miscellaneous	Electrical, lighting, thermal, windows, glazing

[a] Based on Stodolsky et al, 1995a; Bjelkengren, 2008; Lotus Engineering, 2010; the actual system definitions and system component inclusion can vary, and percentage weight breakdown can vary substantially by vehicle

Figure 1.3: Major panels of BIW with closures (AluMATTER, 2011)

Table 1.2: Component weight-reduction potential (Lutsey , 2010)

Vehicle system	Subcomponent	New material or technique [a]	Weight reduction (lb)[b]	Example automaker (models) [c]	Source(s)
Powertrain	Block	Aluminum block	100	Ford (Mustang); most vehicles	Tyell, 2010; Ford, 2010
	Engine, housing, etc	Alum-Mg-composite	112	BMW (R6)	Kulekci, 2008
	Engine	Smaller optimized molds (Al)	55	Toyota (Camry)	Simpson, 2007
	Valve train	Titanium intake valves	0.74	GM (Z06)	Gerard, 2008
	Connecting rod (8)	Titanium	3.5	GM (Z06); Honda (NSX)	Gerard, 2008
	Driveshaft	Composite	7	Nissan; Mazda: Mitsubishi	ACC, 2006
	Cradle system	Aluminum	22	GM (Impala)	Taub et al, 2007
	Engine cradle	Magnesium	11.0-12.0	GM (Z06)	Gerard, 2008; US AMP, 200x
	Intake manifold	Magnesium	10	GM (V8); Chrysler	Kulekci, 2008: US AMP
	Camshaft case	Magnesium	2	Porsche (911)	Kukekci, 2008: US AMP
	Auxiliaries	Magnesium	11	Audi (A8)	Kulekci, 2008

	Oil pan	Modular composite	2	Mercedes (C class)	Stewart, 2009
	Trans. housing	Aluminum	8	BMW (730d); GM (Z06)	Gerard, 2008
	Trans. housing	Magnesium	9-10	Volvo; Porsche (911); Mercedes; VW (Passat); Audi (A4, A8)	Kulekci, 2008; US AMP
Body and closures	Unibody design	Vs. truck body-on-frame	150-300	Honda (Ridgeline); Ford; Kia; most SUV models	Honda, 2010; Motor Trend, 2009
	Frame	Aluminum-intensive body	200-350	Audi (TT, A2, A8); Jaguar (XJ); Lotus; Honda (NSX, Insight)	Brooke and Evans, 2009; EAA, 2007; Audi, 2010
	Frame	Aluminum spaceframe	122	GM (Z06)	Taub et al, 2007
	Panel	Thinner Al- alloy	14	Audi (A8)	Audi, 2010
	Body	Panel Composite	42	BMW	Diem et al, 2002
	closure Doors (4)	Aluminum-intensive	5-50	Nissan (370z); BMW (7); Jaguar (XJ)	Keith, 2010; BMW, 2008; Birch, 2010
	Doors (4)	New production process	86	Porsche (Cayenne)	Stahl, 2010
	Door inner (4)	Magnesium	24-47		Kulekci, 2008; US AMP
	Hood	Aluminum	15	Honda (MDX); Nissan (370z)	Monaghan, 2007; Keith, 2010
	Roof	Aluminum	15	BWW (7 series)	BMW, 2008
	Lift gate	Magnesium	5-10		Kulekci, 2008; US AMP
Suspension and chassis	Chassis	Aluminum	145	Porsche (Cayenne)	Carney, 2010
	Chassis	Hydroformed steel structure, tubular design	100	Ford (F150)	FordF150.net, 2010
	Steering wheel	Magnesium	1.1	Ford (Thunderbird, Taurus); Chrysler (Plymouth); Toyota (LS430); BMW (Mini); GM (Z06)	Kulekci, 2008; Gerard, 2008
	Steering column	Magnesium	1-2	GM (Z06)	Kulekci, 2008; Gerard, 2008
	chassis Wheels (4)	Magnesium	26	Toyota (Supra); Porsche (911); Alfa Romeo	Kulekci, 2008; US AMP
	Wheels (4)	Lighter weight alloy, design	13	Mercedes (C-class)	Tan, 2008

	Brake system	Heat dissipation, stainless steel pins, Al caps	30	Audi (A8)	Audi, 2010
	Tires	Design (low RR)	4	Mercedes (C-class)	Tan, 2008
	Suspension	Control arms (2)	6	Dodge (Ram)	SSAB, 2009
Interior	Seat frame (4)	Magnesium	28	Toyota (LS430); Mercedes (Roadster)	Kulekci, 2008; US AMP
	Instrument panel	Magnesium	7-13	Chrysler (Jeep); GM; Ford (Explorer, F150); Audi (A8); Toyota (Century); GM	Kulekci, 2008; US AMP; Taub et al, 2007
	Dashboard	Fiber-reinforced thermoplastic	18	VW (Golf)	Stewart, 2009
	Console and shifter	Injection molded GFRP	5	Ford (Flex)	Stewart, 2009
Misc.	Windows	Design, material thickness	3	Mercedes (C-class)	Tan, 2008
	Running board	GFRP	9	Ford (Escape)	Stewart, 2009

[a] These technologies can include a change in design, a reduction in parts, a reduction in material amount, and use of various metallic alloys; note that weight (lb) and mass (kg) variables are used in this report. 1 kg = 2.205 lb.

[b] Weight reduction estimates are approximate, based on media sources and technical reports

[c] A number of these models are not available in the U.S.; some model names have changed in recent product changes

1.2. PROBLEM STATEMENT

Design for sustainability (DFS) takes many product development aspects into account:

- Material selection,
- Life cycle energy uses and green house gases (GHG) emissions,
- End-of-life strategies (landfill, recycling, recovery, recycle, etc.),
- Recycling and its corresponding issues, and
- Reuse and remanufacturing of some components.

Actually, DFS does not have well established borders and thus standards do not exist. It involves many complex trade-offs between economical, environmental and social objectives. This issue and other issues like what metrics to be included and what are the boundaries of sustainability model result in a more complicated problem that needs extended work to be solved.

There is a set of questions need to be addressed and answered when talking about DFS and hence this research is organized in such a way to address and answer these questions. The first question needs to be addressed here is: how does this design comply with requirements and what is the ability to meet its extended functions. For example considering whole ultra-lightweight plastic BIW might be the best choice in terms of economical and environmental aspects, however, plastic BIW will not be the best choice in terms of durability and safety. Basically, every design should be pivoted around customer needs, cost efficiency and functionality. By ensuring the above mentioned design goals, the second question arises promptly, is the available technology appropriate to make such changes in design or not, for example is replacing steel by aluminum as easy to OEMs as most of us think. Actually, majority of OEMs still resist using new materials; rather, they prefer using advanced and high strength steel instead of conventional steel grades because once they decide to introduce new material (say Al) there is a high potential for having to adopt different manufacturing and joining technologies. This drawback of using new lighter materials in association with other limitations like weldability and paintability of the new materials might limit their use in automotive sector.

Moreover, other questions that still need answers are:

- Is sustainability considered fundamentally as a material's selection problem? If yes, what kind of engineering materials can replace steel without losing function of any replaced part, how will this replacement result in less environmental impacts and being economically feasible solution to replace conventional steel?

- What will be the most cost-effective choice? Is just replacing steel by other non-ferrous lightweight materials which might force OEMs to change their entire manufacturing processes, or just considering new types of high strength steels that can lead to weight-savings without threatening current manufacturing infrastructure.

- What are the overall environmental, economical and social impacts of any proposed design? Replacing steel by lightweight materials may be considered the best decision to take if environment protection is the only goal we consider. This in turn completely disregards the economical effects and more important the social acceptance if the customers want safe vehicles.

1.3. RESEARCH OBJECTIVES

Generally speaking, this research aims to encourage a way of thinking that supports the creation of sustainable vehicles at roads. In this research, the concept of design for sustainability will be investigated and applied to the automotive applications, with an emphasis on the design of body-in-white (BIW).

The research is guided by the following five goals:

- Establishing a set of metrics that capable of handling and conceptualizing sustainability aspects in future designs;
- Proposing sustainable vehicle design which is conceptualized and directly linked to the broader framework of sustainable development.
- Assessing the vehicle in its entire life-time span, i.e. from pre-manufacturing till the end-of-life stages.
- Proposing a set of sustainable decision-support framework that can provide the design team and customers with a road map for developing their thinking towards sustainability.
- Establishing a framework for eco-material selection process using knowledge based systems (KBS).

In general, this research may be considered as the first stage of a comprehensive and long-term research agenda that will deal with sustainability in automotive industry. It attempts to present a coherent set of tools and approaches that can be used in the future to assess and promote the concepts of design for sustainability and lightweight-sustainable design considerations.

1.3.1. RESEARCH OBJECTIVE SIGNIFICANCE

1. Understand and articulate the concept of design for sustainability in general, and apply this concept to the automotive industry. Body-in-white (BIW) will be the starting point for design for sustainability in this study.

2. Almost, all sustainability models are considered qualitative in nature because they just address the sustainability issues and propose solutions for the problems. Hence, only dealing with question and answers to cope sustainability is not a scientific way of thinking of sustainability in automotive industry. Therefore, there is strong need to establish quantifiable measures for design for sustainability (DFS) and use these measures to assess vehicle's designs from sustainability point of view.
3. Lack of design for sustainability metrics leads to selection of lightweight materials without paying any attention to cost and/or functionality of the replaced parts. So, this study aims to develop a set of sustainable-material selection indices, in which all alternatives being projected and assessed for their abilities to meet given selection criteria, i.e. can material X replace material Y in BIW construction without affecting functionality of that panel? and if it can, how much will sustainable design gain or lose from this replacement? In this research material selection for sustainable body-in-white (BIW) tries to achieve designs that compromise the following:
    I. Functionality.
    II. Cost efficiency.
    III. Environment friendly.
    IV. Technology needed without asking OEMs to change their entire manufacturing procedures and machines to handle new designs. Hence,

the goal is to just find the solutions of adapting current infrastructure to deal the new changes in manufacturing.

4. Develop a decision-making philosophy and associated design for sustainability decision-support framework that incorporates the objectives of sustainable development.
5. Assess the whole life cycle of the selected vehicles and develop a complete analysis that can give the designers and users a clear idea about what happens during the entire life time span.

1.4. RESEARCH APPROACH

This research project involves five main activities:

1. Understanding and conceptualizing design for sustainability by establishing a set of quantifiable metrics that cover all aspect of sustainability (environmental, economical, social and technical).
2. Establishing material selection methodology that takes into consideration all sustainability factors. In this phase, a new set of material selection indices will be developed and all candidate materials will be assessed and ranked based on their capabilities of achieving each selection criterion. The selection criteria will be classified into groups that cover all sustainable design aspects, and all candidate materials will be assessed using selection charts in order to use their corresponding ranks for further analysis.

3. Analyzing current design models (steel-intensive BIW, Al-intensive BIW, Mg-intensive BIW, and composite intensive BIW), and identify if they can replace conventional steel without affecting functionality of any BIW panels.
4. Establishing complete life cycle analysis (LCA) for all proposed designs and assess all designs in their abilities to meet sustainability goals. LCA will cover all stages of vehicle’s life-time from material extraction and processing, manufacturing, use phase, end-of-life and fuel extraction and refining. The latter has been ignored in all previous sustainability models, so linking this phase with other life cycle phases to get one complete LCA model might be a challenge this work aims to overcome.
5. Applying decision supporting methods and knowledge based system to the development process for eco-material selection of vehicle’s body-structure.
6. Quantifying sustainability in a systematic way to get better feeling of the overall selection process.

1.5. LITERATURE REVIEW

1.5.1. AUTOMOTIVE LIFE CYCLE ASSESSMENT (LCA)

Stodolsky et al., (1995a, 1995b) as well as Sundin (2004) defined the life-cycle assessment or LCA as a method that is used to account for the environmental impacts associated with a product or a service from inception to end-of-life or cradle-to-grave. Typical life of any industrial product begins with the extraction and processing of its raw materials, then its manufacturing, distribution, use, and lastly by its end-of-life stage.

Sundin (2004) classified the life cycle assessment into four main stages: the material extraction, manufacturing, use and disposal, pictorially displayed in Fig. 1.4, while Ashby (2009) added one more stage that is the transportation. Ashby (2009) suggested that when assessing the life cycle environmental impact of the vehicle, energy during the use stage can be considered as an indicator of its environmental burden. However, LCA studies and assessment methods in association with the international standards ISO 14040, 14041, 14042, 14043 are important, especially at the inception and design phase. Pennington (2004) and Govetto (2008) categorized the ISO 14000 series into four phases; the goal and scope phase, the inventory analysis, the impact assessment, and interpretation phase.

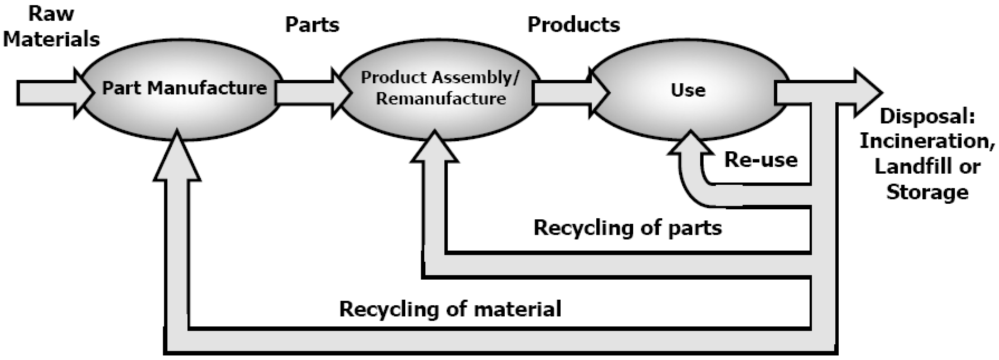


Figure 1.4: The physical product life-cycle (2004).

With the first phase “Goal and scope” is set to define the purpose, the boundary, metrics and the units of the inputs and outputs that will be evaluated, while the second step or “Inventory analysis” basically deals with the data collection. The first two steps are further analyzed in the ISO 14041 (Govetto, 2005, ISO 14000 series). The third phase or “Impact assessment” helps in evaluating the environmental consequences of phases one and two results, with the ISO 14042 guiding the construction of the third phase. Finally, the last phase or "interpretation" is designed to comment and draw conclusions on the three preceding phases or steps; the ISO 14043 articulates this last step.

The life-cycle assessment for an automobile analyzes the vehicle from the pre-manufacturing stage i.e. raw materials to its end-of-life stage, as displayed in details in Table 1.3 for developed and developing countries. The LCA methodology suffers from two main challenges; the first is the diversity and variations in materials, processing techniques, usage durations, and disposal routes, as displayed in and Fig. 1.5 from (Omar 2011). The other challenge is the extended timeline associated with the LCA. According to Mildenberger and Khare (2000), the total life for a vehicle in developed countries ranges from 25-35 years, while in the under-developed countries it reaches 45 years (Table 1.3). This challenges not only identifying the actual life-time, but also the vehicle degradation while in use (e.g. loss of engine efficiency leading to more fuel consumption) and the real value of monetary units.

Table 1.3: Life cycle of the vehicle in developed, developing and under-developed countries (Mildenberger and Khare; 2000)

	Concept and Design (years)	Manufacturing (years)	Use phase (years)	Total life (years)
Developed countries	4-5	7-8	10-12	>25
Developing countries	6-8	10-12	15-20	>35
Under-developed nations	N/A	N/A	20-25	>40

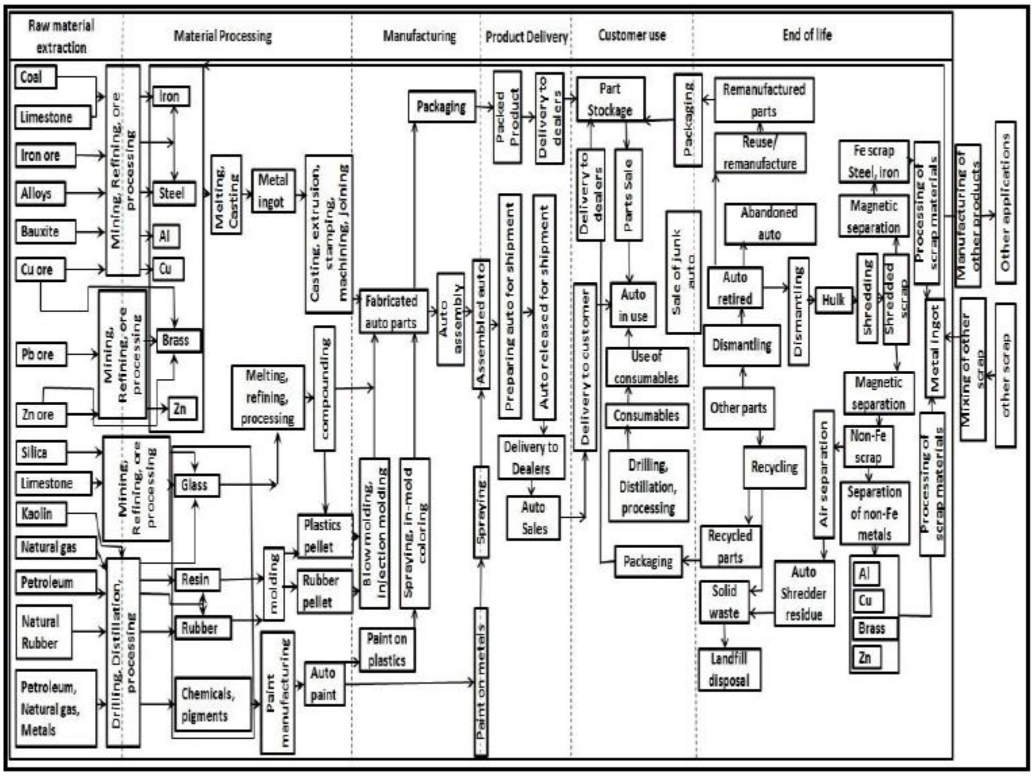


Figure 1.5: Detailed LCA showing materials used in the vehicle, manufacturing processes and end-of-life scenarios (Omar, 2011).

1.5.2. FUEL ECONOMY AND AIR EMISSIONS

Mcauley (2003) stated that almost 87% of a motor vehicle’s life cycle energy consumption is in the “use phase” of the vehicle, as shown pictorially in (Fig. 1.6). Furthermore, other key environmental impacts such as air emissions occur predominantly in the oil extraction, refining and transportation to the customers; followed by vehicle “use phase” (More discussion in next sections).

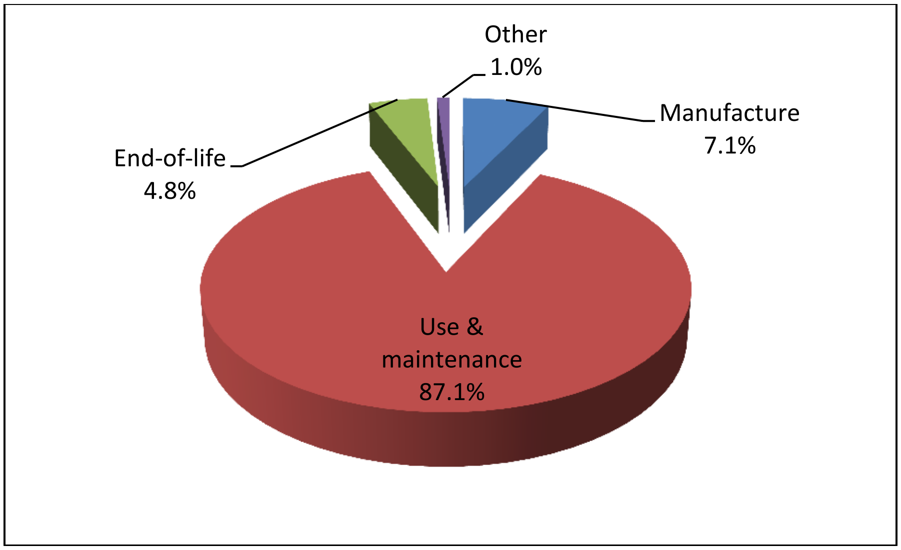


Figure 1.6: Energy consumption in automobile life cycle (Mcauley, 2003)

In the wake of the OPEC oil embargo and the tripling of oil prices in the early 1970s, the U.S. Congress passed the Energy Policy and Conservation Act of 1975. This Act established the minimum Corporate Average Fuel Economy CAFE standards (Mclauy, 2003). As shown in Table 1.4, the average fuel economy for a US passenger car increased from 20 mpg in 1980 to 27.5 mpg in 2009, while for US light trucks, its fuel economy increased from less than 19.5 mpg in 1980 to more than 23 mpg in 2009 (RITA, 2011). This disparity in fuel efficiency has developed in North America because of the tremendous growth in the Sports Utility Vehicles SUV sales, minivans, and pickup trucks. Federal and state governments have initiated numerous policies to move alternative fuels and energy sources into the US motor vehicle fleets. Outside the United States, many countries have put regulations in place to reduce fuel consumption and air emissions, including imposing high taxes on fuels to encourage energy conservation (Maclean et al., 2000).

Table 1.4. Average Fuel Efficiency of U.S. Passenger Cars and Light Trucks (RITA, 2011).

	1980	1985	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Average U.S. passenger car fuel efficiency (mpg) (calendar year)														
Passenger car[a]	(R) 16.0	(R) 17.5	(R) 20.3	(R) 21.1	(R) 21.9	(R) 22.1	(R) 22.0	(R) 22.2	(R) 22.5	(R) 22.1	(R) 22.5	(R) 22.5	22.6	U
Other 2-axle 4-tire vehicle	(R) 12.2	(R) 14.3	(R) 16.1	(R) 17.3	(R) 17.4	(R) 17.6	(R) 17.5	(R) 16.2	(R) 16.2	(R) 17.7	(R) 17.8	(R) 18.0	18.1	U
New vehicle fuel efficiency (mpg)[b](model year)														
Light-duty vehicle														
Passenger car	24.3	27.6	28.0	28.6	28.5	28.8	29.0	29.5	29.5	30.3	30.1	31.2	31.2	32.6
Domestic	22.6	26.3	26.9	27.7	28.7	28.7	29.1	29.1	29.9	30.5	30.3	30.6	31.0	32.6
Imported	29.6	31.5	29.9	30.3	28.3	29.0	28.8	29.9	28.7	29.9	29.7	32.2	31.5	32.6
Light truck (<8,500 lbs GVWR)[c]	18.5	20.7	20.8	20.5	21.3	20.9	21.4	21.8	21.5	22.1	22.5	23.1	23.6	24.2
CAFE standards (mpg)[b](model year)														
Passenger car	20.0	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5
Light truck[d]	U	19.5	20.0	20.6	20.7	20.7	20.7	20.7	20.7	21.0	21.6	22.2	22.5	23.1

KEY: CAFE = Corporate Average Fuel Economy; GVWR = gross vehicle weight rating; mpg = miles per gallon; R = revised; U = data are unavailable. [a] From 1980 to 1994, passenger car fuel efficiency includes motorcycles. [b] Assumes 55% city and 45% highway-miles. The source calculated average miles per gallon for light-duty vehicles by taking the reciprocal of the sales-weighted average of gallons per mile. This is called the harmonic average. [c] Beginning with FY 1999, the total light truck fleet ceased to be categorized by either domestic or import fleets. [d] No combined figure is available for 1980. In 1980, CAFE standard for 2 wheel drive, and 4 wheel drive light trucks were 16.0, and 14.0 mpg respectively.

The primary pollutants from vehicle’s use stage include carbon monoxide (CO), nitrogen oxides (NOx), particulate matter less than 10 μm in diameter, sulfur dioxide, and Volatile Organic Compounds (VOC) (Omar, 2011, Maclean et al., 2000). Large quantities of carbon dioxide, considered as a “greenhouse” gas, are also released.

According to Mcauley (2003), the vehicle usage in the United States accounts for nearly one-third of all domestic energy use and a significant percentage of the total air emissions. Additionally, the US transportation activities account for a third of the nation’s total carbon dioxide emissions, nearly 80% of carbon monoxide emissions, 50%

of nitrogen oxides, 40% of volatile organic compounds, and 33% of carbon dioxide emissions.

The Intergovernmental Panel on Climate Change IPCC concluded that these emission increases have apparent impact on the earth's climate and are believed to be responsible for a significant (1-2°F) increase in the average global temperature since the pre-industrial times (Pehn, 2002). With the global vehicle usage expected to increase by a factor of 3-5 times today's level by 2050, the impact on global air quality, human health, and global climate could be extremely damaging if significant changes in vehicle design are not implemented globally to arrest these negative trends (Pehn, 2002, Maclean et al., 2000).

There are many vehicle design considerations that can impact vehicle air emissions and energy consumption, including the use of alternative fuels or new engine technologies (Pehn, 2002, Maclean et al., 2000, Cheah, 2008, Cheah 2011), reducing rolling resistance, improving vehicles' aerodynamics and drive-train design, and reducing vehicle weight (Mcauley, 2003; Ungureanu et al. 2007a; Ungureanu, 2007b; Davies, 2004). Ungureanu et al. (2007a, 2007b) claimed that vehicle weight is the key source to achieve significant reductions in the life cycle energy consumption and the primary air emissions burdens. This is due to the fact that the rolling resistance and acceleration forces (the essential elements of transportation energy efficiency) are directly proportional to the weight of the vehicle (Ungureanu, 2007b, Pehn, 2002, Cheah, 2011).

1.6. AUTOMOTIVE DESIGN AND MATERIAL SELECTION FOR SUSTAINABILITY PURPOSES

Today, a typical US family vehicle weighs about 1400kg (Mcauley, 2003), with iron and steel accounting for the majority of this weight. However, the new trends in vehicle light-weighting aim not only to enhance vehicle fuel efficiency, but also to improve its driving performance while lowering its emissions at the same time (Mayyas et al., 2011). This can be achieved to a high degree through the use of lighter weight materials like aluminum and plastics (Fuchs et al., 2002). Based on a national study, a ten percent reduction in vehicle weight translates to a 5% increase in miles per gallon (Mayyas et al., 2011). This in turn means that a sizable savings in gasoline and the accompanying emissions will be achieved with an annual build of 15 million passenger vehicles.

1.6.1. MODELS FOR SUSTAINABLE MATERIAL SELECTION FOR AUTOMOTIVE APPLICATIONS

Several methods exist for incorporating the environmental concerns in the materials selection process. Some methods emphasize selecting materials based on assigning portion of a product’s life cycle (e.g. End-of-Life material recovery); while others attempt to consider the entire life cycle, either qualitatively or quantitatively.

Graedel and Allenby (1994) provided a set of material selection guidelines as a set of qualitative selection methodologies. Material selection guidelines are simply rules-of-thumb such as "Choose abundant, non-toxic, non-regulated materials, if possible." Although using qualitative methods can help to classify materials as desirable or not desirable, still the prioritization of certain materials is difficult.

Alternatively, quantitative approaches for environmental material selection rate the materials using specific indicators; including: (1) single environmental indicator, such as the Eco-Indicator used by Wegst and Ashby (1998), or the energy content proposed and used by Ashby (2009), or a set of environmental indicators (e.g., CO_2, SO_x, NO_x, a measure of grade of recyclability, and resource scarcity as suggested by Coulter et al. (1996). (2) An economic indicator, such as the environmental cost used by Ermolaeva et al. (2004).

Ashby (2009) demonstrates that the performance index methodology may also be used to evaluate materials based on individual environmental parameters (e.g., energy consumption) in conjunction with other material factors.

Kampe (2001) developed a model where a lifetime environmental load associated with the selection of a specific material can be routinely assessed as part of the overall decision making process. This model uses classical mass-based material selection indices developed by Ashby then it introduces some modifications to include the total energy consumption prior to, and during, service. For example, the required mass, $\boldsymbol{m}$, for a beam of a design-constrained length, $\boldsymbol{L}$ and a fixed, 2:1 cross-sectional aspect ratio, capable of supporting an anticipated uniformly-distributed load, $\boldsymbol{W}$ (e.g., N/m), along its length without experiencing overload failure can be expressed as (Kampe, 2001):

$$m = \left(\frac{3}{4\sqrt{2}}.W.L^{7/2}\right)^{\frac{2}{3}}.\left(\frac{\rho}{\sigma_f^{\frac{2}{3}}}\right) \quad (1.1)$$

Kampe (2001) extended the above material selection index to include the total energy expenditure, $\boldsymbol{Q}$ which is required to assure the beam availability for the design. This can be obtained by multiplying the derived mass by the energy content, $\boldsymbol{q}$:

$$Q = \left(\frac{3}{4\sqrt{2}}.W.L^{7/2}\right)^{\frac{2}{3}}.\left(\frac{\rho.q}{\sigma_f^{\frac{2}{3}}}\right) \quad (1.2)$$

Table 1.5 provides specific examples for different materials properties and their index values. These indices indicate that steel would represent the heaviest option, whereas the epoxy-Kevlar composite the lightest. Further, this table indicates that a component fabricated from steel would require the least initial (pre-service) energy expenditure while titanium requires the most.

Table 1.5. Representative material data and its implementation into mass and energy selection indices (Kampe, 2001).

Material Option	**Density**	**Failure Strength (MPa)**	**Energy Content (MJ/kg)**	**Mass Index** $\frac{\rho}{\sigma_f^{2/3}}$ $(\frac{kg}{m^3 MPa^{2/3}})$	**Energy Index** $\frac{\rho.q}{\sigma_f^{2/3}}$ $(\frac{MJ}{m^3 MPa^{2/3}})$
1015 Steel	7850	328	66	165	10893
6061-T6 aluminum	2700	270	285	65	18420
Titanium alloy	4480	845	1000	50	50143
Epoxy-Kelvar composite	1325	460	500	22	11118

Starting from the initial energy expenditures required for each of the material options from Table 4, one can now consider how the material selection affects the product energy consumption over its entire lifetime in service. This requires the estimation of a proportionality, or exchange, constant that quantifies the value of mass in terms of lifetime energy consumption. Kampe (2001) stated that this value should rely on the magnitude of the desired lifetime, as well as the origins of how strongly the mass affects the energy consumption. Figure 1.7 illustrates how an estimated value of the exchange constant might vary with the desired vehicle lifetime based on total mileage. According to (Kampe, 2001), Lifetime Energy Consumption LEC can thus be summed using the two components described above, and incorporating the exchange constant to maintain the units' compatibility:

LEC=Initial Energy Content+ Energy Consumed over Lifetime of Vehicle, or in mathematical expression:

$$LEC' = \frac{\rho.q}{\sigma_f^{2/3}} + C_E \frac{\rho}{\sigma_f^{2/3}} \tag{1.3}$$

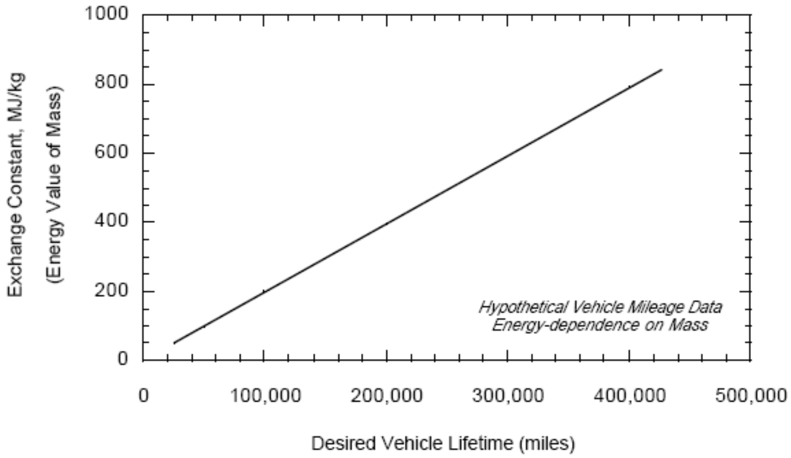


Figure 1.7: Approximated relationship between vehicle mass and lifetime energy consumption, computed as a function of vehicle lifetime in miles (Kampe, 2001).

Equation 1.3 can be easily utilized to assess the lifetime energy consumption for any material option, given the material's properties and a value for the exchange constant for a desired lifetime. Figure 1.8 illustrates a selection chart showing two lines of constant lifetime energy consumption; one computed using a 50,000 mile vehicle lifetime and the other a 200,000 lifetime, for a variety of materials. The LEC for steel was used as the basis for both.

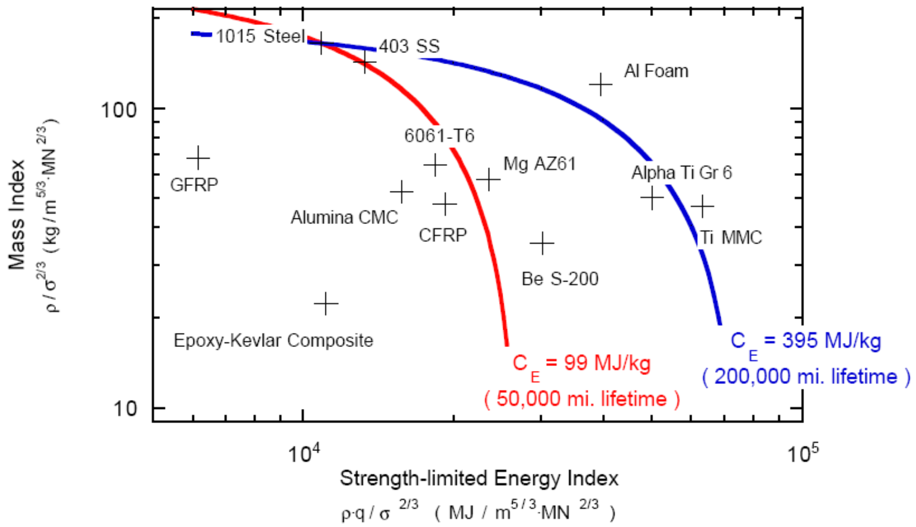


Figure 1.8: The mass index plotted as a function of the energy index (Kampe, 2001).

Materials with indices reside below the lines represent options that would result in lower LEC over the defined lifetime. The search region will be over the LEC line. By doing so, it can be shown that 6061-T6 aluminum, the carbon fiber reinforced plastic (CFRP), the alumina ceramic matrix composite (CMC), the glass-fiber reinforced plastic (GFRP) and the epoxy-Kevlar composite all considered good options in terms of life cycle energy relative to the steel for a defined vehicle lifetime of 50,000 miles, hence they represent more environment-friendly choices. Also it can be noted that, except for the latter two materials, all candidate materials require higher initial energy expenditures, but they need lower in-service energy expenditures. However, if the defined lifetime extension from 50,000 miles to 200,000 miles, then the materials of higher initial energy expenditure becomes more competitive or superior to that of the steel baseline material.

Basically, the main drawback of this model is the fact that it does not consider other life cycle phases (i.e. extraction energy and disposal energy). Usually, introducing these energy terms in any model would change the overall conclusions. For example, the recycling fraction of GFRP is almost zero while aluminum is almost 100% recyclable. This in turn affects overall life cycle assessment of the material options.

One of the most comprehensive LCA models developed by Fitch and Cooper (2004) called the Life Cycle Energy Analysis LCEA, is used mainly for material selection. The basic idea behind LCEA for Material Selection is to estimate the Life Cycle Energy LCE of a component where all life cycle stages are considered. The method is adapted from Sullivan and Hu (1995) approach for estimating the life cycle energy of internal combustion and electric propelled vehicles. Typically, LCE may be used in conjunction with other environmental indicators to provide a more comprehensive evaluation for sustainable material selection. Fitch and Cooper (2004) defined following terms to quantify the selection; **E_{MP}: Material Production Energy** which is the total energy required to extract a raw material from the earth (e.g., mine ore or pump oil) and to process (e.g., wash, concentrate, or refine) it into a material product (e.g., ingot or rolled sheet). **E_{PMP}—Primary Material Production Energy** describes the material production energy for a primary (virgin) material, **E_{SMP}—Secondary Material Production Energy** to represent the material production energy for a secondary or recycled material. **E_{MD}—Material Delivery Energy** is the transportation energy required to deliver a material product to a component fabrication facility, and **E_{CF}—Component Fabrication Energy** is the total energy required to fabricate a component from a useable material form (e.g., ingot or rolled sheet), whereas **E_{CD}—Component Delivery Energy** is the transportation energy required to deliver a component to a product assembly or maintenance facility. Also, **E_{PA}—Product Assembly Energy** describes the total energy required to assemble a product from its individual components. **E_{PD}—Product Delivery Energy** is the transportation energy required to deliver a product to its end user, and **E_{USE}—Use Phase Energy** is the total energy consumed by the normal use of a product throughout its life. **E_{MAINT}—Maintenance Energy** describes the total energy required to maintain the intended function of a component or product throughout the use phase of the product; not including the energy consumed by the normal use of the product. And finally **E_{EOL}—End-of-Life Energy** is the total energy necessarily consumed and actually avoided by the existence of a product after its intended life (e.g., all necessary transportation and disposal energies, and energy credits for the product's value as an energy and material resource).

In the LCEA methodology, the life cycle energy is estimated at the component level as the sum of energy use and between each stage of the life cycle for that component as described in equation 8:

$$LCE_i \approx (E_{MP})_i + (E_{MD})_i + (E_{CF})_i + (E_{CD})_{i_i} + \ldots\ldots + (E_{PA})_i + (E_{PD})_i + (E_{USE})_i + \cdots + (E_{MAINT})_i + (E_{EOL})_i \tag{1.4}$$

Where, LCE$_i$= life cycle energy for a component made from material i (MJ)

Table 1.6 summarizes the life cycle phases, assumptions used and the developed equation for each phase as described by Fitch and Cooper (2004).

Fitch and Cooper (2004) study used the fuel efficiency algorithm that was originally presented by Sullivan and Hu (1995), in addition the Metro-highway fuel efficiency is estimated for both the vehicle without a component and for the vehicle with a component for each material using.

$$MHFE \approx F(M_b - m_b)^{-FEPI} \tag{1.5}$$

$$MHFE'_i \approx F(M_b - m_b + m_i)^{-FEPI} \tag{1.6}$$

Where, MHFE = metro-highway fuel economy of vehicle without component (mpg)

(MHFE')$_i$ = metro-highway fuel economy of vehicle with component made from material i (mpg); F = constant used to balance equation=1052.57 for 2270 lb (1030 kg) vehicle presented by Sullivan and Hu (1995); M_b = baseline vehicle mass (kg); m_b = baseline component mass (kg); m_i = mass of a component made from material i (kg); FEPI = fuel efficiency percentage increase for a 10% weight savings=0.50 for 2270 lb (1030 kg) vehicle presented by Sullivan and Hu (1995).

In this paper, Fitch and Cooper (2004) provided an example of this material selection approach for an automotive bumper-reinforcing beam, with Table 1.7 presenting the beam masses for the different selected materials.

Table 1.6: Summary table for LCEA (Fitch and Cooper, 2004).

Phase	Equation	Term definition
Material production energy	$(E_{MP})_i \approx m_i[(1-\psi_i)(e_{PMP})_i + \psi_i(e_{SMP})_i]$	$(E_{\mathrm{MP}})_i$ = material production energy for a component made from material *i* (MJ) m_i = mass of a component made from material *i* (kg) c_i = recycled content fraction of material *i* $(e_{\mathrm{PMP}})i$ = primary material production energy per unit mass for material *i* (MJ/kg) $(e_{\mathrm{SMP}})i$ = secondary material production energy per unit mass for material *i* (MJ/kg)
Material delivery	$(E_{MD})_i \approx (E_{MD})_i \approx 0$	$(E_{\mathrm{MD}})i$ = material delivery energy for a component made from material *i* (MJ) $(E_{\mathrm{CD}})i$ = component delivery energy for a component made from material *i* (MJ)
Material fabrication	$(E_{CF})_i \approx m_i(e_{CF})_i \approx 0$	$(E_{\mathrm{CF}})i$= component fabrication energy for a component made from material *i* (MJ) m_i= mass of a component made from material *i* (kg) $(e_{\mathrm{CF}})i$= component fabrication energy per unit mass for material *i* (MJ/kg)
Product assembly	$(E_{PA})_i \approx m_i(e_{PA})$	$(E_{\mathrm{PA}})i$= product assembly energy for a component made from material *i* (MJ) *Mi*= mass of a component made from material *i* (kg) e_{PA}= primary material production energy per unit mass for material *i* (MJ/kg)
Product delivery	$(E_{PD})_i \approx m_i(e_{PD})$	$(E_{\mathrm{PD}})i$ = product delivery energy for a component made from material *i* (MJ) *mi* = mass of a component made from material *i* (kg) e_{PD} = primary material production energy per unit mass for material *i* (MJ/kg)
Use phase	$(E_{USE})_i \approx \rho_f(e_{MP})_f L_V(\frac{1}{MHFE'_i} - \frac{1}{MHFE})$	$(E_{\mathrm{USE}})_i$ = use phase energy for a component made from material *i* (MJ) ρ_f = density of fuel (kg/gal) $(e_{\mathrm{MP}})_f$ = material production energy of fuel per unit mass(MJ/kg) *LV* = vehicle life (miles) MHFE= metro-highway fuel economy of vehicle without component (mpg) $(\mathrm{MHFE'})_i$ = metro-highway fuel economy of vehicle with component made from material *i* (mpg)
Maintenance		$(E_{\mathrm{MAINT}})_i$ = maintenance energy for a

and End-of-life	$(E_{MINT})_i \approx m_f\left(\frac{L_V}{L_C} - 1\right)[(1-\psi_i)(e_{PMP})_i + \cdots + \psi_i(e_{SMP})_i] + (e_{CF})_i + (1-\Phi_i)e_{DE} + \Phi_i[(e_{PMP})_i - (e_{SMP})_i]]$ $(E_{EOL})_i \approx m_i[(1-\Phi_i)e_{DE}] + \Phi_i[(e_{PMP})_i - (e_{SMP})_i]$	component made from material *i* (MJ) $(E_{EOL})_i$ = end-of-life energy for a component made from material *i* (MJ) m_i = mass of a component made from material *i* (kg) L_V = vehicle life (miles) L_C = component life (miles); assumed<LV c_i = recycled content fraction of material *i* $(e_{PMP})_i$ = primary material production energy per unit mass for material *i* (MJ/kg) $(e_{SMP})_i$ = secondary material production energy per unit mass for material *i* (MJ/kg) $(e_{CF})_i$ = component fabrication energy per unit mass for material *i* (MJ/kg) ψ_i = recycle fraction of material *i* e_{DE} = disposal energy per unit mass of material *i*

Table 1.7: Mass comparison for equivalent reinforcing beams (Fitch and Cooper, 2004).

Reinforced Beam Materials	Mass (kg)
PP/GF (unidirectional)	2.09
M220HT Steel	2.50
M190HT Steel	2.82
Al 7129-T6	2.84
PUR S-RIM 54% Glass (chopped and mat)	2.90
PC/PBT (injection molded)	3.40
M160HT Steel	3.44
140X or T Steel	3.76
PUR S-RIM 41% Glass (chopped and mat)	3.90
Al 6061-T6	3.90
PP/GF (direct melt/random)	4.50
PC/PBT (blow molded)	4.54
SMC	4.81
PP	6.80
180 Plannja Steel	7.71

The results of the Life Cycle Energy Analysis are presented in Table 1.8. From sustainability point of view, energy consumption is only one aspect by which the material selection affects the environment. Some materials can be toxic, pose potential disposal problems, or cause the destruction of habitat. The selection of certain materials can also lead to increased global warming and changes in land use. Through its influence on vehicle emissions, material selection can also affect air quality (e.g., low level ozone and particulate matter).

Because energy consumption, like any other single metric, is unable to serve as a universal indicator of sustainability, being able to estimate other metrics as quickly and as easily as energy would be advantageous for material selection. However, most other metrics are still hard to estimate and quantify.

Table 1.8. Life cycle energy analysis results for a bumper-reinforcing beam on a 1030 Kg vehicle (Fitch and Cooper, 2004).

Reinforced Beam Materials	Material Production Energy (MJ)	Product Assembly Energy (MJ)	Product Delivery Energy (MJ)	Use Phase Energy (MJ)	Maintenance Energy (MJ)	End-of-life Energy (MJ)
PP/GF (unidirectional)	118	36	2	604	117	-1
M220HT Steel	100	44	2	722	60	-41
M190HT Steel	113	49	3	815	67	-46
Al 7129-T6	558	50	3	820	148	-409
PUR S-RIM 54% Glass (chopped and mat)	143	51	3	838	145	2
PC/PBT (injection molded)	138	60	3	994	82	-56
M160HT Steel	151	66	3	1086	90	-61
140X or T Steel	766	68	4	1126	204	-562
PUR S-RIM 41% Glass (chopped and mat)	214	68	4	1126	216	2
Al 6061-T6	255	79	4	1299	253	-2
PP/GF (direct melt/random)	539	59	3	982	447	-92
PC/PBT (blow molded)	258	84	4	1389	261	2
SMC	720	79	4	1311	597	-123
PP	309	135	7	2224	166	-143
180 Plannja Steel	506	119	6	1962	443	-63

On the other hand, Kasai (1999) presented a quantitative model to evaluate environmental burdens. This model used complete records for material design options and ranked the candidate materials as compared to the baseline model that is made out of Steel (STAM540H). Actual data was tabulated to rank candidate materials based on the %Weight saving, the total reduction of exhaust emissions, and the total energy savings (Material production, part manufacturing, operation and recycling).

Kasai research presented an example of propeller shaft used in middle duty trucks. Table 1.9 shows the conditions and assumptions used (Kasi, 1999), while Table 1.10 shows the results for estimated lifetime of 150,000km (Kasi, 1999).

Table 1.9. Conditions and assumptions (Kasai, 1999).

	Steel (former)	**Steel (current)**	**Al**	**FRP**
Material code (JIS or ISO)	STAM540H	STAM735H	Modified 6061-T8	EP-(CF+GF)70
Tensile strength (MPa)	540	735	365	400
Specific Gravity	7.85	7.85	2.91	1.85
Weight of the part (kg)	20.2	17	13.7	6.2
Energy used for material production (MJ/kg)	25.3	26.8	233	100
Energy used for part production (MJ/kg)	53.8	57	293	100
Weight reduction (kg)	0	-3.2	-6.5	-14.0
Saving of fuel consumption (L/kg) due to weight reduction	0	9	9	9
Reduction of exhaust gas emissions (per kg) due to weight reduction	-21 kg CO2	-21 kg CO2	-21 kg CO2	-21 kg CO2
	-51 g NOx	-51 g NOx	-51 g NOx	-51 g NOx
	-172 g CO	-172 g CO	-172 g CO	-172 g CO
	-26 g SOx	-26 g SOx	-26 g SOx	-26 g SOx
Recyclability (%)	100	100	100	0

This model has some drawbacks; such as some unreasonable assumptions were made including the effect of reducing the vehicle weight on the MPG to be around 9 liter per 150,000 km per kg of weight reduction, and the assumptions used for the end of life scenario where all metals were assumed to be 100% recycled and plastics is assumed to be 100% land-filled.

Table 1.10: LCI results for propeller shaft, total distance"150,000 km (diesel fuel has 38.5 MJ/l) (Kasai, 1999).

	Steel (former)	**Steel (current)**	**Al**	**FRP**
Material code (JIS or ISO)	STAM540H	STAM735H	Modified 6061-T8	EP-(CF+GF)70
Tensile strength (MPa)	540	735	365	400
Specific Gravity	7.85	7.85	2.91	1.85
Weight of the part (kg)	20.2	17	13.7	6.2
Weight reduction (kg)	0	-3.2	-6.5	-14.0
(1) Saving of energy for material production (MJ)	0	-3.2	-6.5	-14.0
(2) Saving of energy for part production (MJ)	0	-55	+2681	+109
(3) Saving of energy for operation (MJ)	0	-118	+2927	-467
(4) Recovered energy through recycling (MJ)	-329	-277	-2202	-4743
Total energy saved= (1)+(2)+(3)+(4)	-329	-1534	+991	-5101
Total reduction of exhaust gas emissions for 150,000 km of operation	0	-67 kg CO2	-136 kg CO2	-294 kg CO2
	0	-153 g NOx	-331 g NOx	-714 g NOx
	0	-533 g CO	-1118 g CO	-2408 g CO
	0	-83 g SOx	-169 g SOx	-364 g SOx
Solid waste at the end of life (kg)	0	0	0	6.2

Saur et al. (2000) provided an example of life cycle assessment for automobile fender design. They ranked the candidate materials; steel, aluminum sheet, rubber modified polypropylene (PP/EPDM), nylon- polypropylene-neoxide blend (PPO/PA), and polycarbonate-polyethylene terephthalate (PC/PBT). In their study, different aspects of sustainability are used to interpret the LCA results, including: energy, resource depletion, water pollution, global warming potential, ozone depletion potential, air pollution, Eutrophication Potential EP, Photochemical Ozone Creation Potential PCOP, human-toxicity, eco-toxicity and the waste produced. Then each material was analyzed based on these metrics for further analysis in order to rank them in comparison to the baseline steel fender. Additionally, Saur et al. (2000) suggested the use of subjective scores for each sustainability metric, this is done by surveying expert and non-expert people to score each of the above metrics. However, this methodology suffers from some drawbacks; specifically, the proposed LCA in their study is limited to the environmental impacts as one can see from the selected life cycle metrics. Also, other drawback is due to the difference in the scorings derived from policy statements, opinion polls among expert people (ecologist and material scientist) and the public. For example, the weights differ significantly between expert people and public (Table 1.11), however; expert people assumed worst case scenarios for emissions and pollutions and focused on the raw material scarcity, while the scorings assigned by non-expert people is based on lesser importance considerations such as energy consumption.

The final results of Saur et al. (2000) research (Table 1.12) showed that the PP/EPDM ranked first while aluminum ranked fourth. Steel ranked in third place making the steel more environmentally friendly than aluminum.

Table 1.11: Scores assigned by policy statement team, expert and non-expert people for LCA (Saur et al. 2000)

Category	Policy GER, EU	Experts GER, EU	Population GER, EU
Energy	7	10	3
Resources	3	7	2
Water	1	1	1
GWP	9	10	6
ODP	10	6	10
AP	7	5	4
EP	4	3	4
PCOP	1	3	3
H-tox	8	8	8
ECO-tox	6	9	9
Waste	3	10	9

Table 1.12. Environmental theme evaluation for some materials that can be used in automobile fender (Saur et al. 2000)

	Al	Steel	PC/PBT	PP/EPDM	PPO/PA
Score	0.237	0.232	0.210	0.165	0.259
In %	91.5%	89.6%	81.1%	63.7%	100.0%
Rank	4	3	2	1	5

1.7. SUSTAINABILITY MEASURES IN THE AUTOMOTIVE INDUSTRY

Even though there are researchers who have introduced several methodologies to assess the environmental aspect of sustainability where the full environmental consequences of a product or a system is evaluated. Still there is no universally accepted method to quantify all the aspects of product sustainability (EPD, no date). Fiksel et al. (2009) stated that the desire to assess all major aspects of sustainability, has pushed product designers to find new methods and tools to improve the existing standards and measurable factors in order to reduce the need for virgin raw materials, choose the right eco-friendly sources of energy, minimize wastes, and maximize the product end-of-life value. The following sections discuss two of the methods developed by the automotive OEMs to assess such impacts based on their production infrastructures and production volumes.

1.7.1. ENVIRONMENTAL PRODUCT DECLARATION (EPD) FROM VOLVO

Implementing sustainability principles in designing and manufacturing new vehicles that is unique and specific to the company goals and product portfolio is becoming a priority for OEMs. Environmental Product Declaration EPD is one of such models that has been developed by the cooperation between Swedish Environmental Institute and the Volvo Car Corporation (Graedel and Allenby, 1994). The purpose of an EPD is to enable customers to evaluate the environmental impact of different vehicles (EPD, no date). The EPD system covers all phases in the life cycle of a vehicle, from production of the raw materials to final disposal and recycling, and provides information on the environmental impact of each. With systems considered being large and complex as well as the approximations made in some cases especially large trucks, are limiting factors for EPD accuracy and reliability. Hence, the results should be treated as a guide to some of the more important environmental parameters in the life cycle of the product. Another limitation of EPD system is the unit used to assess the environmental impact, which is the Environmental Load Unit ELU per kilogram of material used. Actually, ELU is a rating method that ranks the environmental impact of any material to the environmental impact resulted from 1kg of methane (CH_4). However, the ELU still lack the international approval as it is considered as a non-standardized unit. The Volvo trucks EPD system is a derivative of the main EPD; where the Volvo trucks EPD is divided into four sections, also see Fig. 1.9:

- **Materials and production:** which deals with the environmental impacts of raw materials production, manufacturing operations at Volvo truck plants in Europe, production at suppliers' plants and transport.
- **Fuel and exhaust emissions:** deals with the environmental impact of exhaust emissions based on certification tests for each specified engine type.
- **Maintenance:** deals with the environmental impact (based on average values) of the use of consumables and materials in preventive maintenance and parts production.
- **End of life:** deals with the environmental impact of product disposal, waste management and the recycling of truck materials.

Volvo aims to ensure that every new product has a lower environmental impact than the one it replaces. Emissions of nitrogen oxides, carbon monoxide, hydrocarbons and particulates from Volvos trucks have been cut by 60-85% since the mid-1970s. Volvo established a hard target to achieve further reduction of today's emission levels by two-thirds over the next decade. At the same time, the vehicles will become increasingly fuel efficient, which will reduce emissions of carbon dioxide.

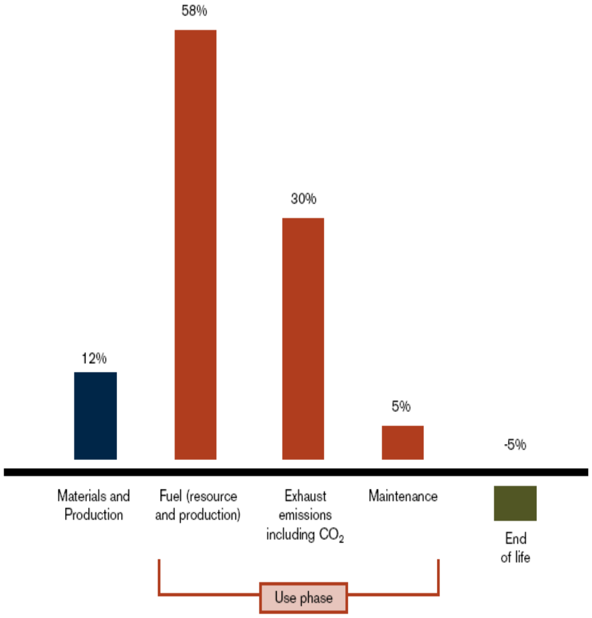


Figure 1.9. Distribution of the environmental impact from a Volvo FH truck in long-haul operation (EPD, no date).

1.7.2. FORD OF EUROPE'S PRODUCT SUSTAINABILITY INDEX

Ford of Europe's Product Sustainability Index is a simple sustainability management tool that can be directly used by engineers, i.e., not by sustainability or life-cycle experts. PSI is composed from eight indicators; mainly the life-cycle Global Warming Potential

GWP, life-cycle air quality potential, sustainable materials, restricted substances and drive by noise, social (mobility capability and safety) and economic (life-cycle cost of ownership) vehicle attributes (Schmidt and Taylor 2006; Schmidt and Taylor, 2007). Table 1.13 shows these eight indicators and their definitions. According to Schmidt and Taylor (2007), Ford Galaxy and S-MAX were the first vehicles to use this tool from their inception phase. The results show significant improvements when compared to the predecessor models (Schmidt and Taylor 2006; Schmidt and Taylor, 2007).

The limitations of this model come from the limited number of sustainability indicators used and the way these metrics are defined. Because, limiting sustainability model to eight indicators may be considered as a shortcoming of the model more than being a simplification. The PSI also defines the “life cycle cost” assuming that the cost is the sum of vehicle price and 3 years of service (See Table 1.13). This means that the PSI accounted for the vehicle cost from the company perspective not the total life cycle of the vehicle.

Table 1.13. Product Sustainability Index metrics (Schmidt and Taylor, 2007).

	Indicator	**Metric / Method**	Driver for Inclusion
Environmental and health	Life Cycle Global Warming	Greenhouse emissions along the life cycle (CO2 and equivalent emissions from raw material extraction through production, use to recovery) – part of an LCA according to ISO 14040	Carbon intensity is the main strategic issue in automotive industry
	Life Cycle Air Quality	Emissions related to Summer Smog along the life cycle (Ethene and equivalent emissions) – part of an LCA according to ISO 14040	Potential trade-offs between CO2 and non-CO2 emissions
	Sustainable Materials	Recycled and natural materials related to all polymers [1]	Resource Scarcity
	Substance Management	Vehicle Interior Air Quality (VIAQ) / allergy-tested interior, management of substances along the supply chain	Substance risk management is key
	Drive-by-Noise	Drive-by-Exterior Noise = dB(A)	Main societal concern
Societal [2]	Safety	Including EuroNCAP stars (including occupant and pedestrian protection)	Main direct impact
	Mobility Capability	Mobility capacity (seats, luggage) to vehicle size	Crowded cities (future issues include: diversity – disabled drivers, etc.)
Economics	Life Cycle Cost	Sum of vehicle price and 3 years service (fuel cost, maintenance cost, taxation) minus residual value (note: for simplification reasons cost have been tracked for one selected market; Life Cycle Costing approach using discounting)	Customer focus, competitiveness

[1] Note: There are, of course, no materials that are inherently sustainable. All materials are linked to environmental, social and economic impacts. However, recycled materials and renewably grown, natural fibers represent an example of how limited resources can be used in a more sustainable way.
The overriding factor is whether or not these materials have, in their specific application, a lower environmental impact through the product life cycle than potential alternative materials (see life cycle related PSI indicators and previous paper (Schmidt et al., 2001).

[2] Note: The social aspects are being refined and developed for the future. Please note that aspects related to labor, rights etc. are part of other Ford of Europe sustainability management tools such as the MSI.

1.8. SOFTWARE USED IN THIS STUDY

1.8.1. CAMBRIDGE ENGINEERING SELECTOR (CES 2008)

CES Selector 2008 is material selection software provided by Granta Design. CES selector 2008 provides unique tools for rational selection of engineering materials (metals, ceramics, polymers, composites, woods) and of manufacturing processes (shaping, finishing, joining, and surface treatment), and for plotting and comparing the engineering, economic, and environmental properties of materials. The following steps show how CES selector works for many application ranging from material selection for a given application to optimization of that selection based on the design objective functions. Figures 1.10-1.11 show some functions of CES 2008 selector, which include classification (Figure 1.10), and chart construction (Figure 1.11).

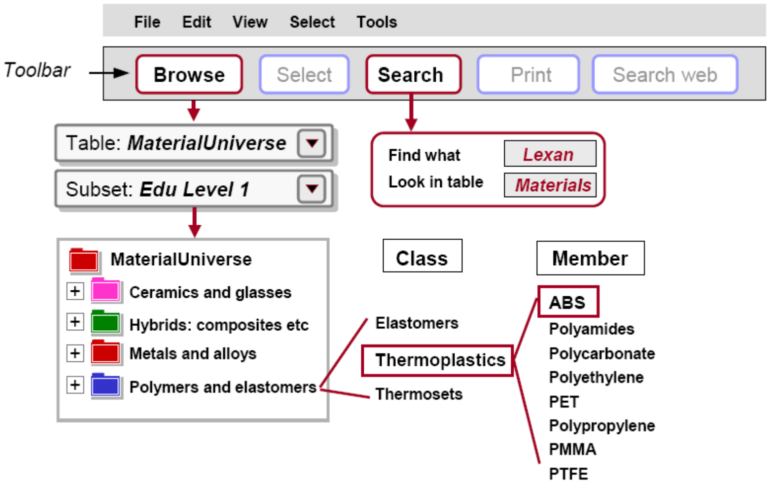


Figure 1.10: Finding information with CES selector 2008

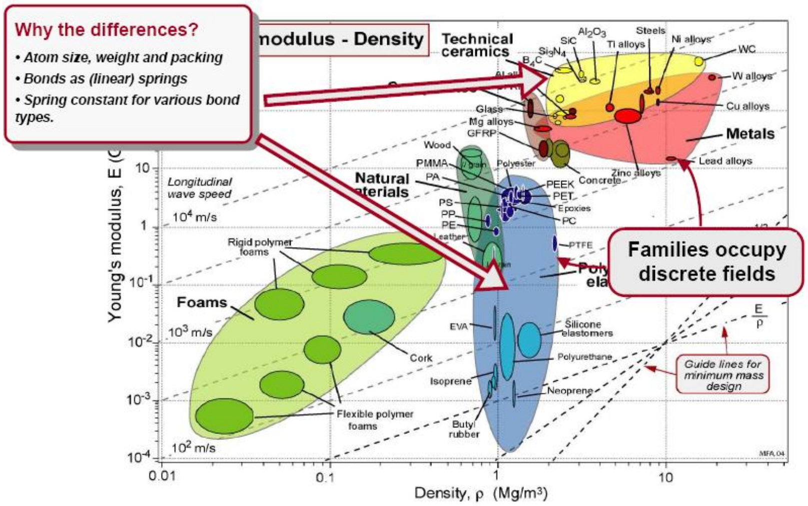


Figure 1.11: Material selection chart construction using CES selector 2008

1.9. DISSERTATION LAYOUT

After describing the general problem statement, and identifying the specific issues that need to be addressed, several steps are then proposed and investigated to tackle these issues, and therefore, to help in solving the sustainability issues in the automotive sector. The following chapters in this dissertation present the details of the work that has been done to achieve that.

An introductory (chapter one) provides some background information about sustainability and its associated issues like material selection, life cycle assessment and some of the used sustainability models by two auto-manufacturers.

Chapter two introduces and discusses sustainability model for auto-body. This chapter targets several body-in-white options and assessing them using eco-material selection indices, which was originally developed by professor Ashby from University of Cambridge, United Kingdom (UK).

Chapter three deals with life cycle assessments and provides complete energy and CO2 emission impacts over the entire vehicle's lifetime from pre-manufacturing to the end of the life. The dissertation then proceeds to discuss some quantifying methods for sustainability. In chapter four, a new scoring method (principal component analysis) is used to quantify overall sustainability score and then benchmarked with another scoring method (preference selection method). Both PSI and PCA avoid the bias that typically arises from assigning weights to different design attributes, as it is not necessary to assign a relative importance scheme between candidate materials. However, such kind of scoring methods have the potential to present an objective selection scheme that balances the technological, economical, societal and ecological constraints of automobile bodies.

The focus in chapters five and six is directed towards selecting best material(s) using multi-attribute decision making methods; namely quality function deployment (QFD) and analytical hierarchy process (AHP) to get better understanding of the performance of different candidate materials from the overall sustainability point of view.

After modeling and quantifying sustainability, followed by assessing different material in terms of their abilities to meet sustainability requirements; chapter seven discusses a new hybrid approach of data mining-knowledge based system (H DM-KBS) which is used to package all of the discussed sustainability findings and to aid design teams in the eco-material selection for lightweight design purposes.

Finally, the concluding remarks and major contributions of this work, in addition to some recommendations for future work, are all summarized in chapter eight.

CHAPTER TWO

SUSTAINABLE LIGHTWEIGHT VEHICLE DESIGN: A CASE STUDY OF ECO-MATERIAL SELECTION FOR BODY-IN-WHITE

Sustainable product development when applied for an automotive structure requires a balanced approach towards technological, economical and ecological aspects. This chapter investigates the main input parameters and the different measures for the vehicular structures Design for Sustainability (DFS) in general and its material selection for sustainable lightweight design in particular. In fact, this chapter discusses a set of metrics for material selection that takes all sustainability aspects into consideration. These metrics include; products' environmental impact, functionality and manufacturability, in addition to the economical and societal factors. The chapter then proceeds to show the material selection methodology and its limitations.

2.1. INTRODUCTION

The need to improve the automobile fuel economy is becoming increasingly important for all automotive Original Equipment Manufacturers OEMs. This is motivated by two factors; the price of oil, which reflects in the price of gas that consumers pay at the pump, has been increasing over the past several years. Also the public is becoming more conscious of the environmental change and global warming (Montalbo et al., 2008), which resulted in higher Corporate Average Fuel Economy CAFE requirements. Light-weighting of vehicle structures represents one of several design approaches that automakers are currently deploying to improve their fleet fuel economy. Light-weighting can be accomplished through downsizing, integrating parts and functions, materials substitution, or by a combination of these methods. The key goal is to reduce vehicle weight, which in turn improves its fuel economy as well as its performance (Montalbo et al., 2008). At the same time, the automotive industry is still facing increasing problems due to global competition, rapid technological change, and waste and recycling of end-of-life vehicles (ELV) (Mcauley, 2003).

Today, the typical US family vehicle weighs about 1400kg (Mcauley, 2003), with iron and steel accounting for the majority of this weight, as displayed in Fig. 2.1. However, the new trends in vehicle light-weighting aims not only to enhance the vehicle fuel efficiency, but also to improve its driving performance while lowering its emissions (Mayyas et al., 2011). This can be achieved to a high degree through the use of low density materials such as aluminum and plastics (Fuchs et al., 2008). Based on a national study, a ten percent reduction in vehicle weight translates into a 5% increase in its Miles per Gallon MPG (American Plastics Council, 2011; Mayyas et al., 2011). At an annual build of 15 million passenger vehicles per year this equates to a sizable savings in gasoline and the accompanying emissions.

The average passenger vehicle weights declined from about 1527kg in 1980 to less than 1400kg in 1991, where the OEM's tried to use less steel in the vehicles, see Fig. 2.2. Over the same time period, the amount of plastics used in a typical US passenger vehicle increased from about 4.6% in 1980 to about 10-12% today (Ungureanu, 2007). However, the customer demand shifted to preference to larger and heavier vehicles (e.g., SUVs) over the past 20 years, the average vehicle weight has increased again (Mcauley, 2003).

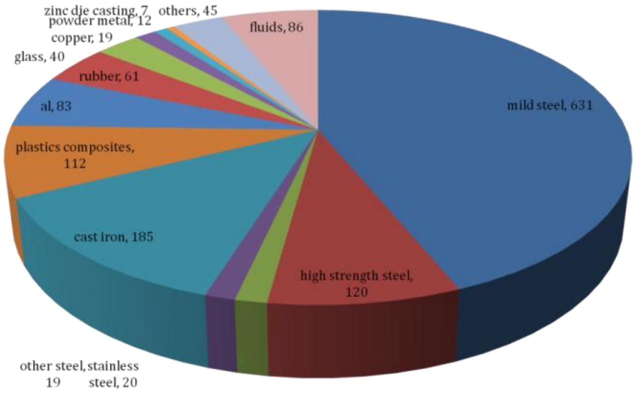


Figure 2.1: Material distribution of total vehicle curb weight (Omar, 2011).

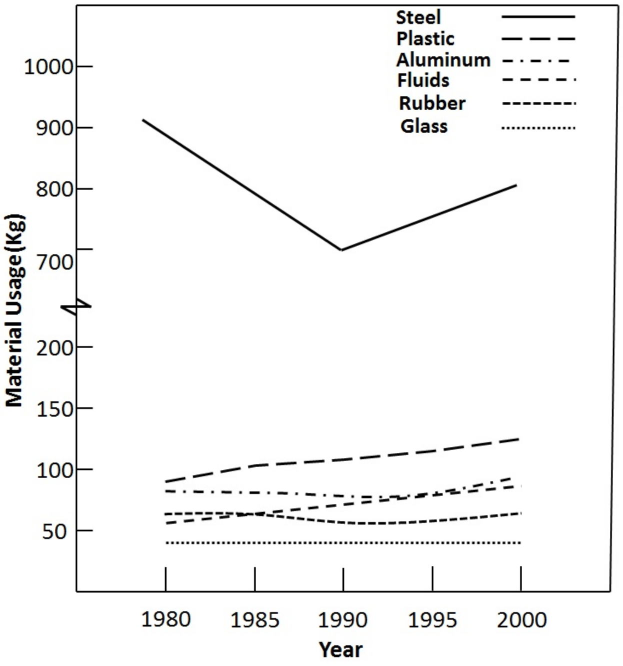


Figure 2.2: Material use in the automobile bodies trends (Omar, 2011).

Although there are various partial sustainability assessment methods available today for material selection, none of these models provide a comprehensive evaluation of sustainability. The main motivation comes from the increased awareness of the sustainable development practices within the automotive industry in particular, how to utilize the sustainability measures in light-weighting the BIW design. So, this study seeks to develop a science-based methodology for material selection.

The structure of the chapter starts by discussing the existing life cycle assessment and sustainability models for automotive applications and their roles in vehicle design. Then the proposed approach assumptions and basic methodology is introduced; after that the results from the material selection process along with the formulation of material indices and their overall sustainability score is discussed for different BIW designs, namely: steel-intensive BIW, Advanced High Strength Steel AHSS-intensive BIW, Al-intensive BIW, Mg-intensive BIW , and a carbon fiber composite intensive BIW.

2.2. LIFE CYCLE ASSESSMENT MODELS

Life cycle assessment (LCA, also known as life cycle analysis) is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and end-of life which includes disposal or recycling). Using LCA as eco-indicator has some benefits which include:

- Collecting an inventory of relevant energy and material inputs as well as environmental releases and emissions;
- Evaluating the potential impacts associated with all inputs and releases or emissions;
- Interpreting the results which help designers and customers to make more eco-informed decisions.

The framework of LCA is constructed through a series of the Environmental Management Standards (EMS), introduced by the International Standards Organization (ISO 14000). From sustainability perspective, LCA is a main branch of environmental factors (see Figure 2.3); actually LCA can be classified under the design for environment (DFE) branch. Detailed vehicle structure LCA flow chart is shown in Figure 2.4.

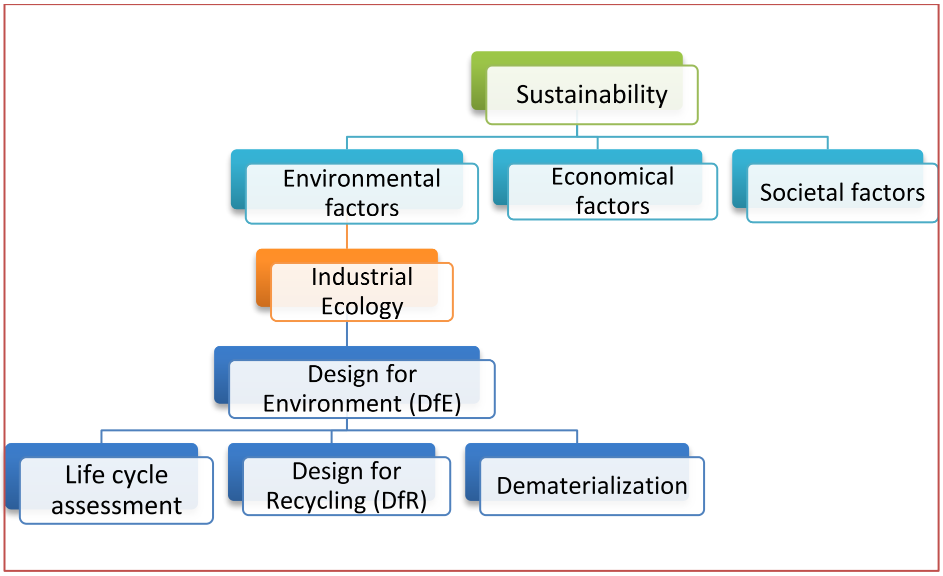


Figure 2.3: Sustainability hierarchy

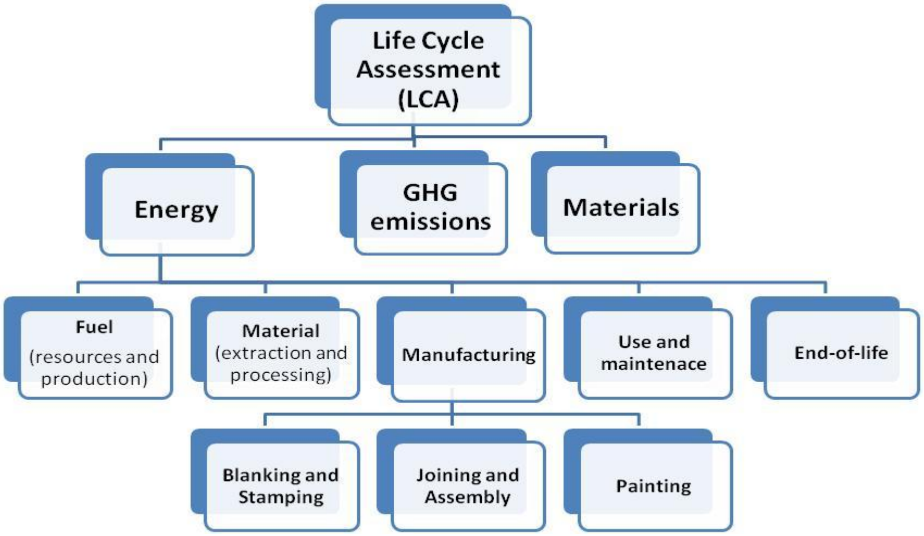


Figure 2.4: Life cycle assessment flow chart for steel BIW

2.3. MODELS FOR SUSTAINABLE MATERIAL SELECTION FOR AUTOMOTIVE APPLICATIONS

Nowadays, several sustainability models for vehicle assessment purposes are available. Some of these models incorporate the environmental concerns within the material selection process in the early design stages. While some methods emphasize selecting materials based on a single portion of a product's life cycle (e.g., energy and emissions associated with use phase); other models attempt to consider the entire life cycle, either qualitatively or quantitatively.

Graedel and Allenby (1998) presented a set of qualitative material selection guidelines, which are simply rules-of-thumb such as "Choose abundant, non-toxic, non-regulated materials, if possible". Although using qualitative methods can help in classifying materials as desirable or non-desirable, still making eco-informed decisions needs more comprehensive sustainability strategies to consider any candidate materials.

Alternatively, quantitative approaches can be used to rate different materials using specific indicators; such as:

- single environmental indicator as in the Eco-Indicator which was firstly used by Wegst and Ashby (1998), energy content indicator which was proposed by Ashby (2009), and a set of environmental indicators (e.g., CO_2, SO_x, NO_x, a measure of grade of recyclability, and resource scarcity index) as suggested by Coulter et al. (1996) and Holloway (1998).
- An economic indicator such as the environmental cost as used by Ermolaeva et al. (2004).

Kasai (1999) presented a quantitative LCA model to evaluate environmental burdens. This model is simply scaling method which scales all candidate materials relative to baseline model made out of Steel (STAM540H). Actual data was tabulated and normalized to rank candidate materials based on the percentage of weight saving, the total reduction of exhaust emissions, and the total energy savings (material production, part manufacturing, operation and recycling). This paper discusses an example of a propeller shaft used in middle duty trucks. A complete life cycle assessment for all candidate materials was performed first, in that study Kasai assumed an estimated lifetime of 150,000 km, and finally different materials were ranked based on the overall energy savings. The final results of Kasai's study showed that the Fiber Reinforced Plastics (FRP) is the best candidate material followed by aluminum.

This model has some drawbacks which mainly come from unreasonable assumptions made, these assumptions include the impact of reducing the vehicle weight on the fuel economy where he assumed that the net effect to be around 9 liter per 150,000 km per kg of weight saved, in addition to the assumptions used for the end of life scenarios, where all the metals were assumed to be 100% recycled while the plastics were assumed to be 100% land-filled.

LCA-based material selection method was also used by Fitch and Cooper (2004) to assess different materials based on their total life cycle energy analysis. Typically, LCE should be used in conjunction with other environmental indicators to provide a more comprehensive evaluation for sustainable material selection.

2.4. DESIGN CONSIDERATION FOR SUSTAINABLE VEHICLES

Current automotive designs are still based on metal-intensive uni-body structures and manufactured using old infrastructures and processing methods, some originating in the early 1900s. The need for sustainable products, however, will ultimately drive vehicle designs toward new materials, such as hybrids (specifically composites, lattice based, segmented and sandwich materials), in addition to lighter weight metals and their Metal Matrix Composites MMC. Some material alternatives can be up to 5 times lighter than ferrous metals (e.g. fiber reinforced plastics (FRP)). However, plastics nowadays make up less than 12% of the average vehicle's weight in the United States. According to

Mcauley (2003) using plastics in light-weight vehicles can save 30 times more energy over the life cycle of an automotive than the energy required for its fabrication.

At the same time, using these new materials poses several manufacturing challenges, mainly in its formability using the current press-based stamping. For example Mg can be better formed through casting and super-plastic forming. At the same time, super-plastic forming or injection-molding can’t produce parts at the required cycle time for an automotive facility.

Stodolsky et al. (1995) identified at least three ways to decrease the weight of a vehicle in order to improve its fuel consumption: reduce its size, optimize its design to minimize weight, and replace the heavy materials currently used in the vehicle construction. Because safety and performance are still perceived to be related to vehicle size, this might have led to more demand and interest for bigger cars. Thusly, Automotive OEMs have investigated new alternative materials to reduce vehicle weight without sacrificing its utility or size.

The selection of these new materials for automobile bodies is driven by a series of techno-economic issues. When a steel part of the BIW is replaced with a different material, there will be associated changes in design, manufacturing, and recycling that might pose additional expenses and risks outweighing the expected benefits (Davies, 2004). At the same time, the best strategy for offsetting the risks and costs against the benefits of using a newer technology is to apply it where the current technology remains an acceptable alternative. Kelkar et al. (2001) compared and analyzed the manufacturing costs of fabrication and assembly for aluminum and steel auto bodies for two vehicle classes; small fuel-efficient designs and mid-size designs; considering the current aluminum prices and using current aluminum fabrication technology. This study identified two keys obstacles for aluminum to become a substitute for steel; the first is the higher material cost and second is the higher tooling costs associated with aluminum panel forming and welding. The study also stated that it is unclear which aluminum design; space frame design or uni-body architecture is more economical and is better suited for mass production scenarios. In order to produce an aluminum intensive car (aluminum percentage in body in white > 30%) with the same overall manufacturing costs as steel, the price of aluminum must drop to be comparable to that of steel (Ungureanu, 2007). However, aluminum has the potential to become the primary material used in the auto body structures if new governmental legislations force the automakers to improve the fleet fuel economy and percent recycled parts. Mayyas et al. (2011) used multi-attribute decision making tools, namely Analytical Hierarchy Process AHP and Quality Function Deployment QFD to rank several engineering materials for substituting the steel baseline body-in-white. This study concluded that steel is still the best choice in terms of functionality, cost and manufacturability.

Studies from the World AutoSteel organization (Geyer 2007) on the life cycle assessment of different combination of vehicle bodies and power-trains; with design options including steel, aluminum, Sheet Molding Compounds (SMC) and Advanced High Strength Steels (AHSS) for body construction, and power-trains including internal combustion engines, hybrid and fuel cell power-trains. The results of this study show that using AHSS steel generates much less environmental damages in terms of the green house gases than that from mild steel or aluminum.

Assuming that the manufacturing and the assembly processes differ slightly, the environmental burdens are quite similar for both materials at the manufacturing phase; however, the use stage generates the most environmental problems in terms of gaseous emissions. Petroleum refining and combustion are assumed to be the two primary sources of effluents. Having a fuel consumption improvement, the study concludes that the AHSS BIW will generate lesser atmospheric emissions than aluminum BIW during the total operational stage. However, in post-use stage the environmental burdens for recycling the aluminum BIW structure are lower compared to the case of mild steel or AHSS steel. Whether aluminum generates sufficient environmental and health benefits to offset its cost disadvantage is difficult to predict because these benefits must be weighed against the monetary cost.

Das (2000) compared the energy usage and CO_2 emission for different BIW options made from conventional mild steel, aluminum and Ultra Light Steel Auto Body ULSAB design at both the vehicle and fleet levels. The main study finding indicated that the benefits of using aluminum in automotive components are significantly reduced when compared to the ULSAB counterpart than when compared to the traditional steel. Regarding the energy usage, the benefits of the lower energy used during the use stage, are compromised by the higher manufacturing energy consumption of aluminum. Thus having the energy saved during the recycling stage to be the main contributor to the total life-cycle benefits of aluminum. In terms of CO_2 emissions, steel and ULSAB have the advantages in the early life-cycle years, due to their relatively low energy use and low emissions during the manufacturing stage, which is diminished each year, because of the better fuel efficiency of aluminum BIW (Ungureanu, 2007, Das, 2000). From both the energy and CO_2 emissions perspectives, it would take about four years and ten years, respectively, for aluminum vehicles to achieve life-cycle equivalence with steel and with the ULSAB. At the fleet level, the benefits of aluminum are delayed, because vehicle replacement occurs over several years rather than all at once (Omar, 2011).

Significant challenges still lie ahead for the automotive industry and its design as well as the advanced materials industry in order to attain the sustainability goals. Yet, society must drive the industry toward sustainable product design in a long term basis. The earth contains limited resources enclosed in a single life-sustaining atmosphere. Therefore, control of global air emissions as well as resource conservation is the major goals to attain long-term sustainability of all living species on Earth.

2.5. SUSTAINABILITY MODEL

When selecting materials, designers and engineers have to take into account a large number of factors, where some of these factors might be conflicting in terms of their economical and environmental impacts. Hence, the design team should handle conflicting objectives (e.g. cost vs. light weight; functionality vs. recyclability, etc.) and establish well-defined and accepted limits for each design requirement.

Figure 2.5 shows the structure of the proposed sustainability model and identifies its sub-model factors. This model is pivoted around material selection for sustainable lightweight design that aims not only at minimizing the weight of the vehicle, but also to ensure that any material selection conforms to the sustainability holistic approach.

Figure 2.5: Sustainability model structure

Therefore, the material selection process should adhere to the sustainability requirements shown above. Following is a description of each factor and its importance in the model:

- **Resource depletion index** address mainly the global reserves and the annual consumption rate of these resources. A resource depletion index can serve as a quantitative tool to evaluate the scarcity level of depletion for natural resources.
- **Water pollution index;** Water pollution is any contamination of water with chemicals or other foreign substances that are detrimental to human, plant, or animal health. These pollutants might have resulted from the extraction and the processing phases, manufacturing, use phase and end-of-life phase. Water

pollution index has two measures: amount of water and toxicity of waste water used in each phase.

- **Life cycle assessment (LCA)**; even though the LCA is used by some researchers as a major indicator of environmental impact, here LCA is used as a branch of environmental impact, to analyze any proposed design over its entire life span (i.e. from cradle to grave). The analysis includes energy, emissions and materials used.
- **Recyclability**; although recyclability might be classified under LCA, here it is used as an indicator of environmental friendliness of materials, however the recyclability measure used here is the recycle fraction (ψ).
- **Economical impact factors** are dealing with the costs associated with each life cycle phase in order to provide customers (i.e. automakers) with a comprehensive financial analysis of a given BIW design. Also, it is important to mention that durability has been linked to economical impact factors because it has a strong, direct relation to the maintenance and replacement costs. For example composite intensive BIW is considered less durable -in terms of ultraviolet (UV) resistance- than steel BIW.
- **Societal factors**; expressed as safety and health and wellness. Safety is an indirect measure for material properties (i.e. toughness and yield strength) while health and wellness is another indirect measure that is governed by:
  - noise-vibration-harshness performance (as controlled by dynamic stiffness of BIW structure and damping capacity of material)

    - Emissions to the environment and their adverse effects like acid rain, global warming potential and ozone depletion.

- **Technical factors**; although sustainability has three main pillars as discussed before, ease of manufacturing and technical requirements are also important factors to be considered through the design process to incorporate both material selection and manufacturing process selection together, which in turn provides decision makers with clearer view about “what if” analysis, if material X is to be used instead of material Y.

2.6. DEVELOPING MATERIAL SELECTION INDICES

In engineering design especially at the conceptual design stage, designers and engineers sit together to decide on the important design criteria, the combination of parameters which best describes it (or needs to be optimized) and the governing mathematical equations for each design consideration. Following this strategy will help in deriving the material selection indices. For example, the minimum weight design of stiff ties, beams, shafts, columns and plates depends on the materials’ density and Young's modulus but in differing proportions (Holloway, 1998).

In the proposed material selection strategy, the objective function for each panel is used to rank the different candidate materials, hence optimizing the overall design. The study employs a conventional uni-body, stamped BIW of a typical passenger vehicle (Figure 1.3). The major panels considered in the study and their main design functions are shown in Table 2.1.

Table 2.1: BiW major panels and their main design functions

No.	**Panel Name**	**Main design functions**
1	Roof	Dent Resistance, NVH, Durability
2	Hood (inner)	Bending Stiffness, NVH, Ease of manufacturing
3	Hood (outer)	Dent Resistance, NVH
4	Trunk (inner)	Bending Stiffness, NVH, Ease of manufacturing
5	Trunk (outer)	Dent Resistance, NVH
6	Trunk Pan	Strength, NVH, Durability
7	Engine Cradle	Crashworthiness, Temperature Performance, NVH, Durability
8	Strut Towers	Bending Stiffness, NVH, Durability
9	Splash Wall	Temperature Performance, NVH, Durability
10	Quarter Panel	Dent Resistance, NVH
11	Front Fender	Dent Resistance, NVH
12	Door (inner)	Bending Stiffness, NVH, Ease of manufacturing
13	Door (outer)	Dent Resistance, NVH
14	Wheel House	Bending Stiffness, NVH, Durability
15	A, B Pillars	Bending Stiffness, NVH, Ease of manufacturing, Durability
16	Floor pan	Strength, NVH, Durability

In most cases of material selection, the design objective can be expressed in terms of either maximizing or minimizing the index value. At the same time and according to Ashby (2008) materials selection indices are most effectively used by mapping them into material selection charts to help isolate a subset of materials which can meet all the design goals.

An example of material selection for stiff, low embodied energy, lightweight panel under bending load, can be derived as following:

Fixed variables: panel, width *w* and length *l* are specified.

Objectives: minimize mass, *m;* and minimize embodied energy, *q*. If we defined energy content to be q=m.q, then:

$$Q = m\ .q = (AL)(\rho).q = (w\ t\ L)(\rho).q \tag{2.1}$$

Constraints: Stiffness of the panel, *S:*

$$\mathrm{S} = \frac{\mathrm{F}}{\delta} \Rightarrow \mathrm{S} = \frac{\mathrm{C\,E\,I}}{\mathrm{L}^3} \tag{2.2}$$

$$\mathrm{I} = \frac{\mathrm{w\,t}^3}{12} \tag{2.3}$$

Where: m = mass; w = width; L = length; ρ = density; t = thickness; S = stiffness; I = second moment of area; E = Young's modulus.

Variables: Material choice and Panel thickness 't'.

Hence, if we eliminate *t* and re-arrange the equation:

$$Q = m.q = \left(\frac{12\ S\ w^2}{C}\right)^{1/3} L^2\ \left(\frac{\rho}{E^{1/3}}.q\right) \tag{2.4}$$

Choose materials with largest:

$$M = \frac{E^{1/3}}{\rho.q} \tag{2.5}$$

To replace material 1 by material 2, then the following equation should be used:

$$\frac{M_2}{M_1} = \frac{\left(E_2^{1/3} / (\rho_2.q_2) \right)}{\left(E_1^{1/3} / (\rho_1.q_1) \right)} > 1.0 \tag{2.6}$$

Another example for deriving material selection index for a strong, recyclable, light panel can be given as follows:

Fixed values: panel width *w* and length *l* are specified.

Objective: Minimise mass, *m;* and maximize recycle fraction, ψ (0≤ ψ ≤1). If we set the objective functions as a minimization problem only, then:

$$m.\left(\frac{1}{\psi}\right) = (AL)(\rho).\left(\frac{1}{\psi}\right) = (w\ t\ L)(\rho).\left(\frac{1}{\psi}\right) \tag{2.7}$$

Constraints: Stiffness of the panel, *S*

$$M_0 \le Z_e \sigma_y = \frac{I}{y_m} \sigma_y = \frac{wt^2}{6} \sigma_y \tag{2.8}$$

$$\mathrm{I} = \frac{\mathrm{w\,t}^3}{12} \tag{2.9}$$

where; *m* = mass; *w* = width; *L* = length; ρ = density; *t* = thickness; M_0 = Moment; and

I = second moment of area

Variables: Material choice and Panel thickness *t*.

$$m.\left(\frac{1}{\psi}\right)=\left(\frac{6\ M\ \ w}{\sigma_y}\right)^{1/2} L\,.\,\rho\left(\frac{1}{\psi}\right) \tag{2.10}$$

Hence, if we eliminate t and re-arrange the equation, the material selection index will be;

$$M=\ \frac{\sigma_y^{1/2}.\psi}{\rho} \tag{2.11}$$

To replace material 1 by material 2, then the following equation should be used;

$$\frac{M_2}{M_1}=\frac{\left(\sigma_{y2}^{1/3}\Big/_{(\rho_{2/\psi_2})}\right)}{\left(\sigma_{y1}^{1/3}\Big/_{(\rho_{1/\psi_1})}\right)}>1.0 \tag{2.12}$$

Similarly, all material selection indices were derived based on their design requirements. Plotting design requirements onto selection charts and using a number of charts sequentially allows the simultaneous consideration of several design goals. Figure 2.6 shows a material selection chart which can be used for the design of stiff, low embodied energy, lightweight component where Figure 2.7 displays the material selection chart that can be used for the design of a strong, recyclable, light component.

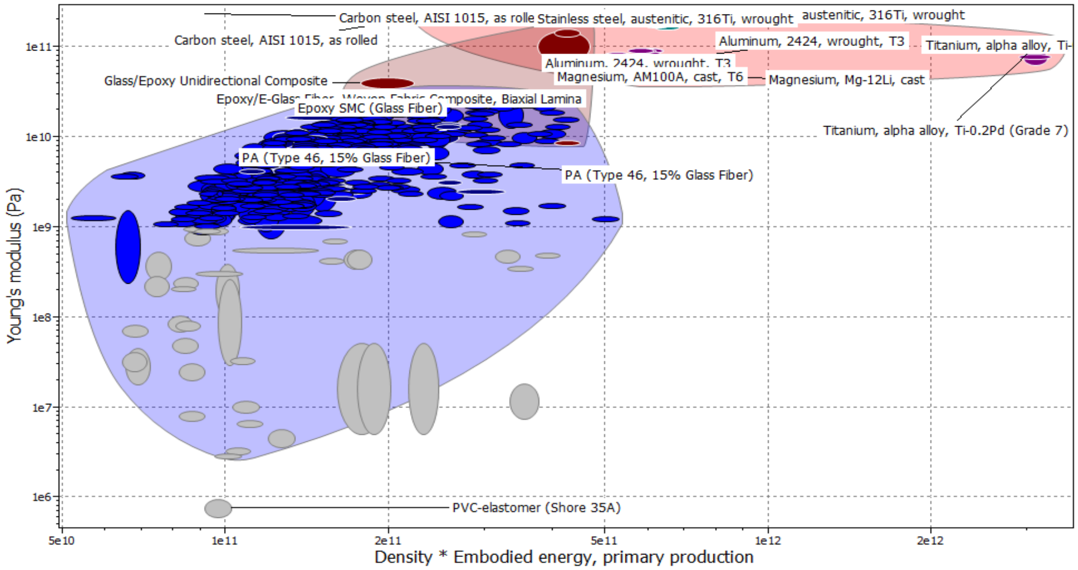


Figure 2.6: Materials for lightweight, low embodied energy and bending stiffness panels (e.g. door inners, hood inner)

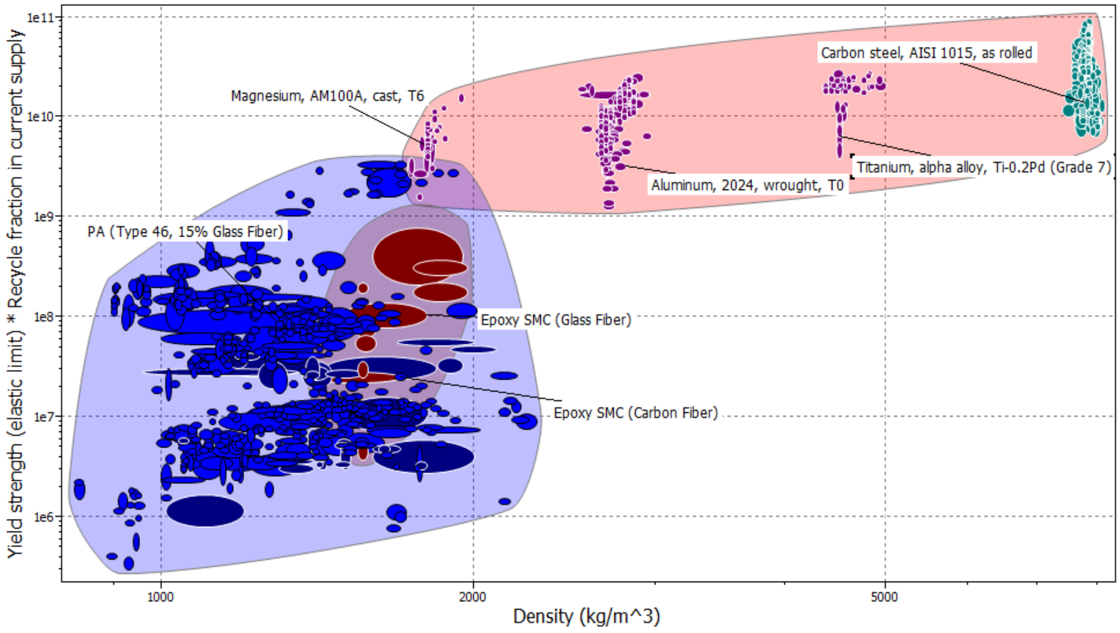


Figure 2.7: Materials for lightweight, recyclable strong panels (e.g. floor pan)

Some sustainability factors are qualitative in nature, for example, materials are classified as having high, medium and low corrosion resistance; the same can be said for fatigue resistance, and wear resistance. Also, societal factors (i.e. safety and health and wellness) should be scaled to show the relative performance of the different materials, as there is no well established scientific method that can quantify these factors; unless the safety is assumed to be mainly controlled by yield strength and material toughness; however health and wellness greatly depends on the emissions. For these reasons, scaling methods are used in this study to describe some of the selection criteria. Scaling is considered as an acceptable tool to address qualitative aspects in many engineering applications and can be very valuable in communicating results or clarifying the relative importance and significance of different factors (Saur et al., 2000).

To summarize all derived material selection indices, all developed indices for sustainable lightweight BIW design are tabulated in Tables 2.2-2.3, for lightweight bending stiffness and lightweight dent resistance materials, respectively. Also, Table 2.5 shows ratings assigned for some durability, societal and technical factors based on (1-10) scale (Mayyas et al., 2011, Davies, 2004, CES, 2008).

Table 2.2: Indices developed for light weight, bending stiff sustainable material selection

Environmental factors	Index	Economical Factors	Index
Minimum resource depletion index for light weight bending stiffness	$\frac{E^{\alpha}}{\rho * RDI}$	Minimum material cost for light weight bending stiffness	$\frac{E^{\alpha}}{\rho * C_M}$
Minimum water pollution for light weight bending stiffness	$\frac{E^{\alpha}}{\rho * WPI}$	Minimum manufacturing cost for light weight bending stiffness	$\frac{E^{\alpha}}{\rho * C_E}$
Minimum life cycle energy for light weight bending stiffness	$\frac{E^{\alpha}}{\rho * LCE}$	Minimum fuel cost for light weight bending stiffness	$\frac{E^{\alpha}}{\rho * C_F}$
Minimum air pollution for light weight bending stiffness	$\frac{E^{\alpha}}{\rho * API}$	Minimum end-of-life cost for light weight bending stiffness	$\frac{E^{\alpha}}{\rho * C_{EOL}}$
Maximum recycle fraction for light weight bending stiffness	$\frac{E^{\alpha} * \psi}{\rho}$		
Minimum recycling embodied energy for light weight bending stiffness	$\frac{E^{\alpha}}{\rho * R_E}$		
Minimum recycling CO_2 footprint for light weight bending stiffness	$\frac{E^{\alpha}}{\rho * FP}$		
Maximum resistance to (salt water/UV/ flammability/wear/ fatigue) for light weight bending stiffness	Rating (1-10)*		

$^{\alpha}$ depends on the shape and dimensions of the panel (α=½ for beam with specified length and shape and has free sectional area; α=1 for beam with specified length and height and has free width; α=1/3 for beam with specified length and width and has free height; α=1/3 for panels and plates with specified length and width and has free thickness).

* The following chosen criteria reflect most important conditions that vehicle faces in the service (salt water, wear and scratch, flammability and sunlight UV). The ranks used here are (very poor=1; poor=3; average=5, good=7; very good=9, Exceed the rating=10)

Table 2.3. Indices developed for light weight, dent resistance sustainable material selection

Environmental factors	**Index**	**Economical Factors**	**Index**
Minimum resource depletion index for light weight dent resistance	$\frac{\sigma_y^{\beta}}{\rho * RDI}$	Minimum material cost for light weight dent resistance	$\frac{\sigma_y^{\beta}}{\rho * C_E}$
Minimum water pollution for light weight dent resistance	$\frac{\sigma_y^{\beta}}{\rho * WPI}$	Minimum manufacturing cost for light weight dent resistance	$\frac{\sigma_y^{\beta}}{\rho * C_M}$
Minimum life cycle energy for light weight dent resistance	$\frac{\sigma_y^{\beta}}{\rho * LCE}$	Minimum fuel cost for light weight dent resistance	$\frac{\sigma_y^{\beta}}{\rho * C_F}$
Minimum air pollution for light weight dent resistance (air pollution index)	$\frac{\sigma_y^{\beta}}{\rho * API}$	Minimum end-of-life cost for light weight dent resistance	$\frac{\sigma_y^{\beta}}{\rho * C_{EOL}}$
Maximum recycle fraction for light weight dent resistance	$\frac{\sigma_y^{\beta} * \psi}{\rho}$		
Minimum recycling embodied energy for light weight dent resistance	$\frac{\sigma_y^{\beta}}{\rho * R_E}$		
Minimum recycling CO_2 footprint for light weight dent Resistance	$\frac{\sigma_y^{\beta}}{\rho * FP}$		
Maximum resistance to (salt water/UV/ flammability/wear/ fatigue) for light weight dent resistance	Rating (1-10)*		

$^{\beta}$ depends on the shape and dimensions of the panel (β=2/3 for beam with specified length and shape and has free sectional area; β=1 for beam with specified length and height and has free width; β=1/2 for beam with specified length and width and has free height; β=1/2 for panels and plates with specified length and width and has free thickness)

* The following chosen criteria reflect most important conditions that vehicle faces in the service (salt water, wear and scratch, flammability and sunlight UV). The ranks used here are (very poor=1; poor=3; average=5, good=7; very good=9, Exceed the rating=10)

Table 2.4. Scaling method that is used for rating societal and technical factors‡

Factor	**Description**	**Rating scheme**
Safety	Crashworthiness rating	(1-10)
Health and wellness	NVH and emissions	(1-10)
Forming		(1-10)
Joining		(1-10)
Painting		(1-10)

‡ The ranks used here are (very poor=1; poor=3; average=5, good=7; very good=9, Excellent=10)

Chapter three discusses life cycle assessment in more details, where complete analytical and mathematical models were developed and overall LCA energy and CO_2 emissions impacts were analyzed.

Finally, for societal and technical factors, as well as durability, a scaling factor of (1-10) is used to evaluate each material performance; Table 2.5 summarizes such values.

Table 2.5. Scoring values for some material selection criteria

Material	**Durability**[‡]			**Societal**		**Technical** [‡‡]		
	Corrosion resistance[‡‡]	Heat resistance[‡‡]	Wear resistance[‡‡]	Health and wellness (NVH[♣])	Crashworthiness rating [♣]	Forming	Joining	Painting
AISI 1015 (annealed)	7	10	8	5	2	8	9	9
AISI 3140 (as rolled)	7	10	8	5	2	8	9	9
Dual Phase 280/600	7	10	8	5	4	6	8	9
HSLA steel 462/524	7	10	8	5	4	6	8	9
Mart steel 950/1200	9	10	8	4	6	4	7	9
Stainless steel, ferritic, AISI 405, wrought, annealed	9	10	9	4	10	4	7	9
Aluminum AA6060[‡‡]	9	9	6	9	1	7	5	8
AZ61 Mg alloy	1	9	6	8	1	4	4	7
Ti/3Al/8V/6Cr/4Zr/4Mo	9	9	9	5	7	6	5	7
High strength carbon fiber/epoxy composite, Isotropic	5	7	7	3	10	8	7	8
Epoxy-glass fiber (SMC)	3	7	7	3	1	8	7	8
High strength glass fiber composite (GF 40-60%)	3	7	7	3	4	8	7	8

[‡] CES 2008 software. [‡‡] Davies, 2004. [‡‡] The tabulated values represent mean value of the same Aluminum alloy, but with different tempers; [♣] NVH greatly depends on the whole vehicle structure and material damping property; [♣♣] Crashworthiness greatly depends on yield strength.

2.7. SUMMARY

Nowadays, the problem of environmental pollution and sustainability becoming more and more serious and hence engineers and designers must take into account the effects that their design decisions have on the local and global eco-systems. Unlike other methods, design for sustainability is a holistic approach that covers all environmental, economical and societal factors. Unfortunately the integration of sustainability aspects into the design process tends to complicate material selection process. In order to ensure that does not happen, there is a need for tools to support designers and help them to achieve their sustainability goals. Rather than attempting to develop local optimization problems (e.g. minimize energy used, reduce CO_2 emissions, minimize the mass, etc.), using current sustainable material selection method may afford best tool to incorporate all sustainability aspects in one design model (i.e. global optimization problem: sustainable lightweight design). Materials selection indices and material selection charts are good tools for materials selection in early conceptual design stage. In the field of mechanical design these charts are a simple and quick way of assessing whether a material is suitable for the case in hand. By taking these charts and extending their range to include sustainability concerns, designers may consider them in exactly the same way they consider other material properties.

CHAPTER THREE

LIFE CYCLE ASSESSMENT-BASED SELECTION FOR A SUSTAINABLE LIGHTWEIGHT BODY-IN-WHITE DESIGN

Nowadays life cycle tools namely; Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Life Cycle Optimization (LCO) are being used to assess new vehicular structures from sustainability and design for the environment perspectives. This chapter implements a Life Cycle Assessment (LCA) based design approach to assess the performance of vehicular Body-In-White's (BIW) through its complete life cycle. The proposed LCA model will aid in the early design stages (i.e. conceptual design stage) serving as an eco-design decision-making support tool. This chapter provides a complete life cycle assessment covering the extraction and the processing of virgin materials, the manufacturing, the use and maintenance stage, the end-of-life stage, in addition to the fuel extraction and production stages. Traditional LCA studies do not usually consider the latter stages which accounts for a significant portion of the energy consumed and the generated CO_2 emissions. This chapter shows that the material selection for vehicular applications is a sensitive process not only to the vehicle lifetime (as expressed in traveled miles), but also to the environmental burdens from the extraction stage and recycling efforts. Additionally, this chapter discusses the design needs when dealing with different materials and the overall impact on the vehicle structure functionality.

3.1. INTRODUCTION

Life Cycle Assessment (LCA) can estimate the environmental aspects and the potential impacts throughout products' lifetime span, called cradle-to-grave. This assessment scope include the raw materials' impact all the way to the final disposal of the product or its sub-assemblies, which encompasses; the materials extraction, its processing, manufacturing, transport, use, re-use, maintenance, and finally its recycling back into the stream (Das, 2011; Song et al., 2009). LCA offers a systematic approach to evaluate products and processes by monitoring the main inputs and outputs in terms of materials, energy and emissions, while identifying and quantifying the material used and the associated energy and emissions (Du et al., 2010).

LCA among other product life cycle technologies, such as Life Cycle Costing (LCC), and Life Cycle Optimization (LCO) have provided new opportunities for the manufacturing companies to innovate sustainable products based on optimized lifecycle performance, not only in the technical aspect, but also in the environmental and the economic domains, as well as the social aspect. Since that substantiality is a holistic approach that incorporates technical, environmental and economic aspects when designing new products or services, sustainable development is best defined by the World Commission on Environment and Development WCED as "How to meet the needs of the present generation, without compromising the ability of future generations to meet theirs" (World Bank, 2010).

Nowadays, LCA literature includes wide range of eco-design tools, methods and principles (Yang, 2007) ranging from the accounting for single environmental impacts (such as improving resource and energy efficiency while reducing waste and toxicity, or recycling materials) (Graedel and Allenby, 1998); to using closed loop feedback to the information flow in design.

The framework of LCA is constructed through a series of Environmental Management Standards EMS introduced by the International Standards Organization (ISO 14000). The Organization for Standardization (ISO) has classified the LCA framework into four phases; namely the goal and scope definition phase, the inventory analysis phase, the impact assessment, and the interpretation phase (ISO 1997). The goal and scope phase defines the purpose, the audience, and the system boundaries, while the inventory analysis step involves the data collection and the calculations needed to quantify the material and the energy inputs and outputs for a product system. The impact assessment phase evaluates the significance of each potential environmental impact based on the inventory analysis; lastly, the interpretation phase evaluates the findings, summarizes the conclusions, and makes recommendations.

The first two steps in the LCA are discussed extensively through the ISO 14041 (ISO 14000, Govetto, 2008), with the third phase or “Impact assessment” is guided by the ISO 14042. The interpretation phase is articulated in the ISO 14043.

This chapter focuses on the LCA implementation for automobiles, which considers the vehicle from the pre-manufacturing stage to the end-of-life stage. This main objective is to develop a LCA model to serve as a numerical analysis tool rather than descriptive tool for sustainable vehicular product design, thus reducing the adverse environmental impacts throughout a vehicle lifetime. Specific objectives include; (1) the development of a complete model for assessing the different BIW design options from environmental performance perspective. (2) To define the life cycle stages and to define the required inputs and outputs of the system in order to be able to assess lightweight, environment-friendliness BIW designs during the development phase; and lastly (3) to implement and show the role of eco-design tools in helping designers and engineers to translate specific sustainability goals in their BIW designs.

3.2. LIFE CYCLE ASSESSMENT (LCA) MODEL

As mentioned before, Life Cycle Assessment studies are time and effort intensive due to the complications that come from the variations in the time frame and the large number of inputs and possible outputs of the LCA system; i.e. possible vehicle usages and end of life scenarios.

To establish a complete LCA for a BIW, one can start by collecting all the required information for needed analyses, mainly the energies and the emissions for all the extraction and the production processes, in addition to the complete records for the manufacturing and the associated energy and emissions, finally, the recycling fractions and the end-of-life strategies for the different selected materials should be investigated. Also, an extra life cycle stage is added to the LCA to account for the fuel extraction and its production. It has been reported by Volvo that a major portion of environmental burdens are associated with the fuel extraction and production, which are typically disregarded in traditional LCA studies (EPD, 2010). Table 3.1 summarizes all conditions and assumptions that are used in this study. It is important to mention here that recycling body-in-white was assumed to be the preferred procedure for retired vehicle's body rather landfilling; in fact, this is the most widely used scenario of the end-of-life strategies which has the advantages of saving materials and energy required to extract virgin materials. However, the recycling strategy also assumes that the damaged parts of BIW will be replaced by new ones where these damaged parts to be recycled too. Table 3.2 summarizes all energy expenditures and CO_2 emissions in the material extraction and manufacturing phase for typical mid-size passenger vehicles. Knowing that the joining energy is a function of boundary perimeter of the welded parts and the painting energy is a function of the surface area; hence, one prefer that the calculated values should be divided by the total BIW weight to get a unified value in all life cycle stages i.e. (MJ/kg).

Table 3.1: Conditions and assumptions

Life cycle phase	Value	Unit
Manufacturing:		
For simplification, blanking and stamping energy analysis is assumed to be the same for all metals		
For simplification, welding and joining energy analysis is assumed to be the same for all metals		
FRP manufacturing process includes both shaping and joining (Advanced sheet molding compound).		
Painting process consumes about 60% of total energy needed by automobile assembly plants *		
FRP BIW manufacturing analysis does not include painting as there is no need to paint.		
Electricity supplied to manufacturing facility is generated from natural gas and oil (1:1 ratio)		
Natural gas heating value	3853.12	MJ/m^3
Natural gas CO_2 footprint	53.119	Kg CO_2/m^3
Crude oil heating value	31.3	MJ/kg
Crude oil CO_2 footprint	2.3285	Kg CO_2/L
Use phase:		
Vehicle life	200,000	mile
Maintenance energy for BIW = 1% of the total use energy		
Gasoline energy content‡	34.8 (0.125)	MJ/l (mmBTU/gal)
Gasoline CO_2 footprint‡	2.36 (9.184)	Kg CO_2/L (Kg CO_2/gal)
Recycling:		
Steel recycle fraction	90	%
Aluminum recycle fraction (%)	95	%
Magnesium recycle fraction (%)	95	%
Titanium recycle fraction (%)	80	%
Composite recycle fraction (%)	<1	%
Shredding and sorting energy	560	MJ/vehicle
Shredding and sorting CO_2 emission **	0.024	Kg CO_2/vehicle
Controlled landfilling energy **	90	MJ/vehicle
Controlled landfilling CO_2 emission **	0.004	Kg CO_2/vehicle
Fuel extraction and production* **		
Well-to-pump energy consumption (Avg. of USA markets)	0.25956 (0.03245)	mmBTU/mmBTU of fuel available at fuel station pumps
Well-to-pump CO_2 emissions (Avg. of USA markets)	15.899 (1.9874) *	kg CO_2/mmBTU of fuel available at fuel station pumps
Well-to-pump NO_x emissions (Avg. of USA markets)	0.04289 (0.00536) *	kg NO_x/mmBTU of fuel available at fuel station pumps
Well-to-pump SO_x emissions (Avg. of USA markets)	0.009998 (0.00125)*	kg SO_x/mmBTU of fuel available at fuel station pumps

*(See: Roelant et al., 2004; Gin et al., 2006); ** From (Hakamada et al., 2007), *** From (GREET 1.7c, 2010), ‡The numbers in parenthesis are equivalent values for gasoline energy content and CO_2 footprint for 1 US gallon.

Table 3.2: Estimated production and manufacturing energy and emissions for typical materials used in BIW

Material	**Embodied energy (MJ/kg)** [1]	**CO_2 Emission form extraction and production (kg/kg)** [‡]	**Manufacturing process**	**Estimated manufacturing and production process energy (MJ/kg)** [‡‡]	**Manufacturing and production process emissions (Kg CO_2/kg)**	**Assembly process**	**Assembly energy (MJ/kg)** [‡‡]	**Assembly emission (Kg CO_2/ kg)**	**Painting energy (MJ/ kg)** [‡‡]	**Painting emission (Kg CO_2/ kg)**
AISI 1015 (annealed)	32	2.485	Rolling and forging, blanking and stamping	9.393	0.244	Welding	1.067	0.178	4.324	2.202
AISI 3140	32	2.485	Rolling and forging, blanking and stamping	9.393	0.448	Welding	1.067	0.178	4.324	2.202
Dual Phase 280/600	32.	2.485	Rolling and forging, blanking and stamping	9.393	0.448	Welding	1.200	0.178	4.414	2.202
HSLA 462/524	32	2.485	Rolling and forging, blanking and stamping	9.393	0.448	Welding	1.200	0.178	4.531	2.202
Mart 950/1200	32	2.485	Rolling and forging, blanking and stamping	9.393	0.448	Welding	1.419	0.178	4.531	2.929
Stainless steel, ferritic, AISI 405, wrought, annealed, low Ni	81.25	5.105	Rolling and forging, blanking and stamping	9.393	0.445	Welding	1.419	0.236	4.531	2.929
AA6060 [‡‡‡]	207.5	12.0	Rolling and forging, blanking and stamping	9.393	0.342	Welding	2.133	0.356	7.008	4.404
AZ61 Mg alloy	350.5	22.1	Rolling and forging, blanking and stamping	9.393	0.425	Welding	2.880	0.480	7.265	5.945
Ti	586.5	36.9	Rolling and forging, blanking and stamping	9.393	0.754	Welding	1.419	0.236	4.531	2.929
High strength carbon fiber composite, Isotropic	273	17.25	Advanced sheet molding compound (SMC)	11.85	1.555	SMC	===	===	===	===
High strength glass fiber composite (GF 40-60%)	112	7.9	Advanced sheet molding compound (SMC)	19.35	1.555	SMC	===	===	===	===

[‡] Cambridge Engineering Selector Software. Granta Design 2008; [‡‡] Sullivan et al. (2010). [‡‡‡] The tabulated values represent mean value of the same Aluminum alloy, but with different temper.

3.2.1. EXTRACTION AND PRODUCTION PHASE

For Life Cycle Energy Analysis (LCEA) the concept of embodied energy is used. The embodied energy of a material refers to the energy used to extract, process and refine this material before being used in the manufacturing, for example the embodied energy for metals (steel, aluminum, magnesium and titanium) used in automotive applications, includes ‘extraction and refining’ energy and ‘casting and rolling energy’ involved to prepare the sheet metal for further applications i.e. stamping and welding etc. Therefore, a correlation exists between the number and the type of the pre-processing steps and the material embodied energy. For example, the fewer and/or the simpler the extraction, the processing and the refining steps, the lower its embodied energy becomes. Eventually, the embodied energy of any material affects its environmental impact as well as its final price.

In some cases, the most technically appropriate material lowers the energy costs over the life cycle of a product. For example, magnesium has a relatively high embodied energy, but when it is used appropriately, it can save energy in a product's use-phase due to its advantageous physical properties, e.g., low density, high strength-to-weight ratio, and high stiffness-to weight ratio.

On the other hand, materials with less embodied energy may often be substituted without a loss in product functionality and performance, if the substitution is optimized with respect to the product's reliability, durability and technical functions.

So, one can estimate the embodied energy of a metal as following:

$$Embodied\ energy = E_{E-R} + E_{C-P} \tag{3.1}$$

Where:

E_{E-R} is extraction and refining energies, and E_{C-P} is casting and processing (rolling and forging) energies

For composite materials, the definition of embodied energy is quite different;

$$Embodied\ energy = \sum_{i=1}^{n}\left(E_{E-R,i}\right) + E_{M-P,i} \tag{3.2}$$

Where:

$E_{E-R,i}$ is extraction and refining energies for component ***i*** *(**i**= fiber or resin)*, and $E_{C-P,i}$ is molding and processing (pultrusion, sheet molding compound (SMC), or lay-up method) energies for product (i.e. BIW panel in this case).

Emission analysis depends greatly on the type of the fuel or the power source used in extraction and processing steps.

The current model tracks only the carbon dioxide emissions associated with the energy sources used during each stage of life-time span. Other fuel-related emissions such as carbon monoxide, nitrous oxides, sulfur dioxide, and other compounds are not considered in this study. Moreover, it is assumed that the main energy source for extraction and refining comes from petroleum products, while main energy sources for casting and processing comes from electricity. In general we can use the following if-then rules to assess CO_2 emission from using different energy sources (the following values were obtained from natural resources Canada, Office of Energy Efficiency publication, 2008):

$$\begin{Bmatrix} if\ energy\ source\ is\ electricity, then\ equivalent\ CO2\ emission\ is\ 856g\ CO2/kWh \\ if\ energy\ source\ is\ heavy\ oil, then\ equivalent\ CO2\ emission\ is\ 3170kg\ CO2/ton \\ if\ energy\ source\ is\ natural\ gas, then\ equivalent\ CO2\ emission\ is\ 56kg\ CO2/GJ \end{Bmatrix}$$

3.2.2. MANUFACTURING PHASE

The typical vehicle body-in-white is made up of several hundred (around 400-500 parts) stamped metal components, which are joined together mainly through spot welding (around 5000 spot welds per vehicle) process, then painted with different layers of protective and finishing color compounds (around 5 layers of paint) (Omar, 2011). So, the main manufacturing steps of a vehicle body are;

- Blanking and stamping;
- Joining and assembly; and
- Painting, in addition to final assembly

Being a highly energy-intensive process, producing virgin non-ferrous metals (e.g. Al, Mg, and Ti) generates more carbon dioxide emissions than producing virgin steel. In the manufacturing processes, three facts should be considered; the first fact is that manufacturing phase accounts for less than 5% of the total life-cycle energy consumed and the CO_2 emissions (Mcauley, 2003; Fitch and Cooper, 2004 ; Ungureanu et al., 2007). The second fact is that all metallic BIW have similar manufacturing processes with some complications being added to the current steel production lines, i.e. some metals have slightly lower formability or slightly lower weldability than mild steel, but such differences in fabrication will not affect the overall calculations. The third fact is that 'blanking and stamping' and 'welding and joining' use electricity to operate the machinery involved, so the amounts of carbon dioxide generated during the manufacturing stage differ slightly. Also, it is important to remember that the painting process consumes about 60% of the total energy expenditure in an automobile assembly plant (Roelant et al., 2004; Gin et al., 2006) and it is performed on the whole BIW after assembly, which means that the painting process is practically the same for all metallic BIW regardless of the metal used in constructing the BIW; with some differences related to anodizing Aluminum parts. Based on these facts, the manufacturing and the assembly processes are assumed to be similar for all metals. However, the vehicle's operational or use stage has the greatest environmental impact in terms of carbon dioxide emissions. Fuel economy, power-train type, vehicle's life (expressed in miles) and the emissions rate are among the most common factors contributing to the amount of carbon dioxide that is generated over the operational stage (Ungureanu et al., 2007).

For plastic composites, the manufacturing processes are completely different. In such case, traditional pultrusion and Sheet Molding Compounds (SMCs) are involved. However, making sheet molding compound is a highly automated, continuous flow process. The compound takes the form of a flexible, leather-like sheet that is easily cut, weighed and placed in the mold for curing to the desired part configuration. Because there is no mixing or extrusion involved in preparing sheet molding compound, the fibers remain undamaged at their original lengths.

The automotive industry is extremely cost sensitive. This is one of the main reasons why compression molding is the most popular fiber-reinforced polymeric composites manufacturing method used (Cabrera-Rios, 2010). SMC compression molding economics are better suited for the automotive industry than processes such as lay-up processes or even the resin transfer molding or any of its variations.

The joining and the assembly processes for the SMC parts can be done by riveting and clinching, or adhesive bonding. Recent joining technology are being proposed to join the Fiber Reinforced Plastics (FRP) to other metallic components called a weld bonding which is a combination of spot welding and adhesive bonding (Berger, 2010). However, all of these joining processes tend to have low energy expenditure and CO_2 emissions (less than 1% of total life cycle impact) (Ungureanu et al., 2007).

3.2.3. USE AND MAINTENANCE PHASE

BIW material choice has a great effect on overall mass, energy and associated CO_2 emissions by the vehicle during its operation, but BIW material embodied energy and emissions, and difficulties of disposal remain independent of vehicle performance; in other words materials that reduce BIW mass may reduce energy use in operation, but introduce greater difficulties in recycling and disposal, leading to greater energy and emissions over the vehicle BIW life.

As mentioned previously, the use stage accounts for significant amount of energy consumption and of the CO_2 emissions. This fact motivated by a cost-driven decisions, have directed the automotive OEMs to choose lightweight materials regardless of other important design aspects such as the extraction and the manufacturing energies, and the CO_2 emitted in the extraction and end-of-life vehicle (ELV).

Material selection that results in a lightweight BIW design should be considered in parallel with the selection of an appropriate power-train that meets the performance requirements (e.g. horsepower and 0-60 mile/hr acceleration). This study focuses on the material selection for the BIW while assuming that the power-train for all the BIW design options can meet the performance requirements by adjusting the engine size; also it is assumed that gasoline is the primary fuel type for all chosen power-train sizes. The most important issue to consider here is the fuel economy of the vehicle, which greatly depends on its curb weight. In this study, the following empirical equation developed by Hakamada et al. (2007) is used to estimate fuel economy of the vehicle:

$$FE = 6.4 \times 10^4 M^{-1.2} \tag{3.3}$$

where FE is fuel economy expressed in km/L and M is the curb weight in kg.

The energy consumption and the CO_2 emissions in this stage are thus evaluated knowing that gasoline has a heating value of 34.8 MJ/L and a CO_2 footprint of 2.36 kg/L, respectively (Hakamada et al. 2007). To get final normalized value of the energy consumption and the CO_2 emission to the environment during the use stage, the total amount of fuel consumed and the amount of CO_2 emitted over the vehicle entire lifetime span (assumed to be 200,000 mile in this study) is to be divided by curb weight as follows in equations (6) and (7);

$$Use\ energy\ \left(\frac{MJ}{kg}\right) = \frac{(3.785\frac{L}{gallon})\times Heating\ value\ of\ gasoline\ \left(\frac{MJ}{L}\right)\times life\ time(mile)}{FE\ (mpg)\times curb\ weight\ (kg)} \tag{3.4}$$

$$Use\ CO2\ emission\ \left(\frac{Kg}{kg}\right) = \frac{\left(3.785\frac{L}{gallon}\right)\times CO2\ footprint\ \left(\frac{kg}{L}\right)\times life\ time(mile)}{FE\ (mpg)\times curb\ weight\ (kg)} \tag{3.5}$$

The maintenance or the replacement of the BIW parts tend to be very rare unless the vehicle gets wrecked or the part is deeply scratched or dented. In any of these cases, the replacement of damaged parts with a new one will add more energy and CO_2 impacts to the environment. This study assumes that the damaged part is only replaced with a new one (i.e. no used parts are considered for replacement); also it’s assumed that the damaged part is to be recycled. Based on these assumptions, the following equations (equation 8 and 9) can be used to estimate the energy and the CO_2 emissions, respectively;

$$E_{maint} = E_{Extr} + E_{Mfg} + E_{Replace} - E_{Recycle} \tag{3.6}$$

$$GHG_{maint} = GHG_{Extr} + GHG_{Mfg} + GHG_{Replace} - GHG_{Recycle} \tag{3.7}$$

Where E_{maint} is maintenance energy; E_{Extr} is extraction and processing energy; E_{Mfg} is manufacturing energy ('blanking and stamping' and painting only); $E_{Replace}$ is replacement energy (negligible); and $E_{Recycle}$ is recycling energy. Similarly for CO_2 emission analysis; GHG_{maint} is maintenance CO_2 footprint; GHG_{Extr} is extraction and processing CO_2 footprint; GHG_{Mfg} is manufacturing CO_2 footprint ('blanking and stamping' and painting only); $GHG_{Replace}$ is replacement CO_2 footprint (negligible); and $GHG_{Recycle}$ is recycling CO_2 footprint.

Although some references suggest that maintenance energy to be ignored as it accounts for non-significant portion of life cycle assessment (e.g. Sullivan et al., 2010,), other references suggest combining maintenance phase with in-use phase or end-of-life phase (e.g. Das 2000; Fitch and Cooper, 2004; Graedel and Allenby, 1998; Hakamada, 1999), also some references suggest using maintenance as an independent phase in LCA (e.g. Kim et al., 2003; USAMP, 1999) where it accounts for less than 5% based on 120,000 mile vehicles' lifetime. At the same time, modeling the maintenance periods for the different BIW parts requires advanced statistical methods, such as the regression analysis and the forecasting tools, which are out of the scope of current study. To overcome this problem, it's assumed that the maintenance energy and CO_2 emission for a vehicle with estimated lifetime of 200,000 miles would account for about 1% of the use energy and the CO_2 emissions, respectively. Another important fact is that any replacement will not change the use and the end-of life analyses as a new part is assumed to be of the same weight and material of the damaged one.

3.2.4. END OF LIFE PHASE

For End-of-Life Vehicle (ELV) strategies different scenarios for retired vehicles are followed; specifically;

- Land-filling all of the vehicle's components, this strategy assumes that the retired vehicle is completely disposed in the designated area of the landfill; however, this strategy is not a preferred route because it adds more environmental problems;
- Recovery and re-use of some components (e.g. body parts; electric components, etc.), which is significantly adopted by junkyards;
- Recycling of the vehicles' major parts, this is adopted by most manufacturers.

In this study the third ELV scenario is assumed, where the retired vehicle is going through a series of steps of disassembling, shredding, sorting, and recycling of the remaining body structure. However, the main advantage of recycling is that a significant amount of energy and CO_2 emissions can be saved, knowing that the recycled steel saves between 40-75 percent of the energy required to produce virgin steel (Ungureanu et al., 2007; AISI, 2010). The following equation, equation (10) describes the end-of-life energy analysis if the recycling scenario is adopted;

$$E_{ELV} = E_{sort} + E_R - \psi \times E_v \tag{3.8}$$

Where: $\mathbf{E_{ELV}}$ is end-of-life vehicle's energy; $\mathbf{E_{sort}}$ is shredding and sorting energy; $\boldsymbol{\psi}$ is the recycle fraction; and $\mathbf{E_v}$ is the embodied energy for virgin material.

Similarly, equation (11) can be used for the CO_2 emissions for end-of-life vehicle stage.

$$GHG_{ELV} = GHG_{sort} + GHG_R - \psi \times GHG_v \tag{3.9}$$

Where

GHG_{ELV} is end-of-life vehicle's emissions (e.g. CO_2, CO, NO_x, SO_x, etc.); **GHG_{sort}** is shredding and sorting emissions (CO_2, CO, NO_x, SO_x, etc.); **ψ** is the recycle fraction; and **GHG_v** is the emissions (e.g. CO_2, CO, NO_x, SO_x, etc.) associated with extraction and producing virgin material.

Hakamada et al. (2007) claim that controlled land-filling of the whole retired vehicle will consume 90MJ/vehicle and produces 0.004kg CO_2/vehicle.

3.2.5. FUEL EXTRACTION AND PRODUCTION

To compare the relative environmental burdens of the different BIW alternatives, the environmental impacts of the entire fuel cycle need to be accounted for in the LCA. The components of a full fuel cycle are shown schematically in Figure 3.1. The boundaries of the fuel cycle analysis can include; the production and burning of the fuel as well as the production and the fuel final fate. The idea of quantifying the total fuel cycle energy and emissions is not new. Fuel cycle analyses have been used for many years to support the energy use analysis and to assess vehicles' environmental impacts.

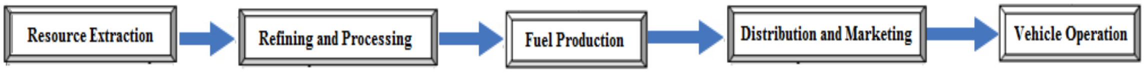


Figure 3.1: Total vehicle's fuel cycle analysis

A full fuel cycle analysis includes the following stages (TIAX, 2007):

1. Feedstock extraction, transport, and storage
2. Fuel production, distribution, transport, and storage
3. Vehicle operation including refueling, consumption, and evaporation

The first two stages track the fuel cycle up to storage at retail and these energy and emissions are commonly referred to as Well-to-Tank (WTT) analysis. Emissions from vehicle refueling and operation are referred to as Tank-to-Wheels (TTW) analysis. The combination of the WTT and TTW emissions represent the energy analysis and emissions associated with the full fuel cycle analysis, and are referred to as the Well-to-Wheels (WTW) analysis (Torchio et al., 2010).

For fuel extraction and production stage, it was found that GREET study prepared by Argonne national laboratory and available in Excel spreadsheet format is a complete and reliable source for estimating energy and emissions associated with fuel extraction and production. In this study, fuel extraction and production energy and emissions calculations were estimated using GREET model (GREET1.7c, 2010). Similar study for European countries was made by a consortium of organizations including European Commission, European Council for Automotive Research and Development (EUCAR) and Concawe (Edwards et al., 2004).

3.3. MATERIAL SELECTION METHOD

The main focus on the vehicle BIW not other components or sub-systems (e.g. power-train, interior trim, etc) is due to the fact that the BIW weight accounts for about 40% of the vehicle curb weight (see Table 1.1). So it has the potential to reduce weight by downsizing or by light weight engineering (Lutsey, 2010) without affecting the vehicle main functionality (power-train; acceleration, horsepower) or comfort level (motorized seats, infotainment system, etc).

In proposed material selection process, the objective function for each panel is used to rank the different competitive materials to optimize the overall design. The study employs a conventional stamped BIW for a typical mid-size passenger vehicle (see Fig. 1.3) as a baseline model; however, U.S. Department of Transportation's definition of a passenger vehicle, to mean a motor vehicle with at least four wheels, used for the transport of passengers, and comprising no more than eight seats in addition to the driver's seat, excluding buses and small or large trucks. The major panels considered in the study and their main design functions are shown in Table 2.1.

Typical material selection indices that incorporate the minimum weight design criteria tend to be in the form of E/ρ (for a tension scenario) or $E^{1/2}/\rho$ for bending loads with a specified shape (Ashby, 2008). Similarly, the design of a stiff plate loaded in bending will rely on a material index of $E^{1/3}/\rho$; where E=Young's modulus and ρ=density (Holloway, 1998). In most cases the design objective can be expressed as the maximization or the minimization of these indices. However, other combinations of material properties and design constraints and objectives may be used to optimize the selection process based on such criteria as; strength-limited design, vibration-limited design and even cost-limited design.

Typically, there are three main steps in compiling material indices as identified by Ashby (2008):1). Function; 2). Objective; and 3). Constraint.

In any replacement, it is important to keep the panel performance and functionality at its current level. By doing so and in order to meet the minimum thickness of the replaced BIW panel, a material selection methodology -as proposed by Ashby- is followed to derive each material selection index for a stiff, lightweight panel in addition to an index for a strong, lightweight panel as well as an index for a dent resistance, lightweight panel. Table 3.3 shows estimated BIW and curb weights for different BIW design options.

Table 3.3: Estimated BIW and curb weights for different materials

	BIW weight	**Curb weight**
Baseline BIW	270	1470
HSS BIW	240	1440
AHSS BIW	203	1403
Al-intensive BIW	135	907
Mg-intensive BIW	100	875
Composite intensive BIW	123	1021

3.4. RESULTS AND DISCUSSION

Once the material selection index has been derived, a new panel thickness can be optimized to meet the functional requirements. After that, one can add up all the new panel weights to get a final BIW weight (Table 3.4). The estimation of the curb weights in this study is based on benchmarking of the current lightweight vehicles available in the market for mid-size passenger cars category; more details are available in (Lutsey, 2010; Cheah, 2008; Das, 2000).

The complete life cycle assessments are shown in Table 3.5 and Table 3.6, respectively. The last column of Table 3.5 shows the total life cycle energy assessment (LCEA), while last column of Table 3.6 shows the total life cycle CO$_2$ emission analysis.

Table 3.4: Material selection indices for lightweight BIW panel

Function	**Material selection index**
Bending stiffness	$\boldsymbol{E^{\alpha}}/(\boldsymbol{\rho})$
Dent resistance	$\boldsymbol{\sigma_y^{\beta}}/(\boldsymbol{\rho})$

$^{\alpha}$ depends on the shape and dimensions of the panel (α=½ for beam with specified length and shape and has free sectional area; α=1/3 for beam with specified length and height and has free width; α=1 for beam with specified length and width and has free height; α=1/3 for panels and plates with specified length and width and has free thickness).

$^{\beta}$ depends on the shape and dimensions of the panel (β=2/3 for beam with specified length and shape and has free sectional area; β=1 for beam with specified length and height and has free width; β=1/2 for beam with specified length and width and has free height; β=1/2 for panels and plates with specified length and width and has free thickness).

Table 3.5: Complete life cycle energy analysis (LCEA)

Material	BIW wt. (kg)	Curb wt. (kg)	Extraction and shaping (MJ/kg)	Total manufac-turing energy (MJ/kg)	Fuel economy (km/L)	Fuel economy (mpg)	Fuel required over use stage (Gallon)	Use Energy (MJ/kg)	Maintenance energy (MJ/kg)	Shredding and sorting (MJ/kg)	Embodied energy for recycling (MJ/kg)	End-of-life (MJ/kg)	Fuel (resources and production) MJ/kg	Total LCEA (MJ/kg)
AISI 1015 (annealed)	270	1470	32.0	14.8	10.13	23.82	8395.1	752.3	7.5	0.381	8.92	-19.50	158.23	945.35
AISI 3140	270	1470	32.0	14.8	10.13	23.82	8395.1	752.3	7.5	0.381	8.92	-19.50	158.23	945.35
Dual Phase 280/600	240	1440	32.0	15.0	10.38	24.42	8189.9	749.2	7.5	0.389	8.92	-19.50	157.58	941.81
HSLA 462/524	240	1440	32.0	15.1	10.38	24.42	8189.9	749.2	7.5	0.389	8.92	-19.50	157.58	941.92
Mart 950/1200	203	1403	32.0	15.3	10.71	25.20	7938.1	745.3	7.4	0.399	8.92	-19.50	156.76	937.40
Stainless steel, ferritic, AISI 405, wrought, annealed	203	1403	81.25	15.3	10.71	25.2	7938.1	745.3	7.4	0.399	22.75	-49.98	156.76	956.16
AA6060	135	907	207.5	18.5	18.07	42.53	4703.0	683.1	6.8	0.617	18.70	-177.81	143.66	881.78
AZ61 Mg alloy	100	875	350.5	19.5	18.87	44.40	4504.6	678.2	6.8	0.640	21.00	-311.34	142.63	886.29
Ti	203	1403	586.5	13.9	10.71	25.20	7938.1	745.3	6.8	0.399	22.30	-446.50	156.76	1057.4
High strength carbon fiber/epoxy composite	123	1021	272.5	11.9	15.68	36.89	5420.9	699.4	7.0	0.548	0.00	0.00	147.10	1137.9
High strength glass fiber composite (GF 40-60%),	123	1021	112.0	19.4	15.68	36.89	5420.9	699.4	7.0	0.548	0.00	0.00	147.10	984.88

Table 3.6: Complete life cycle CO_2 emission analysis (kg CO_2 /kg material)

Material	BIW wt. (kg)	Curb wt. (kg)	Extraction and shaping (kg/kg)	Total mf’g emission (kg/veh)	Fuel economy (km/L)	Fuel required over use stage (Gallon)	Exhaust emission (kg/kg)	Maintenance emission (MJ/kg)	Shredding and sorting (g/kg) *	Emission from recycling (kg/kg)	End-of-life emission (kg/kg)	Fuel (resources and production) kg/kg	Total (kg/kg)
AISI 1015 (annealed)	270	1470	2.485	2.62	10.13	8395.13	50.26	0.503	0.002	0.695	-1.790	11.35	65.43
AISI 3140	270	1470	2.485	2.83	10.13	8395.13	50.26	0.503	0.002	0.695	-1.790	11.35	65.63
Dual Phase 280/600	240	1440	2.485	2.83	10.38	8189.96	50.26	0.503	0.002	0.695	-1.790	11.35	65.63
HSLA 462/524	240	1440	2.485	2.83	10.38	8189.96	50.26	0.503	0.002	0.695	-1.790	11.35	65.63
Mart 950/1200	203	1403	2.485	3.61	10.71	7938.09	49.79	0.498	0.002	0.695	-1.790	11.24	65.84
Stainless steel, AISI 405	203	1403	5.105	3.71	10.71	7938.09	49.79	0.498	0.002	1.430	-3.675	11.24	65.24
AA6060	135	907	12.00	5.12	18.07	4703.00	45.63	0.456	0.002	1.084	-10.92	10.31	62.58
AZ61 Mg alloy	100	875	22.10	6.86	18.87	4504.60	45.30	0.453	0.002	1.325	-20.78	10.23	64.11
Ti	203	1403	36.90	3.68	10.71	7938.09	49.79	0.498	0.002	1.400	-35.50	11.24	
High strength carbon fiber composite	123	1021	17.25	1.56	15.68	5420.98	46.72	0.467	0.002	0.000	0.000	10.55	66.12
Epoxy-glass fiber (SMC)	123	1021	17.25	1.56	15.68	5420.98	46.72	0.467	0.002	0.000	0.000	10.55	76.55
Epoxy/ Glass fiber comp. (GF 40-60%)	123	1021	7.86	1.56	10.13	8395.13	46.72	0.467	0.002	0.000	0.000	10.55	67.15

* Kasai 1999.

Figure 3.2 shows the life cycle energy analysis for the different materials while Figure 3.3 displays the associated CO_2 emission for all the life stages. To facilitate the understanding of the life cycle environmental impacts, two plots are introduced; the first is for the total life cycle energy analysis, and the total life CO_2 emission analysis based on an estimated life assessment of 200,000 miles, and the second plot is for a 50,000 mile life span, both in Figure 3.4. Figures 3.4a and 3.4b show that Al and Mg are good choices from both energy and CO_2 emission perspectives, while the fiber reinforced composite has the worst performance in terms of life cycle assessment for the estimated lifetime of 200,000 mile. On the other hand, when the estimated lifetime decreased to 50,000 mile, steel gets the highest rank as can be seen in figures 3.5a and 3.5b, respectively. Again the fiber reinforced composite material has the worst performance for the 50,000 mile scenario. Figure 3.4 is a simple visual tool that can be used to assess the different BIW designs. When the estimated lifetime is low (less than 100,000 mile), then it can be shown that the steel and Advanced High Strength Steel (AHSS) body-in-white structures perform better than Al-intensive or even Mg-intensive body-in-white. This preference will change when the lifetime exceeds 100,000 mile, both life cycle energy analysis and life cycle CO_2 emission analysis recommend aluminum and magnesium body structures. However, composite-intensive BIW still has the worst performance from energy and CO_2 perspective regardless of the estimated lifetime, because of the zero recyclability of assumed for the plastic composite materials.

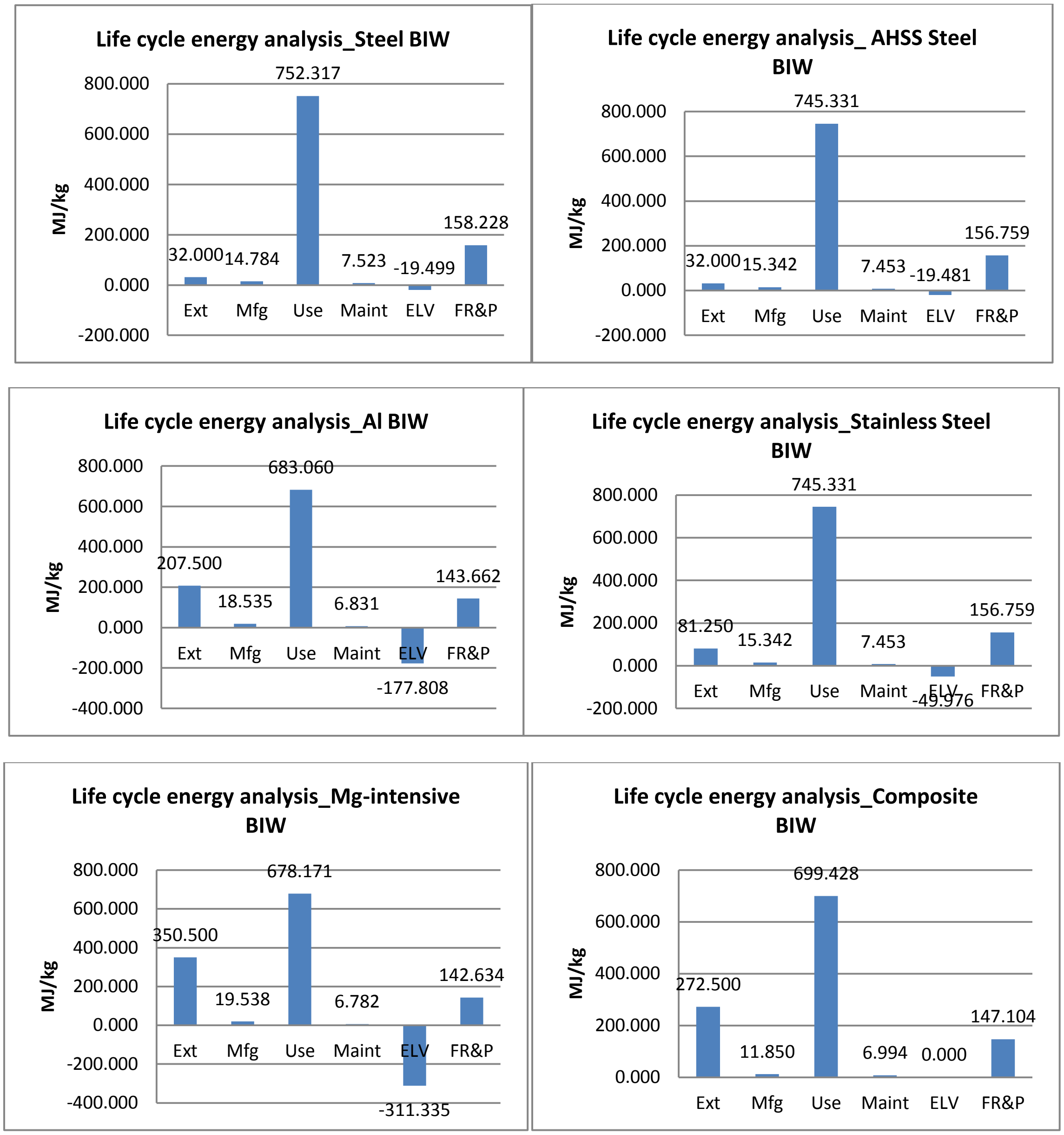


Figure 3.2: Life cycle energy analysis for different BIW designs (Ext: Material extraction and production phase energy; Mfg: Manufactruing phase energy; Use: use phase energy; Maint: Maitnence energy; ELV: end-of-life phase energy; and FR&P: fuel resources and production emissions).

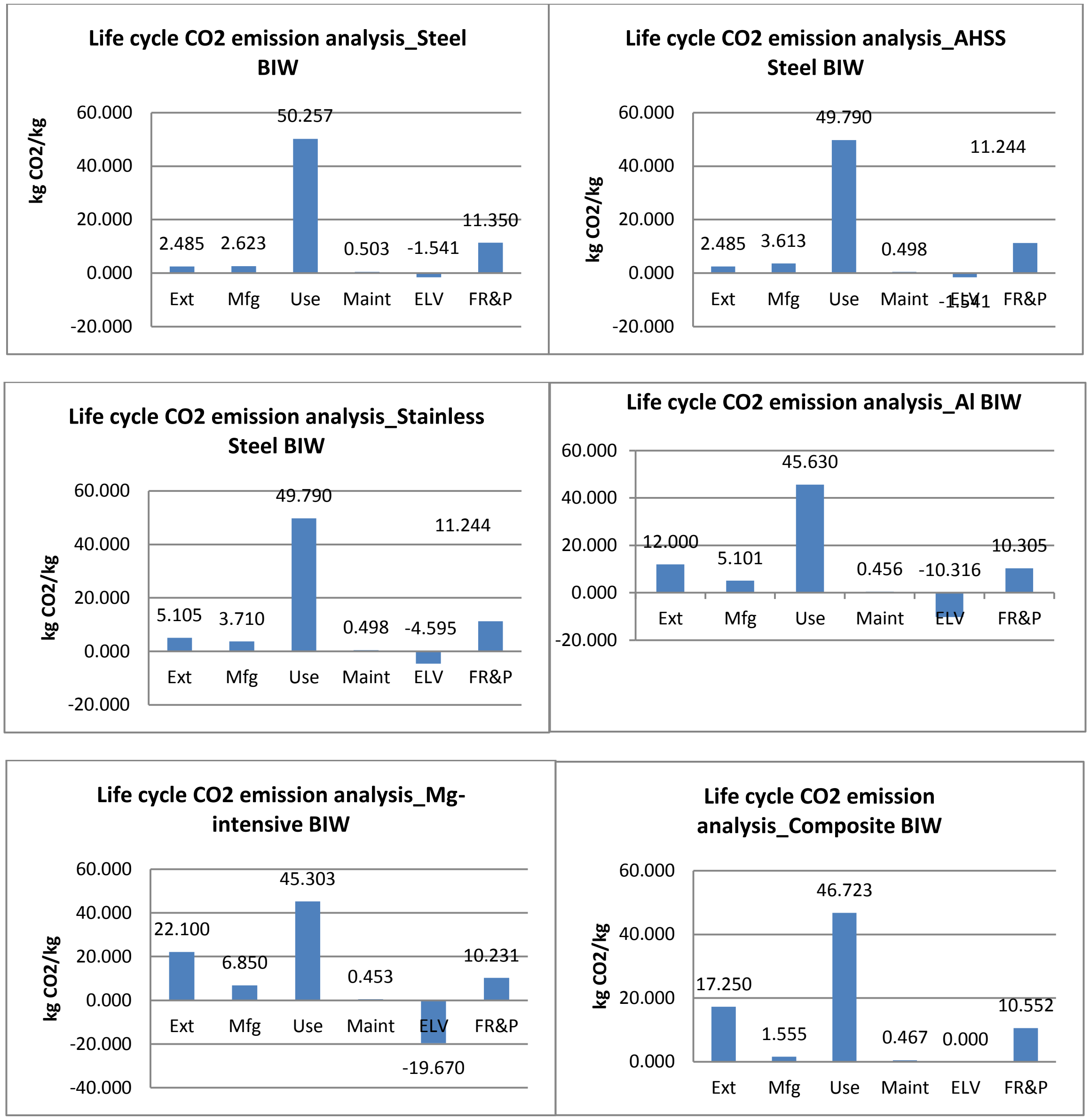
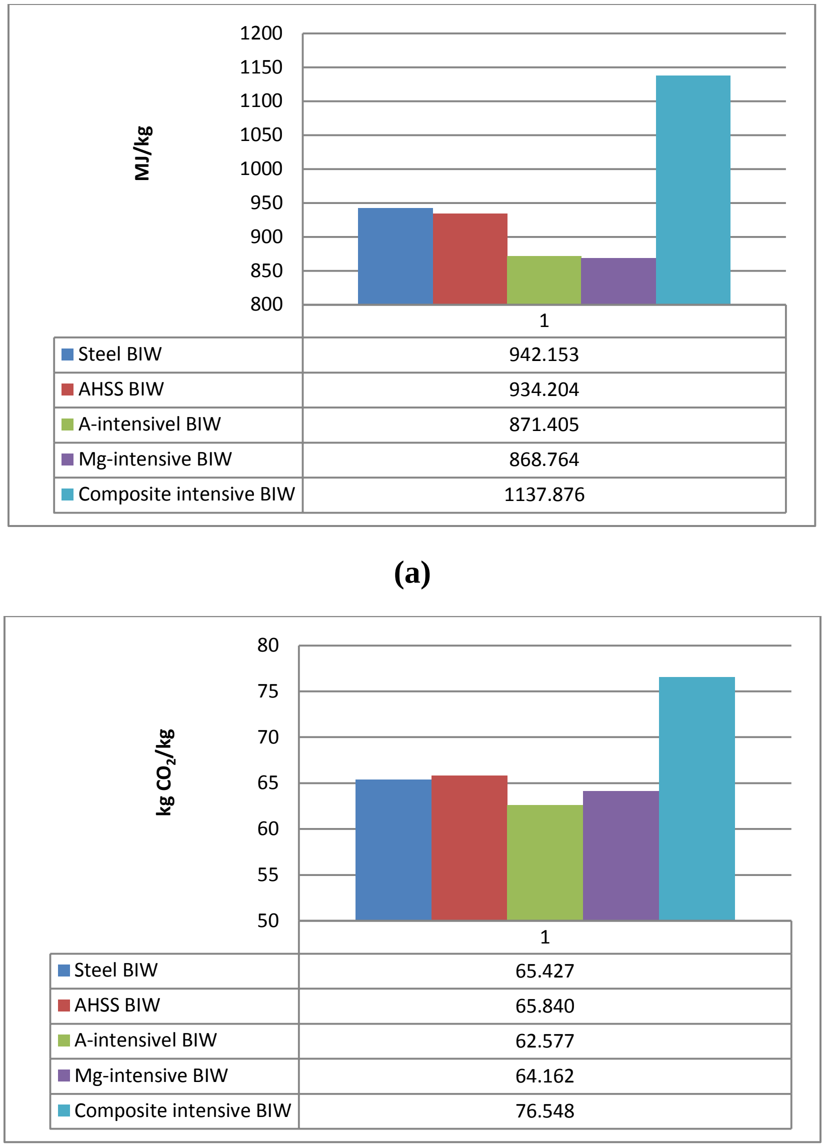


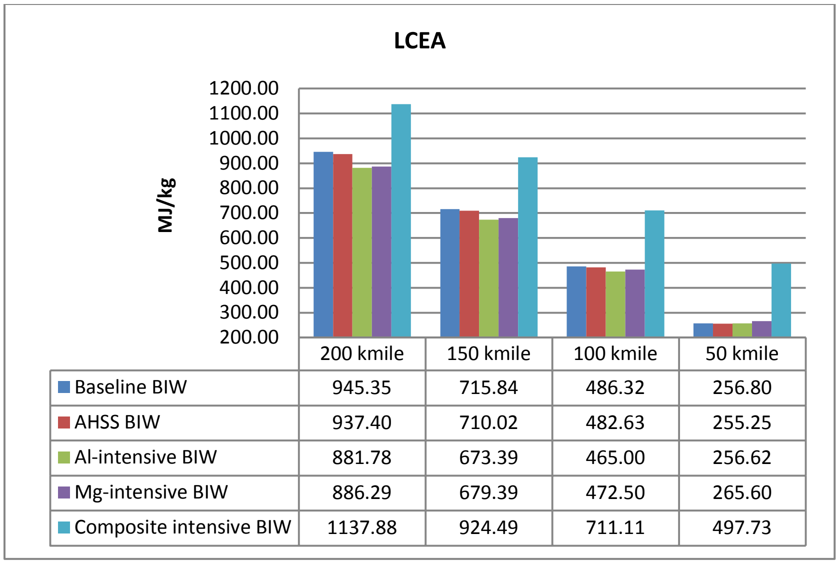
Figure 3.3: Life cycle CO_2 emission analysis for different BIW designs (Ext: Material extraction and production phase emissions; Mfg: Manufactruing phase emissions; Use: use phase emissions; Maint: Maitnence emissions; ELV: end-of-life phase emissions; and FR&P: fuel resources and production emissions).



(a)

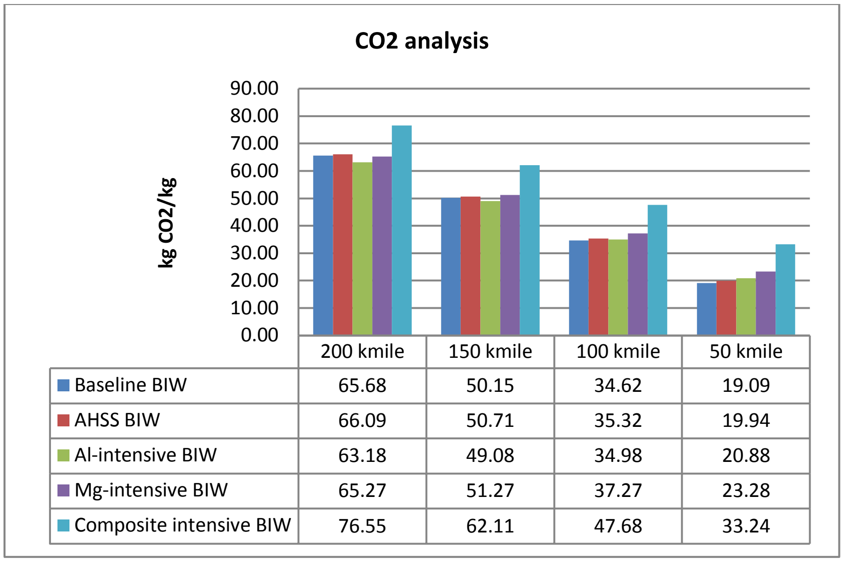
(b)

Figure 3.4: **(a)** Total life cycle energy analysis values for different BIW options (lifetime=200,000 mile); **(b)** Total life cycle CO_2 emission analysis values for different BIW options lifetime=200,000 mile).



	200 kmile	150 kmile	100 kmile	50 kmile
Baseline BIW	945.35	715.84	486.32	256.80
AHSS BIW	937.40	710.02	482.63	255.25
Al-intensive BIW	881.78	673.39	465.00	256.62
Mg-intensive BIW	886.29	679.39	472.50	265.60
Composite intensive BIW	1137.88	924.49	711.11	497.73

(a)



	200 kmile	150 kmile	100 kmile	50 kmile
Baseline BIW	65.68	50.15	34.62	19.09
AHSS BIW	66.09	50.71	35.32	19.94
Al-intensive BIW	63.18	49.08	34.98	20.88
Mg-intensive BIW	65.27	51.27	37.27	23.28
Composite intensive BIW	76.55	62.11	47.68	33.24

(b)

Figure 3.5: **(a)** Total life cycle energy analysis values for different BIW options (different estimated lifetimes); **(b)** Total life cycle CO_2 emission analysis values for different BIW options (different estimated lifetimes).

Since energy consumption and CO_2 emissions, like any other single sustainability metric, are unable to serve as universal indicators of environmental impact, being able to estimate other metrics as quickly and easily as energy and CO_2 emission analysis would be advantageous for material selection. However, most other metrics are still harder to estimate than energy consumption (Ashby, 2008). This is partially due to the fact that energy consumption can usually be tracked using financial records, whereas many emissions cannot be tracked this way (Fitch and Cooper, 2004).

3.5. SENSITIVITY ANALYSIS

Sensitivity analysis was conducted to examine the effects of varying several LCA parameters on the overall life cycle impacts. These parameters and their changes on energy and CO_2 emission are shown in Tables 3.7 and 3.8, respectively. These two tables show six proposed scenarios which represent most important LCA factors in order to examine their impact on LCA final results. Each parameter was changed independently from all others so that the magnitude of its effect on the base case can be assessed independently without significant interaction from other factors.

The proposed percent changes for all factors were based on changing values (±10% of their nominal values). Effect of changing fuel economy has the greatest impact on life cycle energy and life cycle CO_2 emission analysis if compared to other changed factors, a +10% change in fuel economy has an energy impact for metal-based BIW's that ranges between -7.54% for steel intensive BIW and 12.88% in case of Mg-intensive BIW;

however, this significant change on the overall life cycle energy consumptions can be related to the weight of BIW, the lighter the weight of BIW, the higher the impact of changing fuel economy. Not surprisingly, a composite intensive BIW has very light weight compared to steel BIW, but still has the lowest total life cycle energy and CO_2 emission impacts upon changing fuel economy, this is partially resulted from the effect of recycle fraction ($\psi<1\%$) which has stronger effect on the total life cycle energy and CO_2 emission analysis and tend to reduce any change in other LCA factors. The second most significant LCA factor is timespan (expressed in travelled distance); it can be said that lighter BIW's has lower overall LCA energy and CO_2 emission impacts if compared to heavier BIW's because of the total life cycle energy and CO_2 emission are dependent on the amount of gas required to travel the proposed distances. The third important factor to consider is the impact of changing 'Fuel resources and production' phase parameters (i.e. associated energy and CO_2) on the overall life cycle energy and CO_2 emission. Generally speaking an ±10% change ratio in 'Fuel resources and production' parameters would result in the overall change on life cycle energy and CO_2 emission between ±1.30-1.73%.

The other three proposed scenarios (change of embodied energy and CO_2 emission, change of manufacturing energy and CO_2 emission, and change of recycle fraction) have lower impacts on the overall life cycle energy and CO_2 emission for ferrous-based BIW's (i.e. steel-intensive BIW, AHSS-intensive BIW and stainless steel BIW); however, this is not true in case of non-ferrous-based BIW's (i.e. Al-intensive BIW, Mg-intensive BIW and composite intensive BIW). The latter three BIW's tend to be very sensitive in terms of changing extraction and shaping phase as well as manufacturing phase parameters. On the other hand, composite intensive BIW shows very minimal effect on the overall life cycle energy and CO_2 emission impacts upon changing recycle fraction, in fact current plastic reinforced composite BIW has less than 1% recycle fraction.

Table 3.7: Sensitivity analysis showing the effect of changing some LCA parameters in the overall total life cycle energy

	Steel-intensive BIW	**AHSS-intensive BIW**	**Stainless steel-intensive BIW**	**Al-intensive BIW**	**Mg-intensive BIW**	**Composite intensive BIW**
Scenario 1: Embodied energy						
+10 %	+0.34	+0.34	+0.85	+2.35	+4.52	+2.4
-10%	-0.34	-0.34	-0.85	-2.35	-4.52	-2.4
Scenario 2: Manufacturing energy						
+10 %	0.156	0.159	0.164	0.21	0.22	0.149
-10%	-0.156	-0.159	-0.164	-0.21	-0.22	-0.149
Scenario 3: Fuel Economy						
+10 %	-7.54	-7.64	-7.85	-9.28	-11.32	-6.47
-10%	+9.15	+9.24	+9.43	+10.84	+12.88	+7.91
Scenario 4: Travelled distance						
+10 %	+7.65	+7.54	+7.03	+5.51	+3.31	+7.10
-10%	-7.65	-7.54	-7.03	-5.51	-3.31	-7.1
Scenario 5: Recycle fraction (ψ)						
+10 %	-0.30	-0.31	-0.76	-2.24	-4.20	-0.01
-10%	+0.30	+0.31	+0.76	+2.24	+4.20	+0.01
Scenario 6: Fuel resources and production						
+10 %	1.68	1.67	1.64	1.63	1.59	1.30
-10%	-1.68	-1.67	-1.64	-1.63	-1.59	-1.30

Table 3.8: Sensitivity analysis showing the effect of changing some LCA parameters in the overall total life cycle CO_2 emissions

	Steel-intensive BIW	AHSS-intensive BIW	Stainless steel-intensive BIW	Al-intensive BIW	Mg-intensive BIW	Composite intensive BIW
Scenario 1: Extraction and shaping						
+10 %	+0.38	+0.38	+0.78	+1.90	+4.94	+2.25
-10%	-0.38	-0.38	-0.78	-1.90	-4.94	-2.25
Scenario 2: Manufacturing energy						
+10 %	+0.40	+0.43	+0.55	+0.81	+1.05	+0.22
-10%	-0.40	-0.43	-0.55	-0.81	-1.05	-0.22
Scenario 3: Fuel Economy						
+10 %	-6.96	-6.94	-6.82	-6.57	-6.30	-6.33
-10%	+8.48	+8.37	+8.34	+8.03	+7.70	+7.74
Scenario 4: Travelled distance						
+10 % (220,000 mile)	+8.48	+8.37	+8.25	8.02	+7.70	+7.74
-10% (180,000 mile)	-7.63	-7.53	-7.42	-7.22	-6.92	-6.1
Scenario 5: Recycle fraction (ψ)						
+10 %	-0.34	-0.34	-0.69	-1.80	-3.72	-0.01
-10%	+0.34	+0.34	+0.69	+1.80	+3.72	+0.01
Scenario 6: Fuel resources and production						
+10 %	+1.73	+1.70	+1.69	+1.63	+1.57	+1.57
-10%	-1.73	-1.70	-1.69	-1.63	-1.57	-1.57

3.6. SUMMARY

This chapter presented a method to performing a Life Cycle Energy and CO_2 emission analyses, associated with material selection for a vehicle Body in White panels. The proposed method applied a full product analysis to evaluate the different material options, taken into consideration the functionality aspect of the structural parts. By comparing the different material options for the Body-In-White; the aluminum and the magnesium intensive structures were found to result in less energy consumption over the life of the vehicle, which is assumed around 200,000 miles. However, when the life time decreased to around 50,000 miles, steel and the Advanced High Strength Steel AHSS ranked the highest in terms of savings in energy and CO_2 emission.

This study also presented a set of Life Cycle Energy and CO_2 emission terms designed to clearly describe the energy consumption and CO_2 emissions percentages across the different life-phase of an automobile made from different materials. Also, sensitivity analysis was performed to examine the effect of changing some LCA parameters on the overall life cycle energy and CO_2 emission impacts; sensitivity analysis results show that fuel economy has the greatest impact followed by travelled distance and associated impacts from fuel resources and production. Additionally, several opportunities were identified and highlighted through the manuscript to extend this type of life cycle analysis methodology and assumptions beyond automotive components or structural materials.

CHAPTER FOUR

QUANTIFIABLE MEASURES OF SUSTAINABILITY: A CASE STUDY OF MATERIALS SELECTION FOR ECO-LIGHTWEIGHT BODY-IN-WHITE

This chapter proposes an eco-material selection approach based on a set of quantifiable measures for sustainability within the context of an automobile structure or Body-In-White (BIW). As the established sustainability model consists of both quantitative and qualitative factors, the qualitative factors were transformed into numerical values prior to perform materials selection process which was aided by decision-making/supporting tools namely; Preference Selection Index (PSI) and Principal Component Analysis (PCA). Both PSI and PCA avoid the bias that typically arises from assigning weights to different design attributes, as it is not necessary to assign a relative importance scheme between candidate materials. However, this study has the potential to present an objective selection scheme that balances the technological, economical, societal and ecological constraints of automobile bodies.

4.1. INTRODUCTION

Sustainable product development in the mobility sector is becoming an important research topic due to the fact that nowadays, 96% of the world's transportation systems depend on petroleum-based fuels and products. Such global transportation systems account for about 40% of the world's oil consumption of nearly 75 million barrels of oil per day (Mcauley, 2003). According to Curtis and Walker (2001) as well as Orsato and Wells (2007), design for sustainability is a holistic approach that involves balancing social, ethical and environmental issues alongside economic factors within the product or service development process. A typical hierarchal view for automotive sustainability is shown in Figure 2.3 (Mayyas et al., 2012). Curtis et al definition and figure 1 highlight the inherent complexity in sustainability accounting and tracking efforts, which have rendered most of the sustainability studies to be of qualitative nature. At the same time, several scholars proposed different sustainability monitoring indicators to evaluate the sustainable development state using matrix-based evaluations sustainability (Yang et al., 2009), a scoring method (Lee, 1998; Khan et al., 2004), and statistical methods (Janeš, 2011).

This chapter focuses on the use of multivariate statistical techniques as a material selection method because of its efficient display of the complex relationships among design variables and constraints. Multivariate statistical techniques, such as cluster analysis (CA), factor analysis (FA) and discriminant analysis (DA), are further able to process large datasets and mine any implicit knowledge or relationships to evaluate its sustainability characteristics (Böhringer and Jochem, 2007; Wang and Li, 2008).

This chapter starts by introducing some aspects of sustainability evaluation methods specifically; life cycle assessment, eco-material selection. Then, it introduces a design model for sustainable materials dedicated for an automobile body-in-white. Since this sustainability model is made up of qualitative and quantitative factors, section five discusses a methodology to translate these factors into quantifiable measures which, in turn, can be used to compute an overall sustainability score. Two scoring and ranking algorithms; namely preference selection index (PSI) and principal component analysis are used to obtain the relative ranks as well as the sustainability scores for candidate materials.

4.2. QUANTIFYING SUSTAINABILITY MEASURES

4.2.1. PREFERENCE SELECTION INDEX (PSI) METHOD

Most of multi-attribute decision making methods, used for material selection purposes, require the designer to assign relative importance or rankings between attributes. In PSI, it is not necessary to assign relative importance or priorities between material options or their attributes; however, the overall preference values of such attributes are calculated using simple statistics. Using overall preference value, by calculating a preference selection index (I_i) for each alternative with the higher PSI index value as deemed the best option. The detailed steps as described by Maniya and Bhatt (2010) for calculating the PSI is displayed in Fig. 4.1.

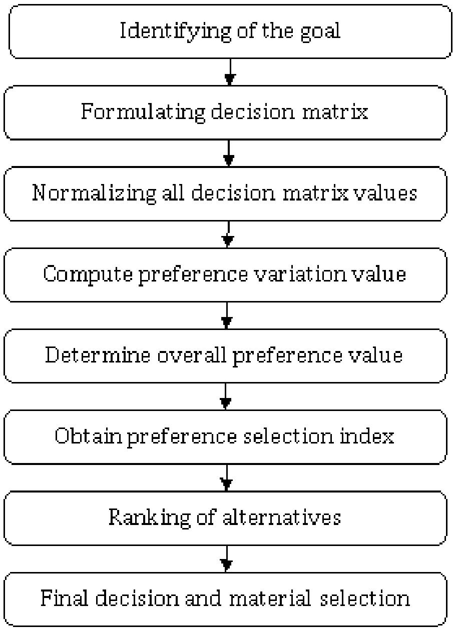


Figure 4.1: Preference selection index (PSI) algorithm.

The following specific steps describe the inner workings of the PSI method:

- *Step I*: Identifies the goal from the selection process; all of the material alternatives, selection criteria and its measures should be collected and tabulated.
- *Step II*: Formulating the decision matrix. The set of alternative; $A = \{A_i$ for $i = 1, 2, 3, \ldots, n\}$, and the set of selection criteria; $C = \{C_j$ for $j = 1, 2, 3, \ldots, m\}$, as well as performance of a given alternative A_i when it examined with respect to criterion C_j which is expressed as x_{ij}, all of these decision matrix entities should be represented in tabular format.
- *Step III*: Normalizing of the data attributes into a range of 0–1 in order to avoid any domination of large value attributes. Normalization of any attribute follows one of the following normalization methods based on the direction of improvement of that given

attributive. For example, if the expectancy is the-larger-the-better (e.g. profit), then the original attribute performance value can be normalized as follows:

$$R_{ij} = \frac{x_{ij}}{x_{j,max}} \tag{4.1}$$

If the expectancy is the-smaller-the-better (e.g. density), then the original attribute performance value can be normalized as follows:

$$R_{ij} = \frac{x_{j,min}}{x_{ij}} \tag{4.2}$$

where x_{ij} is the attribute measures ($i = 1, 2, 3, \ldots, N$ and $j = 1, 2, 3, \ldots, M$)

- *Step IV*: Computes the preference variation value (PV_j). In this step, preference variation value (PV_j) for each attribute is determined using the concept of sample variance analogy:

$$PV_j = \sum_{i=1}^{N} \left[R_{ij} - \bar{R}_j\right]^2 \tag{4.3}$$

$$\bar{R}_j = \frac{1}{N} \sum_{i=1}^{N} R_{ij} \tag{4.4}$$

- *Step V*: Determines the overall preference value (Ψ_j). In this step, the overall preference value (Ψ_j) is determined for each attribute. To get the overall preference value, it is required to find deviation (Φ_j) in preference value (PV_j) and the deviation in preference value for each attribute is determined using the following equation:

$$\Phi_j = 1 - PV_j \tag{4.5}$$

Where the overall preference value (Ψ_j) is determined using following equation:

$$\psi_j = \frac{\Phi_j}{\sum_{j=1}^{M} \Phi_j} \tag{4.6}$$

$$\sum_{j=1}^{M} \psi_j = 1 \tag{4.7}$$

- *Step VI*: Obtains the preference selection index (I_i) using the following equation:

$$I_i = \sum_{j=1}^{M} \left(R_{ij} \times \psi_j \right) \tag{4.8}$$

- *Step VII*: Ranks the alternatives based on the preference selection index (I_i) in ascending order to facilitate the managerial interpretation of the results.

4.2.2. PRINCIPAL COMPONENT ANALYSIS (PCA)

Principal component analysis (PCA) is one of the most valuable embodiments of applied linear algebra. PCA is widely used in all forms of analysis, from computer graphics to social studies, because it is simple, non-parametric method of extracting relevant information from large data sets. PCA is appropriate when someone has collected measures on a number of observed variables and wants to develop a smaller number of artificial variables (called principal components) that account for most of the variance in the observed variables. The number of components to be extracted in a principal component analysis is equal to the number of observed variables being analyzed. This means that a dataset of 9-variables would result in nine components. However, in most analyses, only the first few components account for significant amounts of variance, so only these first few components are retained, interpreted, and used in subsequent analyses and the remaining other components accounts for only trivial amounts of variance, which can be either grouped together or discarded. Also, PCA is considered as a variable reduction procedure, which makes it an efficient statistical method in reducing a complex data set to a lower dimension thus revealing knowledge or patterns that are often hidden in the data. In this case, PCA is useful when someone has collected a large dataset which contains large number of variables, and believes that there is some redundancy in this dataset. In this case, redundancy means that some of the variables are correlated with one another, possibly because they are measuring the same entity. However, this redundancy can be reduced to a smaller number of principal components that account for most of the variance in the observed variables (Holand, 2008).

Below is the general form for the mathematical formula that computes the scores on the first component as extracted in a principal component analysis;

$$PC_1 = b_{11}X_1 + b_{12}X_2 + \cdots + b_{1p}X_p \tag{4.9}$$

or, in matrix notation:

$$PC_1 = b_1^T X \tag{4.10}$$

Where, PC_1 is the score of principal component 1 (the first component extracted), and

b_{1p} is the regression coefficient (or weight) for observed variable p, as used in creating principal component 1, while

X_p is the score of observed variable p.

The first principal component is calculated such that it accounts for the highest possible variance in the data set. Under typical conditions, this means that the first component will be correlated with at least some of the observed variables. It may be correlated with many. Of course, one could make the variance of Y_1 as large as possible by choosing large values for the weights b_{11}, b_{12}, ... b_{1p}. To avoid this, weights are calculated with the constraint that their sum of squares equals 1; i.e.

$$b_{11}^2 + b_{12}^2 + \cdots + b_{1p}^2 = 1 \tag{4.11}$$

The second component extracted has two important characteristics: first, it accounts for the maximum amount of variance in the data set that was not accounted for by the first component, and also has a correlation with some of the observed variables that did not show strong correlations with the first component. Secondly, the second component is uncorrelated with the first component. Literally, if one wants to calculate the correlation between components 1 and 2, the correlation would be zero (Holand, 2008).

The remaining components that are extracted in the analysis have the same two characteristics; each component accounts for a maximal amount of variance in the observed variables that was not accounted for by the preceding components, and is uncorrelated with all of the preceding components. Principal component analysis proceeds in this fashion, with each new component accounting for progressively smaller and smaller amounts of variance (this is why only the first few components are usually retained and interpreted), when the analysis is complete, the resulting components will display varying degrees of correlation with the observed variables, but are completely uncorrelated with one another (Sharma, 1996; Hair et al., 2007).

The second principal component can be calculated in the same way, as in equation (4.12);

$$PC_2 = b_{21}X_1 + b_{22}X_2 + \cdots + b_{2p}X_p \tag{4.12}$$

This continues until a total of *p*-principal components have been calculated, equal to the original number of variables. At this point, the sum of the variances of all of the principal components will equal the sum of the variances of all of the variables; that means that all of the original information has been explained or accounted for. However, all of these transformations of the original variables to the principal components can be expressed as in equation (13);

$$PC = B.X \tag{4.13}$$

The rows of matrix *B* called the eigenvectors of matrix S_x, the variance-covariance matrix of the original data. The elements of an eigenvector are the weights b_{ij}, also known as loadings. The elements in the diagonal of matrix S_y, the variance-covariance matrix of the principal components, are known as the Eigenvalues. Eigenvalues are the variance explained by each principal component, and to repeat, are constrained to decrease monotonically from the first principal component to the last. These Eigenvalues are usually plotted on a scree plot to show the decreasing rate at which variance is explained by additional principal components (Sharma, 1996; Hair et al., 2007).

The positions of each observation in this new coordinate system of principal components are called scores and are calculated as linear combinations of the original variables and the weights a_{ij}. For example, the score for the r^{th} sample on the j^{th} principal component is calculated as in equation (14);

$$PC_{jr} = b_{j1}x_{j1} + b_{j2}x_{j2} + \cdots + b_{jp}x_{jp} \tag{4.14}$$

For interpretation of the principal components, it is important to know the correlations of the original variables with the principal components. The correlation of variable X_i and principal component PC_j is described in equation (15);

$$r_{ij} = \sqrt{\frac{a_{ij}Var(PC_j)}{s_{ii}}} \tag{4.15}$$

Because the goal of principal components analysis is to reduce the dimension of the dataset, focusing on a few principal components versus many variables, several rules have been proposed for determining how many PCs should be considered and how many can be ignored. One common rule is to ignore principal components at the point at which the next PC offers tiny increase in the total variance explained. A second rule is to only consider all PCs up to a predetermined total percent variance explained, usually 90% is used. A third rule is to ignore components whose variance explained is less than 1 when a correlation matrix is used or less than the average variance explained when a covariance matrix is used, with the idea being that such a PC offers less than one variable's worth of information. A fourth standard is to ignore the last PCs whose variance explained is all roughly equal (Holand, 2008; Sharma, 1996; Hair et al., 2007).

To get the final sustainability score of each variable (i.e. candidate material in this study), principal components that account for more than 90% of variability in data have been chosen and multiplied by their proportional Eigenvalues according to equation (4.16);

$$Z_x = \sum_{j=1}^{n} \lambda_{xj} \times PC_j \tag{4.16}$$

Where;

Z_x is the final score of variable x; λ_{xp} is proportional Eigenvalue ($\sum_{i=1}^{n} \lambda_{xj} = 1$); and PC_j is the j^{th} principal component.

4.3. RESULTS AND DISCUSSION

In any material selection process, the objective function is designed to select the material that fits the panel or structure functionalities while considering other factors such as environmental, economical (cost), and technical factors. Nowadays, most automotive OEMs still use steel in their vehicle's BIW because of its attractive properties..

The methodology used in the present study can be used at the conceptual design stage where a screening process is conducted to yield a set of candidate materials for a given body panel. This is achieved by employing both the PSI and the PCA calculations as decision-aid tools to benefit from their simplicity and their ability to rank choices in the order of their effectiveness in meeting design goals.

However, some sustainability factors are qualitative in nature, for example, materials are classified as having high, medium and low corrosion resistance; the same is true for fatigue resistance, and wear resistance. Also, societal factors (i.e. safety, and health and wellness) have no quantifiable measures and should be scaled to show the relative performance of the different materials; unless safety is assumed to be mainly governed by the yield strength and the material toughness. However health and wellness greatly depends on the vehicle emissions. For these reasons a scaling methods is used here to first quantify some of the descriptive sustainability factors; these factors where no mathematical objective function can be established. Scaling is considered as an acceptable tool to address qualitative aspects in many engineering applications and can be very valuable in communicating results or clarifying the relative importance and significance of different factors (Saur et al., 2000). As mentioned earlier in Table 2.6, the scaling method used to rate different engineering materials based on their performance with respect to each of sustainability factors, referring to Table 2.6, different ratings assigned for some durability, societal and technical factors based on (1-10) scale for a set of 21 candidate materials that are commonly used in automotive applications; these scores have been collected from different resources deal with eco-material selection (Mayyas et al., 2012, Mayyas et al., 2011, Davies, 2004, CES, 2008).

In this study, eight classes of engineering materials have been considered, namely: forming grade steels, advanced high strength steels, aluminum alloys, magnesium alloys, titanium, and carbon fiber reinforced plastics (CFRP), and glass fiber reinforced plastics (GFRP). Before performing PSI and PCA, normalization of all sustainability factors is performed in order to avoid domination of any sustainability factors with large values over the others that have lower values. Normalized material properties are shown in Table 4.1. Normalization method is based on the direction of improvement of the given factor as discussed earlier.

Table 4.1. Normalized values for all material properties used in establishing DFS

	General		Mechanical					Technical			Durability		Environmental				
Material properties and their Direction of improvement	**Density (g/cc)**	**Price ($/kg)**	**E Modulus (GPa)**	**YS (MPa)**	**UTS (MPa)**	**Shear modulus (GPa)**	**Total Elongation (%)**	**Formability**	**Joinability**	**Paintability**	**Heat Performance**	**Resistance to salt water**	**RDI**	**Water usage (L/kg)**	**Life cycle energy (MJ/kg)**	**Life cycle CO2 footprint (kg/kg)**	**Recycle fraction (ψ), %**
	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↓	↓	↓	↓	↑
Carbon steel AISI 1015 (as rolled)	0.20	0.74	1.00	0.17	0.23	1.00	0.98	1.00	1.00	1.00	1.00	0.75	0.00	1.00	0.68	0.72	0.95
Carbon steel AISI 1015 (annealed)	0.20	0.75	1.00	0.15	0.21	1.00	0.93	1.00	1.00	1.00	1.00	0.75	0.00	1.00	0.66	0.73	0.95
Carbon steel AISI 3140	0.20	1.00	1.00	0.24	0.38	0.98	0.63	1.00	1.00	1.00	1.00	0.75	0.00	1.00	0.66	0.73	0.95
Dual Phase steel 280/600	0.20	0.78	1.00	0.15	0.32	0.98	0.85	0.75	0.89	1.00	1.00	0.75	0.00	1.00	0.66	0.73	0.95
HSLA 462/524	0.20	0.95	1.00	0.25	0.28	0.98	1.00	0.88	0.89	1.00	1.00	0.75	0.00	1.00	0.66	0.73	0.95
Martensite steel 950/1200	0.20	0.70	1.00	0.51	0.65	0.98	0.18	0.50	0.78	1.00	1.00	0.75	0.00	1.00	0.66	0.73	0.95
Stainless steel AISI 201; Austenitic	0.20	0.14	0.94	0.46	0.61	0.95	0.38	0.63	0.78	0.89	1.00	0.75	0.00	0.20	0.58	0.60	0.95
Stainless steel, ferritic, AISI 405	0.20	0.26	0.95	0.12	0.24	0.96	0.53	0.63	0.78	0.89	1.00	0.75	0.00	0.20	0.69	0.73	0.95
Aluminum alloy AA5005	0.57	0.25	0.34	0.08	0.09	0.32	0.28	0.75	0.56	0.89	1.00	1.00	0.01	0.05	0.90	0.91	1.00
Aluminum alloy AA2424	0.56	0.31	0.33	0.04	0.10	0.33	0.50	0.88	0.56	0.89	1.00	1.00	0.01	0.05	1.00	1.00	1.00
Aluminum alloy AA6060	0.57	0.25	0.33	0.05	0.09	0.32	0.50	0.88	0.56	0.89	1.00	1.00	0.01	0.05	0.93	0.95	1.00
AZ61 Mg alloy	0.86	0.14	0.21	0.10	0.16	0.21	0.30	0.50	0.44	0.78	1.00	0.38	1.00	0.01	0.78	0.77	1.00
Mg-Li(12%) as cast	0.88	0.08	0.22	0.04	0.08	0.21	0.20	0.50	0.44	0.78	1.00	0.38	1.00	0.01	0.87	0.88	1.00
Ti/3Al/8V/6Cr/4Zr/4Mo	0.32	0.01	0.49	0.61	0.66	0.47	0.23	0.75	0.56	0.78	1.00	1.00	0.00	0.05	0.42	0.43	0.84
Epoxy-carbon fiber (SMC)	1.00	0.04	0.48	0.14	0.16	0.61	0.08	1.00	0.78	0.33	0.80	1.00	0.00	0.05	0.24	0.21	0.00
High strength carbon fiber/epoxy composite, 0°	1.00	0.02	0.67	1.00	1.00	0.06	0.03	1.00	0.78	0.33	0.80	1.00	0.00	0.05	0.24	0.21	0.00
High strength carbon fiber/epoxy composite,90°	1.00	0.02	0.04	0.02	0.02	0.06	0.01	1.00	0.78	0.33	0.80	1.00	0.00	0.05	0.24	0.21	0.00
High strength carbon fiber/epoxy, Isotropic	1.00	0.02	0.26	0.16	0.16	0.25	0.01	0.88	0.78	0.33	0.80	1.00	0.00	0.05	0.24	0.21	0.00
Epoxy-glass fiber (SMC)	0.94	0.16	0.10	0.08	0.10	0.10	0.03	1.00	0.78	0.33	0.30	1.00	0.00	0.22	0.24	0.21	0.01
High strength G-fiber (GF 40-60%)	0.87	0.04	0.19	0.38	0.38	0.20	0.06	0.75	0.78	0.33	0.40	1.00	0.00	0.22	0.24	0.21	0.01
S-Glass Fiber/Epoxy, 0/90° Biaxial Lamina (30-60%GF)	0.83	0.03	0.13	0.25	0.25	0.06	0.04	0.88	0.78	0.33	0.30	1.00	0.00	0.22	0.24	0.21	0.01

All corresponding calculations for PSI method like the values of preference variation (PV_j), overall preference values (Ψ) of attributes and overall preference selection index (I_i) are summarized in Table 4.2. Ranking of different alternatives based on descending order of preference selection index values (I_i) is shown in Table 4.3. PSI relative ranks show that high strength low alloy steel (HSLA 462/524) has the highest rank followed by annealed carbon steel (AISI 1015) in the second place and dual phase steel in the third place.

Table 4.2. Preference selection index calculations

Aspect	**Attribute**	$\bar{R}_j$	PV_j	**Φ**	**ψ**
General	Density (g/cc)	0.57	2.39	-1.39	0.07
	Price ($/kg)	0.33	2.62	-1.62	0.09
Mechanical	E Modulus (GPa)	0.56	2.77	-1.77	0.09
	YS (MPa)	0.24	1.14	-0.14	0.01
	UTS (MPa)	0.29	1.22	-0.22	0.01
	Shear modulus (GPa)	0.53	2.99	-1.99	0.11
	Total Elongation (%)	0.37	2.30	-1.30	0.07
Technical	Formability	0.82	0.64	0.36	-0.02
	Joinability	0.75	0.57	0.43	-0.02
	Paintability	0.72	1.67	-0.67	0.04
Durability	flammability	0.87	1.13	-0.13	0.01
	Resistance to salt water	0.85	0.78	0.22	-0.01
	Resistance to UV	0.96	0.07	0.93	-0.05
Environmental	RDI	0.10	1.80	-0.80	0.04
	Water usage (L/kg)	0.36	3.58	-2.58	0.14
	Life cycle Energy	0.56	1.42	-0.42	0.02
	Life cycle CO_2 footprint (kg/kg)	0.58	1.68	-0.68	0.04
	Recycle fraction (ψ), %	0.64	4.28	-3.28	0.17

Table 4.3. Ranking of candidate materials based on PSI

Material	Preference selection index (I_i)	Rank
Carbon steel AISI 1015 (as rolled)	0.910	3
Carbon steel AISI 1015 (annealed)	0.908	4
Carbon steel AISI 3140	0.884	5
Dual Phase steel 280/600	0.913	2
HSLA 462/524	0.920	1
Martensite steel 950/1200	0.870	6
Stainless steel AISI 201; Austenitic	0.594	8
Stainless steel, ferritic, AISI 405, wrought, annealed, low nickel	0.603	7
Aluminum alloy AA5005 ‡‡	0.383	13
Aluminum alloy AA2424 ‡‡	0.400	11
Aluminum alloy AA6060 ‡‡	0.399	12
AZ61 Mg alloy	0.422	9
Mg-Li(12%) as cast	0.405	10
Ti/3Al/8V/6Cr/4Zr/4Mo	0.320	14
Epoxy-carbon fiber (SMC)	0.197	15
High strength carbon fiber/epoxy composite, 0° unidirectional lamina	0.159	17
High strength carbon fiber/epoxy composite,90° unidirectional lamina	0.064	21
High strength carbon fiber/epoxy composite, Isotropic	0.118	20
Epoxy-glass fiber (SMC)	0.154	18
High strength glass fiber composite (GF 40-60%), unidirectional lamina	0.179	16
S-Glass Fiber/Epoxy Composite, 0/90° Biaxial Lamina (30-60%GF)	0.139	19

‡‡ Represents same Aluminum alloy with different tempers

The corresponding calculations for PCA method are summarized in Tables 4.4 and 4.5, where Table 4.4 shows the proportional Eigenvalues and their contribution in the final principal components (also see scree plot in Fig. 4.2); however, from the results shown in Table 4.4, it can be concluded that the first 5 principal components will account of ~93%

of the variability in data. Principal components shown in Table 4.5 represent linear combinations of input variables (i.e. sustainability factors).

Table 4.4. Principal component analysis results

	Eigenvalue	Proportion	Cumulative
PC1	8.9005	0.468	0.468
PC2	4.0333	0.212	0.681
PC3	2.2101	0.116	0.797
PC4	1.4369	0.076	0.873
PC5	1.1085	0.058	0.931
PC6	0.6349	0.033	0.964
PC7	0.2538	0.013	0.978
PC8	0.1859	0.01	0.988
PC9-PC20	0.1733	<0.01	1.00

Table 4.5. Principal components and their corresponding scores

Variable	PC1	PC2	PC3	PC4	PC5
Density	-0.321	-0.095	0.018	-0.059	0.069
Price	0.266	-0.219	0.167	-0.052	-0.18
Modulus of elasticity (GPa)	0.284	0.23	-0.016	-0.142	0.025
Yield Strength (MPa)	-0.024	0.348	-0.366	-0.033	-0.339
UTS (MPa)	0.034	0.346	-0.381	-0.069	-0.34
Shear modulus (GPa)	0.297	0.152	0.062	-0.138	0.117
Total Elongation (%)	0.29	-0.004	0.204	-0.033	0.143
Formability	-0.07	0.213	0.483	0.225	0.097
Joinability	0.111	0.331	0.399	-0.22	-0.022
Paintability	0.322	-0.102	-0.084	0.054	0.048
flammability	0.231	0.129	-0.06	0.534	-0.035
Resistance to salt water	0.168	0.342	-0.063	-0.097	-0.014
Resistance to UV	0.235	-0.051	-0.259	0.128	0.487
RDI	-0.145	0.209	0.203	0.58	-0.177
Water usage (L/kg)	-0.304	-0.039	0.022	-0.337	0.038
Life cycle energy (MJ/kg)	0.244	0.154	0.249	-0.281	-0.087
Life cycle CO2 footprint (kg/kg)	0.29	-0.191	-0.183	0.072	0.073
Recycle fraction (ψ)	0.198	-0.363	-0.017	0.012	-0.283

Equation 4.16 is used to get the final sustainability scores, then all of candidate materials are ranked based on a descending order of their sustainability scores (Z_x) as shown in Table 4.6. However, PCA relative ranks show that high strength low alloy steel (HSLA 462/524) has the highest rank followed by dual phase steel in the second place and rolled carbon steel (AISI 1015) in the third place. Interestingly, it has been found that the relative PCA ranks follow the PSI ranks with slight changes. Tables 4.3 and 4.6 show that the first six preferred choices are different grade of steels, which means that steel is still competitive from sustainability perspective. The second material group that likely to meet sustainability goals is stainless steel; however, aluminum and magnesium alloys get medium relative ranks. This means that aluminum and magnesium alloys have the ability to reduce energy and emissions during vehicle's use phase, but they are less preferable from economical and technical point of view. As expected, it can be said that the plastic reinforced composites are among materials that have lower relative scores; making them less preferable from the sustainability perspective due to their, high initial cost combined with almost zero recyclability as well as their low durability, these factors might restrict the consideration of plastic composites in automotive applications.

Finally, it can be said that both PSI and PCA have the ability to translate sustainability factors into the final product design through a ranking method. For example, the ranking results from PSI and PCA for best candidate materials, for body-in-white applications, show that the high strength steel grades are the best choice for replacing the current BIW mild steel bodies. Some deviations in the rank are found; however, the difference in the rank is rather nominal and does not affect the overall ranking of lightweight material candidates for BIW panels. This means that as more candidate materials are considered in the selection process, slight changes in the rank would arise due to the different algorithms used in the ranking method; PSI and PCA.

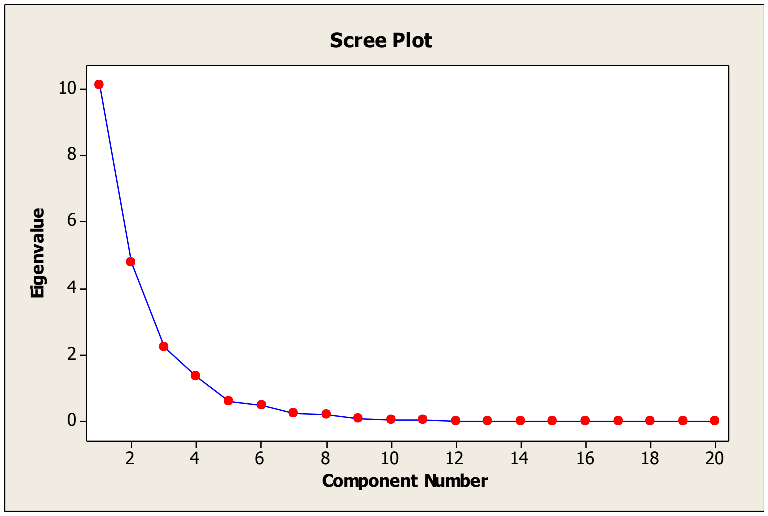


Figure 4.2: Scree plot of principal components showing all principal components and their Eigenvalue; also it can be seen that a tiny change in the Eigenvalues appears after the first four principal components.

Table 4.6. Overall sustainability score based on corresponding principal component scores

Material	PC1 score	PC2 score	PC3 score	PC4 score	PC5 score	Overall Sustainability Score	Rank
Carbon steel AISI 1015 (as rolled)	2.420	0.573	0.867	-0.273	0.016	1.334	2
Carbon steel AISI 1015 (annealed)	2.405	0.565	0.872	-0.270	0.020	1.326	3
Carbon steel AISI 3140	2.383	0.597	0.757	-0.285	-0.156	1.297	4
Dual Phase steel 280/600	2.395	0.505	0.653	-0.307	-0.058	1.275	5
HSLA 462/524	2.483	0.554	0.803	-0.314	-0.076	1.343	1
Martensite steel 950/1200	2.186	0.673	0.081	-0.346	-0.396	1.124	6
Stainless steel AISI 201; Austenitic	1.819	0.943	0.116	0.006	-0.172	1.055	8
Stainless steel, ferritic, AISI 405, wrought, annealed, low nickel	1.934	0.598	0.452	0.029	-0.040	1.084	7
Aluminum alloy AA5005	1.401	0.171	0.391	0.412	-0.212	0.757	12
Aluminum alloy AA2424	1.516	0.111	0.532	0.431	-0.253	0.814	10
Aluminum alloy AA6060	1.470	0.158	0.516	0.435	-0.192	0.804	11
AZ61 Mg alloy	0.884	0.150	0.382	1.069	-0.296	0.558	15
Mg-Li(12%) as cast	0.871	0.040	0.421	1.096	-0.340	0.533	16
Ti/3Al/8V/6Cr/4Zr/4Mo	1.299	0.994	-0.180	0.398	-0.139	0.821	9
Epoxy-carbon fiber (SMC)	0.803	0.899	0.450	0.209	0.346	0.656	13
High strength carbon fiber/epoxy composite, 0° unidirectional lamina	0.684	1.453	-0.234	0.175	-0.295	0.597	14
High strength carbon fiber/epoxy composite,90° unidirectional lamina	0.490	0.630	0.503	0.364	0.352	0.472	19
High strength carbon fiber/epoxy composite, Isotropic	0.617	0.780	0.344	0.265	0.270	0.531	17
Epoxy-glass fiber (SMC)	0.506	0.597	0.523	-0.021	0.303	0.440	20
High strength glass fiber composite (GF 40-60%), unidirectional lamina	0.603	0.825	0.173	-0.071	0.118	0.479	18
S-Glass Fiber/Epoxy Composite, 0/90° Biaxial Lamina (30-60%GF)	0.514	0.717	0.323	-0.051	0.201	0.438	21

4.4. SUMMARY

A design for sustainability model is proposed in this research from the material selection aspect, where the materials are selected to meet sustainability needs without compromising the structure functionality. Also, in the present study, the sustainability model is developed to include two ranking and evaluation methods; namely the preference selection index (PSI) and the principal component analysis (PCA). PSI and PCA are used to select and rank different candidate materials for the vehicle BIW panels based on their ability to meet sustainability requirements. Both PSI and PCA have a distinct advantage over other ranking methods because there is no need to consider any relative importance between attributes and design goals; hence the bias that is usually associated with other materials selection methods is eliminated. Another advantage of proposed selection approach is its ability to rank the candidate materials for any given application, even when large number of attributes is involved in the selection process.

From sustainability point of view, the current analysis reveals that different steel grades are still the best choice for BIW panels over other candidates, which explains the current OEMs focus on developing improved steel alloys and grades.

CHAPTER FIVE

ECO-MATERIAL SELECTION ASSISTED WITH DESIGN MAKING TOOLS, GUIDED BY PRODUCT'S ATTRIBUTES; FUNCTIONALITY AND MANUFACTURABILITY

This Chapter proposes an eco-material selection approach assisted with decision making tools namely; Analytical Hierarchy Process AHP and Quality Function Deployment QFD. The study derives the material selection indices for an automobile structural and closures' panels based on each panel; manufacturability, functionality requirements (load bearing characteristics). Additionally two constraints are mainly defined; the cost (economical aspect) and the environmental impact (using embodied energy and recyclability). The decision making tools prioritize the derived metrics based on current Original Equipment Manufacturers OEMs perspective. The developed approach is then applied to rank different light-weight material options for vehicular panels. This study has the potential to present a balanced scheme between technological, economic and ecological aspects of automotive Body in White BiW design, and to be implemented in a Life-Cycle Assessment LCA study.

5.1. INTRODUCTION

Material selection process is recently getting recognized as one of the major branches of the materials science and engineering discipline. Typical material selection process starts by considering all materials for a given application and ends by selecting the most appropriate one based on the application functionality and the design requirements. Professor Ashby from University of Cambridge is one of the first researchers who established roles of scientific based materials selection; however, his work in ranking and material spaces is considered pioneering in the field (Ashby, 2008). Among the different branches of material selection processes, green material selection and material selection for environment have been given more attentions for many reasons including high price rates of oil as well as impact of emissions on the local and global environment. Due to that fact, automotive industry in particular and transportation sector in general are focusing more on using environment-friendly lightweight materials to replace conventional steel in vehicles. For example, the transportation sector in United States is responsible for two-thirds of total petroleum consumption and about 60% of the nation's greenhouse gas emissions (GHG) (Cheah, 2010). Today, more concerns over energy security, and the impacts of global climate change are raised. One important and effective policy option is to raise the minimum standards for vehicle's fuel economy.

In the U.S., Corporate Average Fuel Economy (CAFE) program has enforced these standards since the late 1970s. The standard has remained mostly unchanged for the past three decades; however, recently rules have been issued in 2010. As shown in Figure 5.1, new passenger cars and light trucks, including sport utility vehicles (SUVs), pickups, and minivans, are now required on average to achieve at least 34.1 miles per gallon (MPG) by year 2016 (Cheah et al., 2010b). This adds more pressure on auto manufacturers in order to improve the fuel efficiency of their vehicles.

These standards will be applied to passenger vehicles, light-duty trucks, and medium-duty passenger vehicles, covering model years 2012 through 2016 (Cheah, 2010a). These standards also require all vehicles on the roads to meet an estimated combined average emissions level of 250 grams of carbon dioxide (CO_2) per mile in model year 2016, which equivalent to 35.5 miles per gallon (mpg) if the automotive industry were to meet this CO_2 level all through fuel economy improvements (Cheah et al., 2010b).

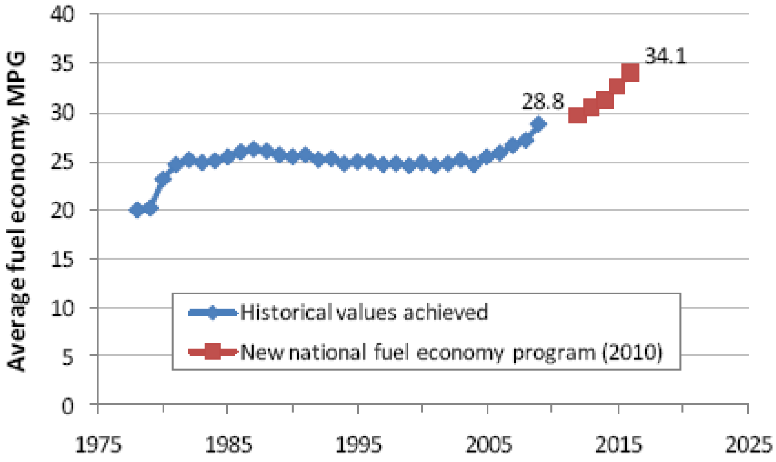


Figure 5.1: Average fuel economy of new U.S. light-duty passenger vehicles (Cheah, 2010)

Two scenarios can be followed to reduce vehicle weight; this can be achieved either by downsizing or using lightweight engineering materials. While size reduction is one known strategy to improve fuel economy in vehicles, and presents an opportunity to reduce fuel use from the transportation sector. By reducing the mass of the vehicle, the inertial forces that the engine has to overcome when accelerating are less, and the work or energy required to move the vehicle is thus lowered. However, significant improvements in vehicle efficiency in terms of the mile per gallon will require larger reductions in the vehicle weight. To quantitatively describe the relationship between the vehicle weight and its fuel efficiency, several correlations have been proposed in the literature and are listed through equations (1) to (3), which were obtained from (Omar, 2011):

$$MPG = 895.24\ (mass^{-0.463}) \tag{5.1}$$

$$MPG = 8627.4(mass^{-0.74584}) \tag{5.2}$$

$$mass = 2.015 \times FE^2 - 194.85 \times FE + 6375.54 \tag{5.3}$$

Where, the *MPG* is the mile per gallon and the *mass* is the curb weight in Lbs, while the *FE* is the fuel economy (MPG).

A general rule of thumb is that; for every 10% reduction in vehicle weight, the fuel consumption of vehicles is reduced by 5-7% (Mayyas et al., 2011, Omar, 2011).

In fact, the above mentioned reasons of using lightweight materials in automobile structures direct the development of a more quantitative material selection process which takes into consideration not only design requirements, but also environmental and economical aspects for the different vehicular structures and panels. However, Design For Sustainability (DFS) is the umbrella which covers all of the above mentioned economical, environmental, and design requirements.

On the other hand, Multi-Attribute Decision Making (MADM) tools have been widely used to address the vehicle body design, which usually compromise between conflicting objectives and many constraints. However, the integration of the material selection principles with decision making methods represents and advanced multi-attribute material selection method instead of dealing with only one objective at a time (Jee and Kang , 2000; Rao and Davim, 2008). This integration has resulted in new material selection disciplines including Sustainability Decision Support System (SDSS), Environmental Priorities System (EPS), and material selection using artificial intelligence methods (Rao, 2008; Mayyas et al., 2011; Manshadi et al., 2007).

Miller et al., (2005) used QFD to improve and optimize the vehicle body design of the vehicle door design. Other publication by Banu et al. (2006) utilized QFD to the design of car body structures to prioritize the impacts of design modifications on the customer satisfaction.

On the other hand, AHP among the other decision making methods present a distinct advantage of combining both qualitative and quantitative approaches (Chen et al, 2007). In the qualitative sense, AHP decomposes the design problem into a systematic decision hierarchy with different hierarchal levels that starts by objective function at the upper level, through more detailed branches which cover customer needs at the middle levels and design requirements at the lower level. It then uses a quantitative ranking using numerical ranks and weights in which a pair-wise comparison is employed to determine the priority weights and finally the overall ranking of proposed alternatives. Applications of AHP range from using it as a general tool to aid customer to priories his/her preferences as that one used by Byun et al. (2001) where they used AHP methodology to select the car model to purchase. However; the limitation of this paper comes from selection criteria which were basically focused on the customer needs more than on design and reliability. Hambali *et al.* (2009) proposed a concept selection model called Concurrent Design Concept Selection and Materials Selection (CDCSMS) to assist designers in selecting the most appropriate design concepts and materials for automotive composite components at the conceptual design stage using AHP. In this paper, eight design models of automotive composite bumper beams were considered and the most appropriate one was ultimately identified using the AHP process. Bovornsethanant and Wongwises in (2010) used two multi-attribute decision making tools, namely AHP and Vector Projection Approach (VPA) in order to determine the useful service life of lubricants; the VPA is a simple numerical approach based on trending all the model variables. In this study AHP was also used to analyze the variables and rank the final service life prediction. Another example of using QFD and AHP was discussed by Mayyas et al., (2011) where they used both QFD and AHP to rank different materials for automobile body-in-white panels. The selection method was based on ranking different engineering materials based on their abilities to meet design functions and meet satisfy customer needs.

However, these multi-attribute decision making tools considered as complimentary methods for determining how and where priorities are to be assigned in the product development. In fact, both QFD and AHP present tools that can be used in all engineering stages and mainly at the conceptual design stage.

This chapter focuses on some of the key sustainability issues facing the automotive industry and how these issues could influence future automotive design. To aid decision making at early design stages of body-in-white, this paper also focuses on the use of two specific decision making tools the Quality Function Deployment (QFD), and the Analytical Hierarchy Process (AHP). The ultimate goal of using QFD and AHP is to help designers in developing new or existing product by incorporating customer needs, into engineering characteristics of the product. By doing so, the planners can then prioritize each product attributes to set the levels needed to achieve such characteristics. In addition, this paper introduces the basics of material selection that incorporates sustainability requirements in its framework.

5.2. USING MULTI-ATTRIBUTE DECISION MAKING METHODS FOR MATERIAL SELECTION PURPOSES

5.2.1. QUALITY FUNCTION DEPLOYMENT (QFD)

In proposed material selection process, a set of objective functions for each panel is used to rank the different competitive materials in order to optimize the overall design.

First step in constructing QFD is to set all constraints to be used in the optimization method; the following constraint subsets were developed:

- Material constraints (e.g. modulus of elasticity, weight, strength, etc.)
- Environmental constraints (e.g. resource depletion, water usage, energy expenditures, CO_2 emissions, etc.)

- Economical constraints which mainly focus on cost associated with material extracting, material production and manufacturing.
- Technical constraints (e.g. formability, joinability, paintability, etc.).

Correlations among these constraints were developed and tabulated in the inter-relationship matrix which shows the relation between the engineering metrics and provides a complete view of how an increase in score of one of the metric might reflect in the others. In order to get this set of constraints, we can either use a relative score between 1 and 10 or just use the numerical equations (e.g. dent energy vs. thickness, strength vs. stiffness, etc.).

One of the merits of QFD over other decision making systems is that QFD provide flexible space for the designer to correlate both design needs and engineering metrics through assigning scores and weights for each, and at the same time it defines the direction of improvement for each metric, in other words there are some metrics that are directly proportional while others are inversely proportional.

However, for the QFD house to be established the design needs and engineering metrics should be first identified. Moreover, scores have to be assigned for each design need as well as for each design need- engineering metric entity, for instance a score of 10 will be assigned for dent resistance as a high valued design need for those panels that are prone to dent such as roof, the front and rear fenders, quarter panels, and door outers. Meanwhile lower dent resistance scores and higher bending stiffness scores are assigned to the A, B and C pillars due to the fact that they are not prone to dent, but they are structural panels which prone to bending. Table 5.1 illustrates the design needs and the associated scores for BIW panels as suggested by design team.

Table 5.1: Associated score of customer needs for BIW panels.

	Design Requirements												
BIW Panel	**Lightweight (Density)**	**Cost**	**Mechanical performance**	**Durability**	**NVH**	**Technical (manufacturability)**	**Life cycle energy impact**	**Life cycle emissions**	**Recycleability**	**Fuel economy**	**Dent resistance**	**Bending stiffness**	**Crashworthiness**
Roof	9	5	9	9	9	6	6	8	8	8	9	3	5
Hood (inner)	9	5	9	9	9	9	6	8	8	8	3	9	9
Hood (outer)	9	5	9	9	9	6	6	8	8	8	9	3	5
Trunk (inner)	9	5	9	9	9	9	6	8	8	8	3	9	9
Trunk (outer)	9	5	9	9	9	6	6	8	8	8	9	3	5
Trunk Pan	9	5	9	9	9	9	6	8	8	8	3	9	9
Engine Cradle	9	5	9	9	9	9	6	8	8	8	3	9	9
Strut Towers	9	5	9	9	9	9	6	8	8	8	3	9	9
Splash Wall	9	5	9	9	9	9	6	8	8	8	3	9	9
Quarter Panel	9	5	9	9	9	6	6	8	8	8	9	3	5
Front Fender	9	5	9	9	9	6	6	8	8	8	9	3	5
Door (inner)	9	5	9	9	9	9	6	8	8	8	3	9	9
Door (outer)	9	5	9	9	9	6	6	8	8	8	9	3	5
Wheel House	9	5	9	9	9	9	6	8	8	8	3	9	9
A B Pillars	9	5	9	9	9	9	6	8	8	8	3	9	9
Floor pan	9	5	9	9	9	9	6	8	8	8	3	9	9

5.2.1.1. QFD HOUSE CONSTRUCTION

For each BIW component, an independent QFD house was constructed and properly scored according to previously mentioned methodology as shown in Figure 5.2. Basically, QFD house consists of the following matrix elements:

1. Design needs or “what” window in Fig. 5.2. Design needs here represent OEM’s and their material selection perspectives.
2. Engineering requirements metrics or “How” window in the figure.
3. Weights for design requirements where scores (1 to 10) were assigned for each costumer need; however, score of 10 represents the most important criterion where the lower scores reflects less importance criterion (i.e. score of 1 is the least important need).
4. Design requirements versus engineering metric relationship scores, where scores (1 to 10) were used to define the relationship between the design needs and the engineering metrics according to the following scheme: 1 weak, 5 for medium and 10 for strong relationship specified by “relationship matrix”. Other scoring numbers are corresponding to intermediate values between weak-medium and medium-strong relationships.
5. Interrelationship between engineering metrics, symbols (-1, 0 and 1) define the interrelationship between the engineering metrics where score of -1 represents an inversely proportional relationship, 0 represents no relationship and 1 represents directly proportional relationship.
6. Direction of improvement to indicate whether the score defines the relationship between design needs and engineering metrics mentioned in part tow is being improved as the score increases or decreases.

7. At the bottom of house of quality under ‘Target block’ a set of metrics are tabulated to show QFD results like: raw score, relative weight, rank, technical requirement targets, technical rank.

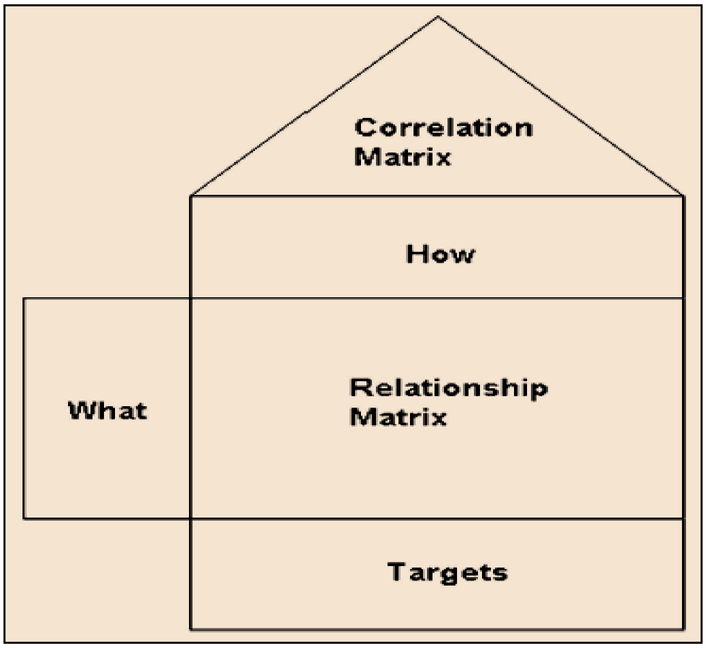


Figure 5.2. House of quality matrix diagram

5.2.1.2. QFD DECISION ALGORITHM

Figure 5.3 shows the structure of the QFD used in this study, which basically consists of two mating QFD’s. The first QFD is used to get the score of engineering factors ‘How’ based on the design requirements ‘What’, while the second QFD uses the outputs from the first QFD by transposing the engineering factors row in the first QFD to become ‘What’ column in the second QFD matrix in order to get the score of all candidate materials or what so called ‘How’ in the second QFD. The structure of the QFD consists of the following elements:

1. BIW panel to be studied.
2. Engineering factors or ‘How’ which were classified into five subgroups (general properties, mechanical properties, manufacturability, durability, and environmental factors).
3. Design needs or design objectives for that panel (i.e. ‘How’); however, some objectives function have to be minimized (e.g. density and cost) while others should be maximized (e.g. dent resistance and crash worthiness).
4. Direction of improvement which corresponds to the objective function itself (maximization functions were indicated by ↑, while minimization functions were indicated by ↓).
5. Weights assigned to each objective function; for example dent resistance of roof panel is more important than crash worthiness and so on for other functions.
6. Relationship matrix between design needs and engineering factors. The weight assigned to each entity is ranged between 0-10 depending on the relative influence of that engineering factor on the design need.
7. Outputs of QFD matrix which has four sub-elements: raw score, normalized score; relative weight and rank. Normalized score was calculate by dividing raw scores by the maximum score in that raw; while relative weights was calculated by dividing each normalized score by the summation of all scores in the same raw. Rank was calculated based on the normalized scores.
8. Correlation matrix for design needs vs. engineering factors.

9. Engineering factors that have been used in the first QFD; however, engineering factors now represent the ‘what’ in the second QFD.
10. Normalized weights which were calculated from the first QFD and stored in normalized score row.
11. Candidate materials.
12. Relationship matrix between engineering factors and candidate materials.
13. Second QFD matrix outputs.

The following is the summary of the QFD algorithm:

Let A_l be the design needs; l=1, 2, …..; B_m be sustainability factor; m=1,2, ….; and C_n is the candidate material; n=1,2, …..

Φ_j is the weight of the design requirements ($1 \leq \Phi_j \leq 10$)

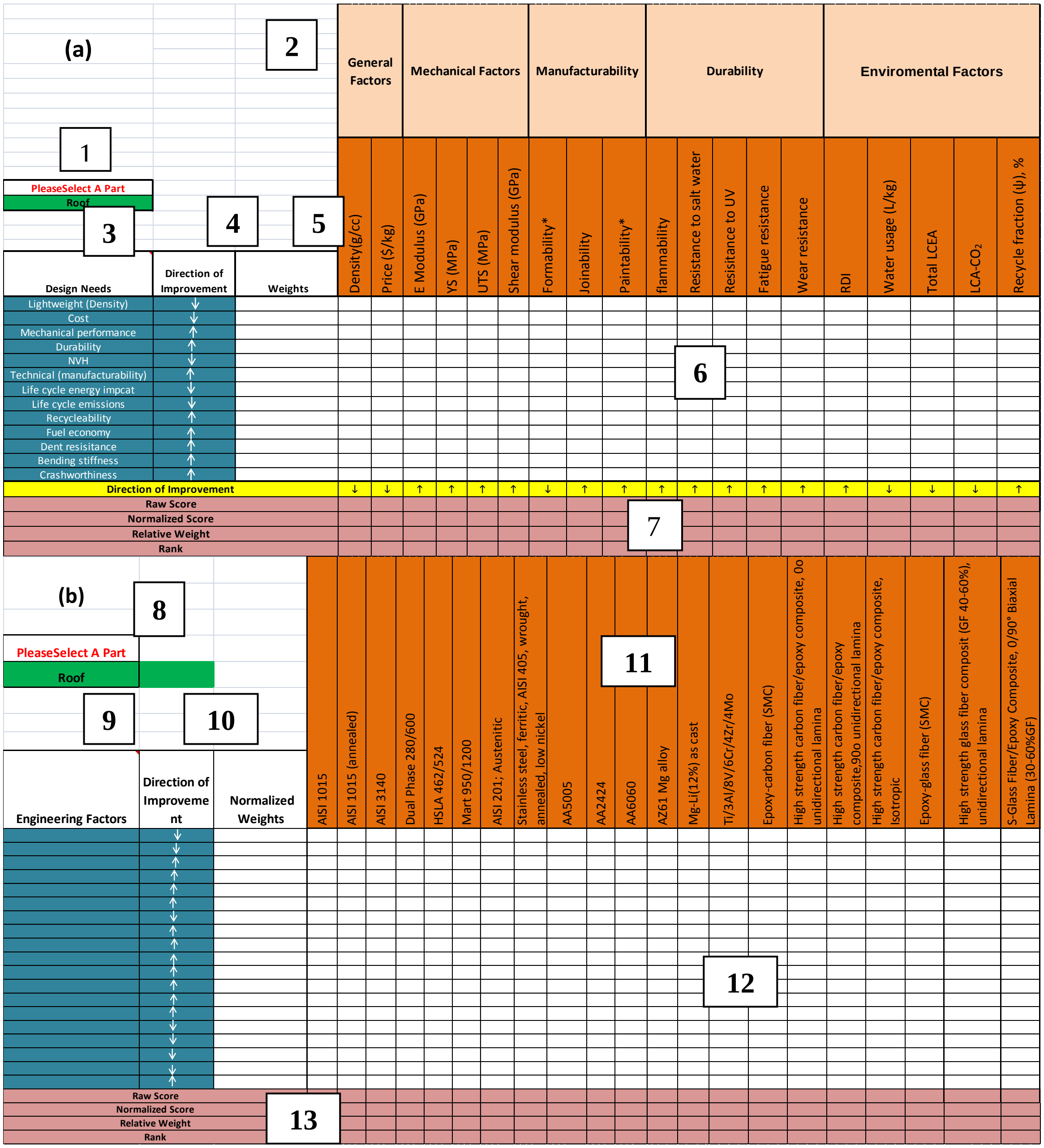
ω_{ij} is the weight of design need with respect to the given sustainability factor ($1 \leq \omega_{ij} \leq 10$).

The following are the calculations for elements 7 and 13:

$$Raw\ score; \alpha = \sum_{j=1}^{n} \omega_{ij} \times \Phi_j \tag{5.4}$$

$$Normalized\ score; \beta = \frac{Raw\ score}{\sum Raw\ score} = \frac{\sum_{j=1}^{n} \omega_{ij} \times \Phi_j}{\sum_{i=1}^{m} (\sum_{j=1}^{n} \omega_{ij} \times \Phi_j)} \tag{5.5.}$$

$$Relative\ weight; \gamma\ = \frac{Normalized\ score; j}{\sum Noramaalized\ score} = \frac{\beta_j}{\sum_{j=1}^{n} \beta_j} \tag{5.6}$$



(a)

PleaseSelect A Part

Roof

			General Factors		Mechanical Factors				Manufacturability			Durability					Enviromental Factors				
Design Needs	Direction of Improvement	Weights	Density(g/cc)	Price ($/kg)	E Modulus (GPa)	YS (MPa)	UTS (MPa)	Shear modulus (GPa)	Formability*	Joinability	Paintability*	flammability	Resistance to salt water	Resistance to UV	Fatigue resistance	Wear resistance	RDI	Water usage (L/kg)	Total LCEA	LCA-CO_2	Recycle fraction (ψ), %
Lightweight (Density)	↓																				
Cost	↓																				
Mechanical performance	↑																				
Durability	↑																				
NVH	↓																				
Technical (manufacturability)	↑																				
Life cycle energy impcat	↓																				
Life cycle emissions	↓																				
Recycleability	↑																				
Fuel economy	↑																				
Dent resisitance	↑																				
Bending stiffness	↑																				
Crashworthiness	↑																				
Direction of Improvement			↓	↓	↑	↑	↑	↑	↓	↑	↑	↑	↑	↑	↑	↑	↑	↓	↓	↓	↑
Raw Score																					
Normalized Score																					
Relative Weight																					
Rank																					

(b)

PleaseSelect A Part

Roof

Engineering Factors	Direction of Improvement	Normalized Weights	AISI 1015	AISI 1015 (annealed)	AISI 3140	Dual Phase 280/600	HSLA 462/524	Mart 950/1200	AISI 201; Austenitic	Stainless steel, ferritic, AISI 405, wrought, annealed, low nickel	AA5005	AA2424	AA6060	AZ61 Mg alloy	Mg-Li(12%) as cast	Ti/3Al/8V/6Cr/4Zr/4Mo	Epoxy-carbon fiber (SMC)	High strength carbon fiber/epoxy composite, 0o unidirectional lamina	High strength carbon fiber/epoxy composite,90o unidirectional lamina	High strength carbon fiber/epoxy composite, Isotropic	Epoxy-glass fiber (SMC)	High strength glass fiber composit (GF 40-60%), unidirectional lamina	S-Glass Fiber/Epoxy Composite, 0/90° Biaxial Lamina (30-60%GF)
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Raw Score																							
Normalized Score																							
Relative Weight																							
Rank																							

Figure 5.3. QFD structure

The advantage of the QFD comes from the ability of QFD to compute the rank of different selection criteria (i.e. design requirements) as well as the rank of all candidate materials through relating the interrelation scores and the engineering metrics scores.

However; the benefit of the returned rank is to guide the designer to the relative importance for all engineering metrics and candidate materials that meet design requirements.

5.2.2. ANALYTIC HIERARCHY PROCESS (AHP)

The Analytic Hierarchy Process (AHP) is a structured technique developed by Saaty in 1970s for dealing with complex multi-attribute decisions (Saaty, 1990). Nowadays, AHP and its refinements are widely used around the world in many decision making fields (education, psychology, industry, healthcare, etc.). In its basic, AHP is considered as a multi-attribute decision making tool that uses a systematic approach for comparing a list of objectives or alternatives.

Manufacturers must consider all mechanical, manufacturing and environment, economical and societal aspects to ensure that their vehicles conform to sustainability requirements. By doing so, all materials are considered candidate for a given design if they meet the design requirements in the conceptual design stage.

The basic idea of AHP is to decompose the decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. Once the hierarchy is built, the DM evaluates the various elements of the hierarchy by comparing them to one another using pair-wise comparison methods (Byun, 2001).

AHP can be used as a decision making tool in the conceptual and embodiment design stages (Byun, 2001). The most efficient design attributes for different BIW panels have been determined based on the AHP results; because the selection decision is a multi-attribute problem, AHP is able to rank both the decision criteria and candidate materials as it will be discussed later. AHP methodology consists of many sequential steps arranged in a hierarchy. The first step in AHP is to identify the problem and determine its goal. The goal is “selecting the best material for a given BIW panel”. All major panels are considered in this paper (Table 1). The second hierarchy level contains the main selection criteria, which are developed by expert engineering team. Both the goal and selection criteria should be clearly stated and decision makers have to identify the factors or subcriteria affecting the selection process. The last hierarchy level consists of the candidate materials (Mayyas et al., 2011).

In making the comparisons, the DM can use both objective information about the elements as well as the subjective opinions about the elements’ relative meaning and importance. The AHP has the ability of converting qualitative-based evaluations to numerical values that are processed and compared over the entire range of the problem. A numerical weight or priority is then derived for each element of the hierarchy, which in turn allows incommensurable elements to be compared to one another in a rational and consistent way. At its final step, numerical priorities are calculated for each of the decision alternatives. These numbers represent the alternatives’ relative ability to achieve the decision goal.

The main steps in deploying AHP method can be summarized in the following steps (see Figure 5.4):

(a) Data collection; in this phase all required data to construct the model should be collected. Both numerical data and attributes can be used in this phase. However, attributes should be converted into numerical values based on a proper scaling or weighting method. This latter step is achieved by establishing a judging scale of each attribute and their impact on achieving ultimate goal. By doing so, all attributes can be examined and weighed by assigning them the following scoring scheme (e.g. very strong=9, strong=7; average=5; weak=3, and very weak=1)

(b) Model the problem as a hierarchy which should contain the decision goal in the upper level, the criteria for evaluating the alternatives in the second hierarchy level and the alternatives or candidates in the third hierarchy level. However, a more complex hierarchy can be constructed when dealing with more branched problem, by adding more hierarchy levels between criteria and subcriteria.

(c) Establish a pair-wise comparison between two elements at a time. Table 5.2 shows the scaling values that used by Saaty which is based on a scale between 1-10. This will result in a series of judgments that gives a prioritizing of all elements in lower levels of the hierarchy.

(d) Check the consistency of the judgments (weights) we assigned to all elements in the AHP. If the matrices in the AHP are inconsistent, the scores should be revised to get more accurate judgments; this can be achieved by revising pairwise comparison. Consistency index (C.I.) can be calculated using the following equation (Mayyas et al., 2011):

$$C.I. = \frac{\lambda_{\max} - n}{n - 1} \tag{5.7}$$

Where $\boldsymbol{\lambda_{max}}$ is the largest eigenvalue and $\boldsymbol{n}$ is the number of attributes in the square matrix.

However, the conclusion about the consistency of the matrix can be drawn from the consistency ratio (CR). CR is defined as the ratio between C.I. and the random consistency index (RI), where RI was obtained from a large number of simulation runs and varies depending upon the order of matrix and has been tabulated in Table 5.3 (Mayyas et al., 2011):

$$CR = \frac{CI}{RI} \tag{5.8}$$

(e) Synthesize results to yield a set of overall priorities for the hierarchy; and finally

(f) Compute the final decisions based on the results of this process and select the alternative with the highest priority.

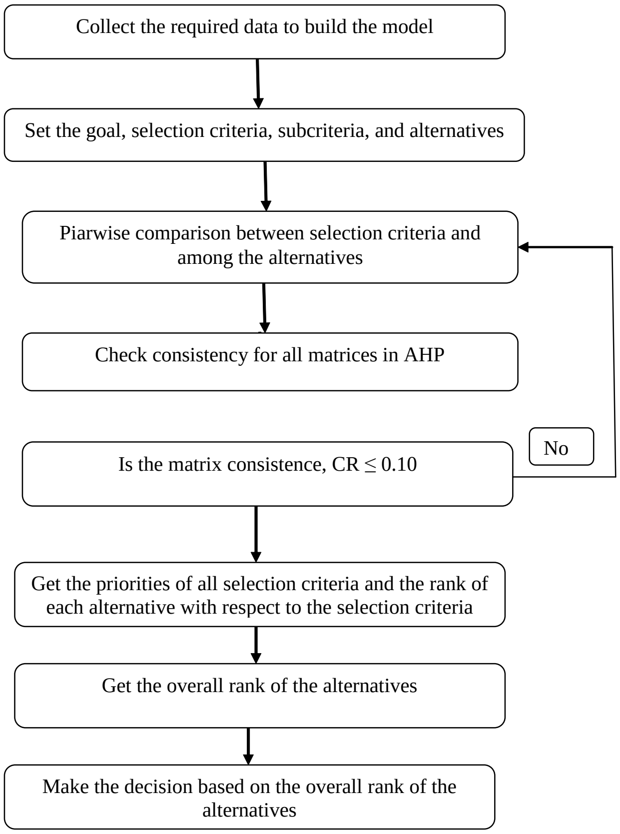


Figure 5.4: AHP algorithm

Table 5.2: Saaty rating scale for pairwise comparison (Saaty, 1990)

Value	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgment slightly favor one over the other.
5	Much more important	Experience and judgment strongly favor one over the other.
7	Very much more important	Experience and judgment very strongly favor one over the other. Its importance is demonstrated in practice
9	Absolutely more important.	The evidence favoring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed

Table 5.3: Random consistency index (Bayazit, 2005)

n	1	2	3	4	5	6	7	8
R.I.	0	0	0.52	0.89	1.11	1.25	1.35	1.4

5.3. RESULTS AND DISCUSSION

In any material selection process, the objective function aims to select the material that fits the panel or structure functionalities taken into consideration other environmental, economical, and technical factors. Nowadays, most automotive OEMs still use steel in their vehicle's BIW because of its attractive properties, cost and ability to meet design functionality. Typically a conventional stamped steel sheet is widely used for automotive BIW applications in a typical family vehicle (Omar 2011; Mayyas et al., 2011).The arising question now, what is the possibility of replacing steel while keeping the functional requirements? Some panels are not subjected to sever environments rather they are subjected to heavy loads (e.g. trunk lid and outer door panel) (Davies 2004)

The methodology used in the present study can be used at the conceptual design stage where a screening process takes place to come up with a set of best material for a given panel of BIW. This can be achieved by utilizing both the QFD and the AHP as decision-aid tools that combine both simplicity and ability to rank choices in the order of their effectiveness in meeting the objective.

Eight classes of engineering materials have been considered in this study, namely: forming grade steels, advanced high strength steels, aluminum alloys, magnesium alloys, titanium, and carbon fiber reinforced plastics (CFRP), and glass fiber reinforced plastics (GFRP). Normalized method for different material properties is discussed in chapter four, while all normalized values are tabulated in Table 4.3.

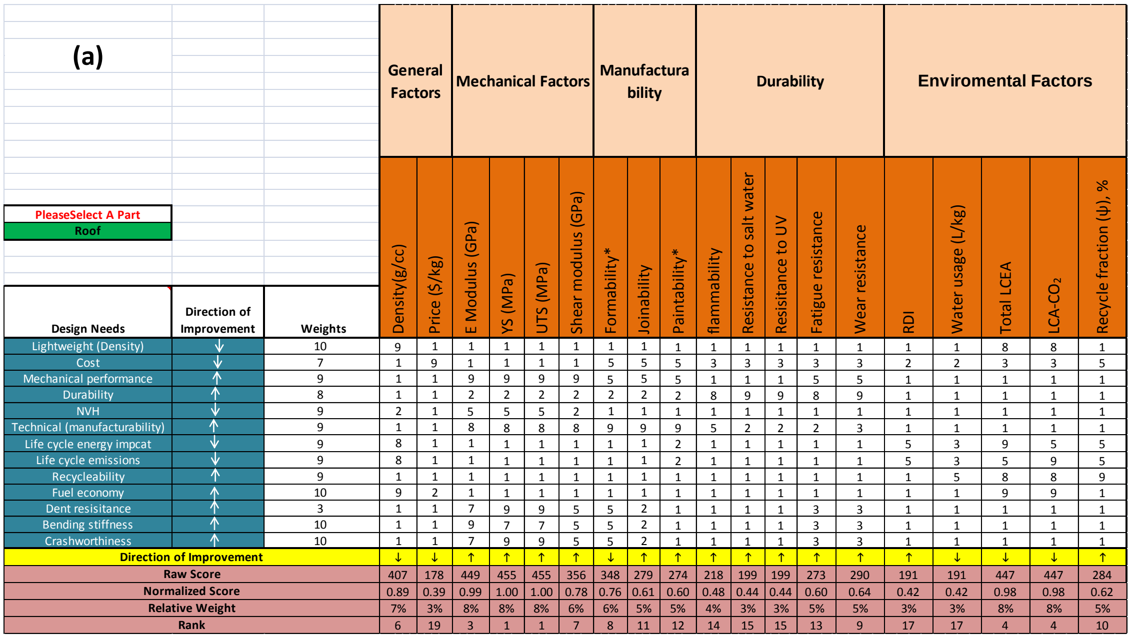
5.3.1. BEST MATERIAL SELECTION USING QFD

Subsequent to determination of the technical rank for all engineering metric without scarifying the customer voice (design requirements), it is more effectual to prioritize the candidate materials in the material space for each BIW component. Recalling that for each BIW component there is a need to specify the most and least engineering metric, so for each part, the results of corresponding QFD are pulled out and the values of the properties for every candidate material in the material space is recorded. Consequently, the material selection table is constructed based on the returned scores from the QFD house for each BIW component as displayed in Figure 5.4.

5.3.2. BEST MATERIAL SELECTION USING AHP

Nowadays, the majority of manufacturers are considering the selection criteria beyond the range of physical and mechanical properties on which old selection method is based (Roth et al., 2001; Fuchs et al., 2008). However, the legislative requirements concerning, for instance, emissions and end-of-life (ELV) disposal are now influencing the initial choice of material, and increasingly the process chain or successive stages (Das, 2000).

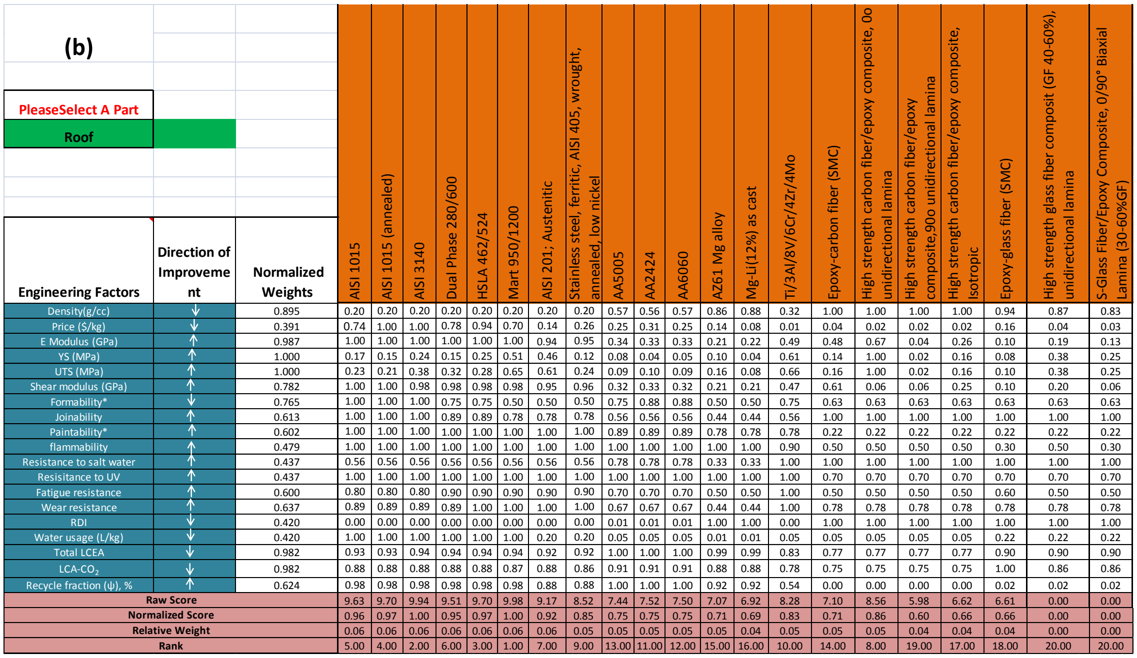
In fact, The most critical and time consuming task is the pair-wise comparison, which begins by comparing the relative importance of the two selected items at a time and it ends with a complete comparison matrix, however, this matrix must be consistent to be used in the next steps. Figure 5.5 shows all of the pair-wise comparison and relative importance values assigned to the selection criteria of roof material. This relative importance is then translated into numerical values and incorporated in the AHP.



(a)

PleaseSelect A Part
Roof

			General Factors		Mechanical Factors				Manufacturability			Durability					Enviromental Factors				
Design Needs	Direction of Improvement	Weights	Density(g/cc)	Price ($/kg)	E Modulus (GPa)	YS (MPa)	UTS (MPa)	Shear modulus (GPa)	Formability*	Joinability	Paintability*	flammability	Resistance to salt water	Resisitance to UV	Fatigue resistance	Wear resistance	RDI	Water usage (L/kg)	Total LCEA	LCA-CO_2	Recycle fraction (ψ), %
Lightweight (Density)	↓	10	9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	8	8	1
Cost	↓	7	1	9	1	1	1	1	5	5	5	3	3	3	3	3	2	2	3	3	5
Mechanical performance	↑	9	1	1	9	9	9	9	5	5	5	1	1	1	5	5	1	1	1	1	1
Durability	↑	8	1	1	2	2	2	2	2	2	2	8	9	9	8	9	1	1	1	1	1
NVH	↓	9	2	1	5	5	5	2	1	1	1	1	1	1	1	1	1	1	1	1	1
Technical (manufacturability)	↑	9	1	1	8	8	8	8	9	9	9	5	2	2	2	3	1	1	1	1	1
Life cycle energy impcat	↓	9	8	1	1	1	1	1	1	1	2	1	1	1	1	1	5	3	9	5	5
Life cycle emissions	↓	9	8	1	1	1	1	1	1	1	2	1	1	1	1	1	5	3	5	9	5
Recycleability	↑	9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	8	8	9
Fuel economy	↑	10	9	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	9	9	1
Dent resisitance	↑	3	1	1	7	9	9	5	5	2	1	1	1	1	3	3	1	1	1	1	1
Bending stiffness	↑	10	1	1	9	7	7	5	5	2	1	1	1	1	3	3	1	1	1	1	1
Crashworthiness	↑	10	1	1	7	9	9	5	5	2	1	1	1	1	3	3	1	1	1	1	1
Direction of Improvement			↓	↓	↑	↑	↑	↑	↓	↑	↑	↑	↑	↑	↑	↑	↑	↓	↓	↓	↑
Raw Score			407	178	449	455	455	356	348	279	274	218	199	199	273	290	191	191	447	447	284
Normalized Score			0.89	0.39	0.99	1.00	1.00	0.78	0.76	0.61	0.60	0.48	0.44	0.44	0.60	0.64	0.42	0.42	0.98	0.98	0.62
Relative Weight			7%	3%	8%	8%	8%	6%	6%	5%	5%	4%	3%	3%	5%	5%	3%	3%	8%	8%	5%
Rank			6	19	3	1	1	7	8	11	12	14	15	15	13	9	17	17	4	4	10

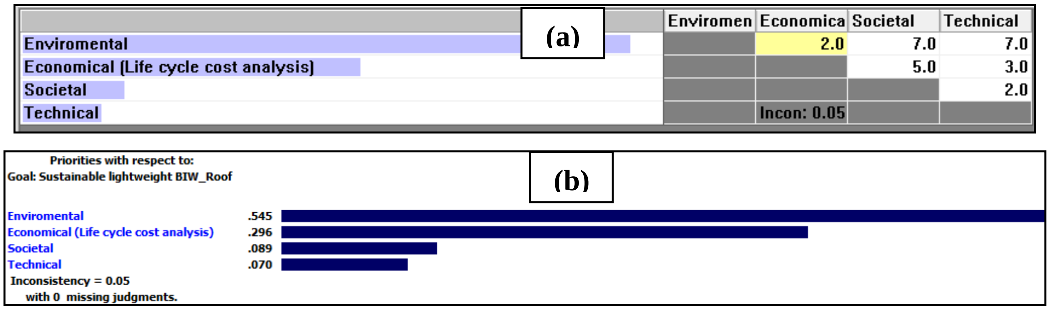

(b)

PleaseSelect A Part

Roof

Engineering Factors	Direction of Improvement	Normalized Weights	AISI 1015	AISI 1015 (annealed)	AISI 3140	Dual Phase 280/600	HSLA 462/524	Mart 950/1200	AISI 201; Austenitic	Stainless steel, ferritic, AISI 405, wrought, annealed, low nickel	AA5005	AA2424	AA6060	AZ61 Mg alloy	Mg-Li(12%) as cast	Ti/3Al/8V/6Cr/4Zr/4Mo	Epoxy-carbon fiber (SMC)	High strength carbon fiber/epoxy composite, 0o unidirectional lamina	High strength carbon fiber/epoxy composite,90o unidirectional lamina	High strength carbon fiber/epoxy composite, Isotropic	Epoxy-glass fiber (SMC)	High strength glass fiber composit (GF 40-60%), unidirectional lamina	S-Glass Fiber/Epoxy Composite, 0/90° Biaxial Lamina (30-60%GF)
Density(g/cc)	↓	0.895	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.57	0.56	0.57	0.86	0.88	0.32	1.00	1.00	1.00	1.00	0.94	0.87	0.83
Price ($/kg)	↓	0.391	0.74	1.00	1.00	0.78	0.94	0.70	0.14	0.26	0.25	0.31	0.25	0.14	0.08	0.01	0.04	0.02	0.02	0.02	0.16	0.04	0.03
E Modulus (GPa)	↑	0.987	1.00	1.00	1.00	1.00	1.00	1.00	0.94	0.95	0.34	0.33	0.33	0.21	0.22	0.49	0.48	0.67	0.04	0.26	0.10	0.19	0.13
YS (MPa)	↑	1.000	0.17	0.15	0.24	0.15	0.25	0.51	0.46	0.12	0.08	0.04	0.05	0.10	0.04	0.61	0.14	1.00	0.02	0.16	0.08	0.38	0.25
UTS (MPa)	↑	1.000	0.23	0.21	0.38	0.32	0.28	0.65	0.61	0.24	0.09	0.10	0.09	0.16	0.08	0.66	0.16	1.00	0.02	0.16	0.10	0.38	0.25
Shear modulus (GPa)	↑	0.782	1.00	1.00	0.98	0.98	0.98	0.98	0.95	0.96	0.32	0.33	0.32	0.21	0.21	0.47	0.61	0.06	0.06	0.25	0.10	0.20	0.06
Formability*	↓	0.765	1.00	1.00	1.00	0.75	0.75	0.50	0.50	0.50	0.75	0.88	0.88	0.50	0.50	0.75	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Joinability	↑	0.613	1.00	1.00	1.00	0.89	0.89	0.78	0.78	0.78	0.56	0.56	0.56	0.44	0.44	0.56	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Paintability*	↑	0.602	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.89	0.89	0.89	0.78	0.78	0.78	0.22	0.22	0.22	0.22	0.22	0.22	0.22
flammability	↑	0.479	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.90	0.50	0.50	0.50	0.50	0.30	0.50	0.30
Resistance to salt water	↑	0.437	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.78	0.78	0.78	0.33	0.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Resisitance to UV	↑	0.437	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Fatigue resistance	↑	0.600	0.80	0.80	0.80	0.90	0.90	0.90	0.90	0.90	0.70	0.70	0.70	0.50	0.50	1.00	0.50	0.50	0.50	0.50	0.60	0.50	0.50
Wear resistance	↑	0.637	0.89	0.89	0.89	0.89	1.00	1.00	1.00	1.00	0.67	0.67	0.67	0.44	0.44	1.00	0.78	0.78	0.78	0.78	0.78	0.78	0.78
RDI	↓	0.420	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Water usage (L/kg)	↓	0.420	1.00	1.00	1.00	1.00	1.00	1.00	0.20	0.20	0.05	0.05	0.05	0.01	0.01	0.05	0.05	0.05	0.05	0.05	0.22	0.22	0.22
Total LCEA	↓	0.982	0.93	0.93	0.94	0.94	0.94	0.94	0.92	0.92	1.00	1.00	1.00	0.99	0.99	0.83	0.77	0.77	0.77	0.77	0.90	0.90	0.90
LCA-CO_2	↓	0.982	0.88	0.88	0.88	0.88	0.88	0.87	0.88	0.86	0.91	0.91	0.91	0.88	0.88	0.78	0.75	0.75	0.75	0.75	1.00	0.86	0.86
Recycle fraction (ψ), %	↑	0.624	0.98	0.98	0.98	0.98	0.98	0.98	0.88	0.88	1.00	1.00	1.00	0.92	0.92	0.54	0.00	0.00	0.00	0.00	0.02	0.02	0.02
Raw Score			9.63	9.70	9.94	9.51	9.70	9.98	9.17	8.52	7.44	7.52	7.50	7.07	6.92	8.28	7.10	8.56	5.98	6.62	6.61	0.00	0.00
Normalized Score			0.96	0.97	1.00	0.95	0.97	1.00	0.92	0.85	0.75	0.75	0.75	0.71	0.69	0.83	0.71	0.86	0.60	0.66	0.66	0.00	0.00
Relative Weight			0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.04	0.05	0.05	0.05	0.04	0.04	0.04	0.00	0.00
Rank			5.00	4.00	2.00	6.00	3.00	1.00	7.00	9.00	13.00	11.00	12.00	15.00	16.00	10.00	14.00	8.00	19.00	17.00	18.00	20.00	20.00

Figure 5.5: **(a)** QFD matrix for design requirements vs. engineering metrics; and **(b)** QFD matrix for engineering metrics vs. candidate materials.



	Enviromen	Economica	Societal	Technical
Enviromental		2.0	7.0	7.0
Economical (Life cycle cost analysis)			5.0	3.0
Societal				2.0
Technical		Incon: 0.05		

Priorities with respect to:
Goal: Sustainable lightweight BIW_Roof

Enviromental	.545
Economical (Life cycle cost analysis)	.296
Societal	.089
Technical	.070

Inconsistency = 0.05
with 0 missing judgments.

Figure 5.6: **(a)** Pair-wise comparison between the main sustainability aspects (major selection criteria); and **(b)** Relative importance of these sustainability aspects.

The judgment values or ratings (Figure 5.6) are based on the expert's opinion and materials handbooks. The priority vectors and consistency test for the main criteria with respect to the goal are shown in Figure 5.5b. Taking the roof as an example, it can be shown that pair-wise comparison shows that environmental aspects are the most important selection criteria with priority vector (*p*) of 0.545, followed by economical aspects with priority vector of 0.296. The other two sustainability selection criteria for roof have relative priority values as follows: societal aspects (p=0.089), and technical aspects (p=0.070). However, these latter selection criteria have lower relative importance with ($p \leq 0.10$). This does not mean that these sustainability aspects are not considered in the selection, but they had low contribution levels in the roof selection attributes. The overall inconsistency was $0.05 \leq 0.10$, which means acceptable level of inconsistency.

The judgments for all levels are acceptable as CR was always kept less than 0.1. The ranking of the material alternatives for roof is shown in Figure 5.7. It shows that the Martenstic steel is the best candidate with a weight of 0.060 (6%) that satisfies the design requirements for roof material. The second choice is annealed steel AISI 1015 with a weight of 0.056 (5.6%), and the third choice is steel AISI 3140 with a weight of only 0.056 (5.6%). In fact different grades of steel get the highest ranks because they possess three main advantages: they have low relative cost and have lower environmental impacts (particularly embodiment and recycling phases), they are relatively easy to manufacture and they have good NVH and safety properties.

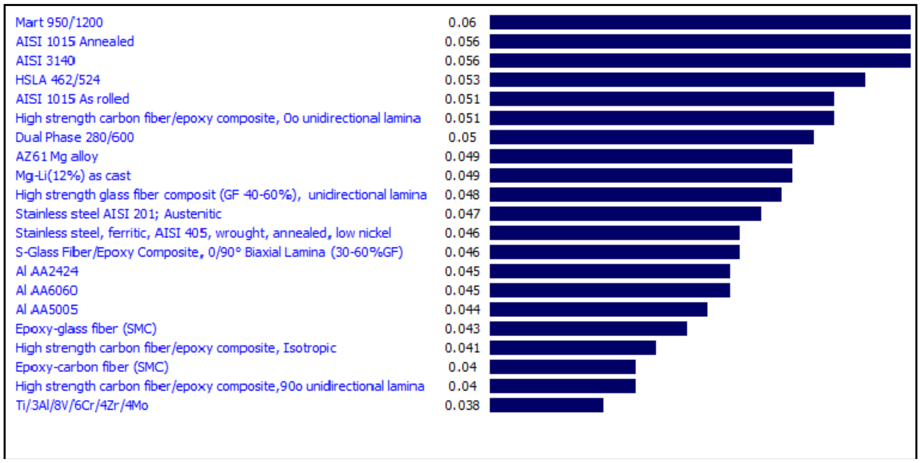


Figure 5.7: Final rank of candidate materials for roof panel

5.3.3. ADVANTAGES AND LIMITATIONS OF USING QFD AND AHP IN MATERIAL SELECTION

Mayyas et al. (2011) discussed the advantages and limitations of QFD and AHP when they used as tools that aid designers and decision makers during material selection and design processes. They showed that both QFD and AHP work well, but AHP has the ability to adjust its weights if any inconsistency is found more easily than QFD does. However, such inconsistency index could be used in QFD, even though no established role of this inconsistency index is present in the literature. Another advantage of AHP over QFD comes from the way of judging the alternatives; in AHP the pair-wise comparison between all of the selection criteria and candidate materials among themselves and among each other should be performed to get the final results. On the other hand, both QFD and AHP have the ability to translate design needs into the final product through ranking method (Mayyas et al., 2011; Byun, 2001).

For example, the ranking results of best materials for roof panel (see Table 5.4 for all BIW panels), show that the new steel grades are the best choice for replacing the current BIW mild steel bodies. Some deviations in the rank are found as in the material rank; however, the main difference is in the rank of the second and third choice. This means that as many candidate materials considered in the selection process, slight change in rank would arise due to weights assigned by different persons.

Table 5.4. Comparison between QFD and AHP results for materials selection for different panels

No.	**BIW Panel**	**QFD**			**AHP**		
		First choice	Second Choice	Third Choice	First choice	Second Choice	Third Choice
1	Roof	AHSS Mart. 950/1200	HSS AISI 3140	HSLA 462/524	AHSS Mart. 950/1200	HSS AISI 1015	HSS AISI 3140
2	Hood (inner)	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015	AHSS Mart.950/1200	HSS AISI 3140	HSS AISI 1015
3	Hood (outer)	AHSS Mart. 950/1200	HSS AISI 3140	HSLA 462/524	AHSS Mart.950/1200	HSS AISI 1015	HSS AISI 3140
4	Trunk (inner)	AHSS Martenistic 950/1200	HSS AISI 3140	HSS AISI 1015	AHSS Mart.950/1200	HSS AISI 3140	HSS AISI 1015
5	Trunk (outer)	AHSS Mart. 950/1200	HSS AISI 3140	HSLA 462/524	AHSS Mart.950/1200	HSS AISI 1015	HSS AISI 3140
6	Trunk Pan	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015
7	Engine Cradle	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015	AHSS Mart.950/1200	HSS AISI 3140	HSS AISI 1015
8	Strut Towers	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015	AHSS Mart.950/1200	HSS AISI 3140	HSS AISI 1015
9	Splash Wall	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015	AHSS Mart.950/1200	HSS AISI 3140	HSS AISI 1015
10	Quarter Panel	AHSS Mart. 950/1200	HSS AISI 3140	HSLA 462/524	AHSS Mart.950/1200	HSS AISI 1015	HSS AISI 3140
11	Front Fender	AHSS Mart. 950/1200	HSS AISI 3140	HSLA 462/524	AHSS Mart. 950/1200	HSS AISI 1015	HSS AISI 3140
12	Door (inner)	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015
13	Door (outer)	AHSS Mart. 950/1200	HSS AISI 3140	HSLA 462/524	AHSS Mart.950/1200	HSS AISI 1015	HSS AISI 3140
14	Wheel House	AHSS Mart. 950/1200	HSS AISI 3140	HSLA 462/524	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015
15	A B Pillars	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015
16	Floor pan	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015	AHSS Mart. 950/1200	HSS AISI 3140	HSS AISI 1015

5.4. SUMMARY

The proposed design for sustainability model is a holistic approach that covers major environmental, economical, societal and technical factors to come up with a material that can meet sustainability needs without compromising functionality of that part. However, and index-based DFS methodology presented in this paper is attractive framework which aids the designers to establish and then determine the best alternatives material for the BIW upon exploiting decision making systems like quality function deployment and analytical hierarchy process in the early design stages. An optimal index-based material selection process was proposed in this paper which accompanied with multi-attribute decision making methods to facilitate material selection for automotive body-in-white structures. As comprehensive tools, both QFD and AHP were used in order to rank different engineering materials for the BIW designs based on a complete DFS model. It was found QFD is a superior tool to decide on material selection for automotive body panel replacement for light weight BIW without scarifying the necessities of other design requirements. From sustainability point of view, the analysis reveals that different steel grades are still the best choices for BIW over the other candidates. However, other candidates might work in some cases, but in trade off cost, environmental impact or ease of manufacturing. Unsurprisingly, this tells us why majority of OEMs still consider steel as the main materials for their manufactured vehicles.

CHAPTER SIX

USING QUALITY FUNCTION DEPLOYMENT (QFD) AND ANALYTICAL HIERARCHY PROCESS (AHP) FOR MATERIAL SELECTION FOR BODY-IN-WHITE (BIW)

This chapter discusses the usage of multi-attribute decision making tools to assist in the material selection for vehicular structures mainly the automotive Body-in-White BIW panels at the conceptual design stage using Quality Function Deployment QFD and Analytical Hierarchy Process AHP.

The main advantage of using QFD and AHP is their abilities to rank choices in the order of their effectiveness in meeting the objective. AHP discriminates between competing options where interrelated objectives need to be met; AHP is based on straightforward mathematical formulations. QFD on other side is customer focused method that usually starts by collecting customer needs and tries to integrate these needs into the product. In this study, it was found that different grades of steel are still attractive and gained the first ranks for almost all panels in the BIW. Actually, this tells us that steel is the best, but other alternatives could work in trade-off with cost and manufacturability.

6.1. INTRODUCTION

New trends in vehicle light-weighting not only aim at enhancing the vehicle fuel efficiency, but also at improving its driving performance in addition to lowering its emissions (Fuchs et al., 2008). Weight saving might be achieved through replacing current high density materials such as Steel, in chassis and suspension, and other power-train and driveline vehicular sub-systems with lightweight to achieve small weight savings. However, significant improvements in vehicle efficiency in terms of the mile per gallon will require larger reductions in the vehicle weight.

The direct replacement of steel structures with other less dense materials has been the usual route for earlier light weight engineering efforts, especially using more Aluminum in the BIW. However this trend is challenged by the following; (a) the complexity associated in forming aluminum using the standard press based stamping, which limits the minimum bending radius to panel thickness ratio hence limiting the geometries and the vehicle styling. Even though some OEMs have used space frame platforms to facilitate the use of aluminum such the Audi A3 and the Rolls Royce, the space frame is not easily manufactured for high volume vehicles. (b) Aluminum is weaker than steel and its Young's modulus is almost 1/3 that of steel affecting its stiffness negatively. To provide a quantitative example, to replace a steel panel with aluminum while conserving the torsional stiffness of the panel requires the designers to match the panel thicknesses based on $\frac{t_{Al}}{t_{steel}} = \frac{E_{steel}}{E_{Al}} = 3$, which not only neutralizes the weight reduction achieved but also complicated the forming process. Still Additionally (c) the introduction of new steel grades with higher strengths leading to lesser thicknesses and hence lighter weight, such grades include; the High Strength Steel HSS such as the High Strength Low Alloy HSLA and the advanced High Strength Steel AHSS, which include; the Transformation Induced

Plasticity TRIP, Dual Phase DP steels. Lastly, the high cost of aluminum (almost 4 times that of mild steel) limits its wide use in vehicular structures.

Recently, automotive manufacturers have developed intensive aluminum vehicles with two competing designs: the conventional uni-body platform and the space frame. However, the space fame design cannot be applied readily for mass produced vehicles due to the high manual work-content associated with its joining process. Also the aluminum uni-body design is challenged in the stamping stage due to the aluminum lower formability, which restricts the aluminum usage to the flat to semi-flat panels such as the hood, the roof, and the deck lids.

However, aluminum is still far from being a material of choice for auto bodies. The substitution of aluminum for steel is partly influenced by regulatory pressures to meet fuel efficiency standards by reducing vehicle weight, and to give more advantages to the recycling standards. The main obstacles associated with using aluminum in such case are the high cost of primary aluminum as compared to steel and added manufacturing costs of aluminum panels. However, automotive industries are struggling to make aluminum a cost-effective alternative to steel (Roth et al., 2001).

The above mentioned facts about using aluminum in auto bodies leads us to discuss the role of material selection in engineering design. Material selection is now considering one of the major branches of the materials science and engineering. It starts by considering all materials and ends by selecting the most appropriate one based on the functionality of the application. Due to the fact that we encounter engineering design that have conflict objectives and multi-attribute problems, decision making methods start to take place more and more in this science. One of the interesting trends in material selection process is the integration of material selection principles with decision making methods. Among these methods, quality function deployment (QFD), analytical hierarchy process (AHP), Environmental Priorities System (EPS), Sustainability Decision Support System (SDSS), fuzzy logic, have been used widely for material selection and engineering design (Rao, 2008; Rao and Davim, 2008; Jee and Kang, 2008).

Decision making (DM) today is an important science, not in the management field only, but an all fields like engineering, quality monitoring, healthcare, and almost all other science fields. Making the right decision at the right time is still a major concern of all people who are dealing with all management levels starting from upper management (managers and directors) to lower management (e.g. machine operator in a factory). The ability to make a right decision at the right time will reflect in the future success of both person who took that decision and the enterprises.

The ultimate goal of using QFD is to help designers in developing a new or existing product or service by incorporating customer needs (the voice of the customer “VOC”) into engineering characteristics for a product or service. By doing so, the planners then can prioritize each product or service characteristic in order to set the levels to achieve these characteristics. However, QFD can be considered as a complimentary method for determining how and where priorities are to be assigned in product development. The intent is to employ objective procedures in increasing detail throughout the development of the product (Chen et al., 2006). Hence QFD presents as a tool that can be used in all engineering stages and mainly can be applied in the conceptual design stage.

A limited number of papers in the open literature discussed the using of QFD to improve and optimize body design of the car. Among these papers, QFD method in order to incorporate simple observations and electrical technology to improve the vehicle door design were used (Miller et al., 2005), which could significantly reduce the effort required in opening and closing the vehicle door. The objective of this work was to optimize customer comfort when opening and closing the door. The authors used different methods to incorporate the customer needs into new door design. They used a ranking method, morphological chart, and controlled convergence matrix to organize data.

On the other hand, Banu et al. 2006) applied QFD method to the design of bodywork (body car) in which QFD was applied in case to determine the priorities to be considered by the car makers in order to improve the customer satisfaction. By using QFD they determined the feasible improvement and proposed a base for other solutions.

Among other decision making methods AHP is the one we are going to use in this paper. AHP is being widely used in the decision-making analysis in various fields such as social, political, economic and management sciences. However, AHP has an advantage of combining both qualitative and quantitative approaches (Chen et al., 2007). In the qualitative sense, it decomposes an unstructured problem into a systematic decision hierarchy. It then uses a quantitative way using numerical numbers and weights in which a pair-wise comparison is being employed to determine the local and global priority weights and the overall ranking of the alternatives. Byun (2001) used AHP for selecting the car model to purchase. The selection criteria were basically focused on the customer needs more than on design and reliability. However, the proposed methodology is still attractive as the car market becomes more competitive and still there is a greater demand for innovation that provides better customer service and strategic competition in the business management. Hambali *et al.* (2009) proposed a concept selection model called concurrent design concept selection and materials selection (CDCSMS) to assist designers in selecting the most appropriate design concepts and materials for automotive composite components at the conceptual design stage using analytical hierarchy process (AHP). Eight design concepts of automotive composite bumper beam were considered in that study and the most appropriate one is determined by using the analytical hierarchy process (AHP). To get the final decision which reflects in a more robust design, they used the sensitivity analysis in order to study the effect of the different factors on deciding the best decision option. Bovornsethanant and Wongwises (2010) used AHP and Vector Projection Approach (VPA) to determine the useful life of lubricant in order to reach its maximum usefulness. Vector Projection Approach (VPA) is a simple numerical approach based on the trend of all model variables. However some variables have downward trend while some have upward trend. Their study approach started by collecting data that indicates deterioration of lubricant by increasing mileage which includes total base number, viscosity, iron and flash point. Then the data was analyzed by means of Analysis Hierarchy Process (AHP). After that, they used these variables to construct a model for calculating appropriate useful life of lubricant by using vector projection approach. It was found from this study that the defined mileage for changing lubricant, which is generally at 5,000 km, is not appropriate. Results of the study suggest that the most appropriate mileage for change of lubricant is at 12,000 km.

In this study, both QFD and AHP were used as decision supporting methods to direct the design team towards the best materials that compete steel. By doing so, the new multi-material BIW will be able to meet the functional requirement while try to reduce the vehicle weight as much as possible.

6.2. METHODOLOGY

6.2.1. QFD HOUSE CONSTRUCTION

For each BIW component, an independent QFD house was constructed and properly scored according to the previously mentioned methodology. The previously mentioned elements of QFD which shown in figures 5.5 and 5.6 were planned and deployed for each panel independently. It is important to mention that to fill in the cells of the QFD house is a complicated process and requires an expertise with an intensive knowledge to fill in these scores and weights (Chen et al., 2007), because a designer has to know what is the relationship between the customer needs and the engineering metrics, for example; someone has to know what are the relations between r-value as an engineering metric and the design requirements from one side, and the interrelationship between r-value and other engineering metrics like n-value, density, young’s moduli, etc.

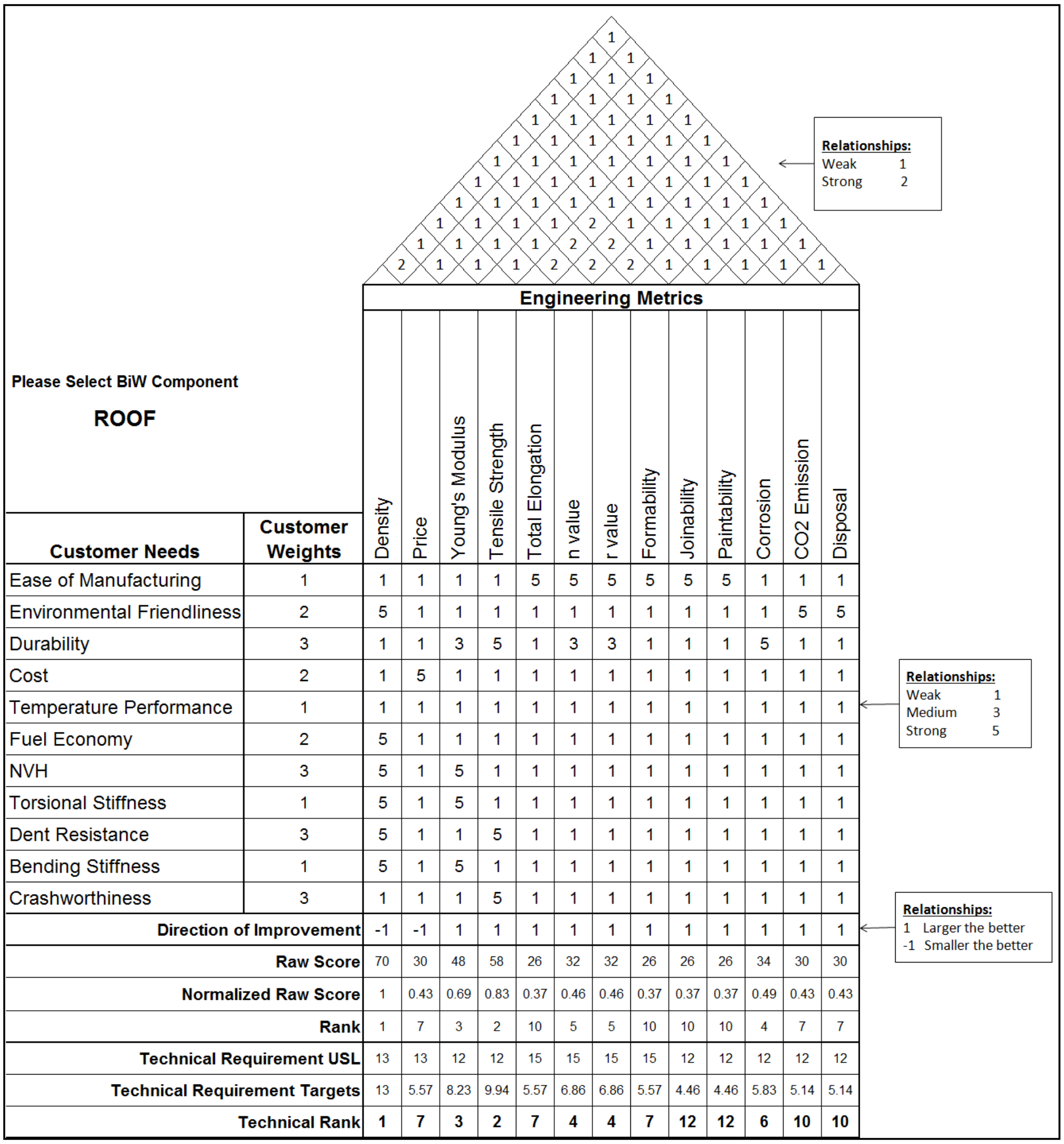
However, a detailed description for each of these elements and scores assigned using a scale of 1-3, are tabulated in Table 5.1.

6.2.2. QFD AND AHP DECISION ALGORITHMS

First of all; it is important to understand how the QFD algorithm does calculate the output results, in order for someone to pull out the results of the QFD for further process; which are turned out at the bottom rows in the QFD house. The following results are turned out by the QFD as shown in the bottom six raw in Fig. 6.1.

- Raw scores.
- Normalized raw scores.
- Rank.
- Technical requirements.
- Technical requirements targets.
- And, technical ranks.
- Initially, the raw scores were calculated as the sum of the product of the customer needs weights by the scores assigned for every engineering metric in the same row, see Fig. 6.1.
- Next was to normalize row scores by dividing every row score by the maximum score in the row, then relative weights were calculated by dividing each normalized score by the summation of all scores in the same row.
- Then the rank was calculated by prioritizing the previously calculated raw scores, however, this rank reflects only the importance of the engineering metrics. Nonetheless, in order to relate the costumer needs to the engineering metrics, QFD will return the USL (upper specification limit) which is nothing but technical requirements; the technical requirements define the engineering metrics

interrelationship. USL was calculated as sum product of the engineering metrics interrelation scores in the same raw.



Please Select BiW Component

ROOF

Customer Needs	**Customer Weights**	Density	Price	Young's Modulus	Tensile Strength	Total Elongation	n value	r value	Formability	Joinability	Paintability	Corrosion	CO2 Emission	Disposal
Ease of Manufacturing	1	1	1	1	1	5	5	5	5	5	5	1	1	1
Environmental Friendliness	2	5	1	1	1	1	1	1	1	1	1	1	5	5
Durability	3	1	1	3	5	1	3	3	1	1	1	5	1	1
Cost	2	1	5	1	1	1	1	1	1	1	1	1	1	1
Temperature Performance	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Fuel Economy	2	5	1	1	1	1	1	1	1	1	1	1	1	1
NVH	3	5	1	5	1	1	1	1	1	1	1	1	1	1
Torsional Stiffness	1	5	1	5	1	1	1	1	1	1	1	1	1	1
Dent Resistance	3	5	1	1	5	1	1	1	1	1	1	1	1	1
Bending Stiffness	1	5	1	5	1	1	1	1	1	1	1	1	1	1
Crashworthiness	3	1	1	1	5	1	1	1	1	1	1	1	1	1
Direction of Improvement		-1	-1	1	1	1	1	1	1	1	1	1	1	1
Raw Score		70	30	48	58	26	32	32	26	26	26	34	30	30
Normalized Raw Score		1	0.43	0.69	0.83	0.37	0.46	0.46	0.37	0.37	0.37	0.49	0.43	0.43
Rank		1	7	3	2	10	5	5	10	10	10	4	7	7
Technical Requirement USL		13	13	12	12	15	15	15	15	12	12	12	12	12
Technical Requirement Targets		13	5.57	8.23	9.94	5.57	6.86	6.86	5.57	4.46	4.46	5.83	5.14	5.14
Technical Rank		**1**	**7**	**3**	**2**	**7**	**4**	**4**	**7**	**12**	**12**	**6**	**10**	**10**

Figure 6.1: QFD house showing scores assigned for customer needs and ranking of other engineering metrics.

Though, the previous rank prioritize the engineering metric with respect to the values of its scores and scores of customer needs, the advantage of the QFD appeared in computing the technical rank through relating the interrelation scores and the engineering metrics scores, hence, targeted technical requirements was evaluated by product multiplication of the normalized raw score with its associated technical requirements (USL).

Then the technical requirements targets were prioritized to turn out what is called technical rank for every engineering metric, the technical rank prioritize all engineering metrics according to costumer point of view with a compromise of the technical requirements and interrelationship among all of these metrics, however, it is important to know that this technical rank prioritize the engineering metrics in ascending order. Of course ;(i.e. the higher the score the more important the engineering metric).

However; the returned technical rank will tell the designer the relative importance for all engineering metrics, in this paper top three metrics were considered in the analysis remembering that this decision does not conflict with the fact that for each part there a different functionality encircled by certain material properties, hence the relative scores were assigned for the engineering metrics based on its relative importance depending of the functional requirements of the part under consideration.

AHP algorithm as well as other parameters related to constructing and using AHP in material selection is presented in chapter four.

6.3. RESULTS AND DISCUSSION

In any material selection process, the objective function will try to select the material that fits the functions. However, most OEMs use steel in their vehicle’s BIW. Typically a conventional stamped steel sheet is widely used for automotive BIW applications in a typical family vehicle (Davies, 2003).The arising question now, what is the possibility of replacing steel while keeping the functional requirements? Some panels are not subjected to sever environments rather they are subjected to heavy loads (e.g. trunk lid and outer door panel).

The methodology used in the present study basically depends on the selection of the best material for a given panel of BIW at the conceptual design stage. Bothe QFD and AHP were used as decision-aid tools that combine both simplicity of use and ability to rank choices in the order of their effectiveness in meeting the objective.

Ten classes of engineering materials have been considered in this study, namely: forming bake hardenable steel (BH), dual phase steel (DP), high strength low alloy steel (HSLA), martenistic steel, aluminum 5xxx and aluminum 6xxx sheets, magnesium sheets, titanium sheets, carbon fiber reinforced plastic (CFRP) and high density polyethylene (HDPE). Material properties are shown in Table 6.1 while Table 6.2 summarizes the major functionality and selection criteria for realistic selection of BIW materials.

Table 6.1: Main criteria and ratings for realistic selection of automotive body materials (Davies, 2003).

Material	Design parameters					Ease of manufacturing			Environmental friendliness		Cost
	YS (MPa)	UTS (MPa)	A_{80} min%	E (GPa)	Density (g/cm^3)	Forming	Joining	Painting	CO_2 emission	Disposal	(forming steel =1)
Forming grade steel EN 10130 DCO4+Z	140	270	40	210	7.87	8	9	9	7	9	1
HSS EN 10292 H300YD+Z	300	400	26	210	7.87	6	8	9	8	8.5	1.1
UHSS-Martensitic	1150	1450	5	210	7.87	4	7	9	8	8.5	1.5
Aluminum 5xxx	110	240	23	69	2.69	6	5	8	9	9	4
Aluminum 6xxx	120	250	24	69	2.69	6	5	8	9	9	5
Magnesium sheets	160	240	7	45	1.75	4	4	7	9.5	6	4
Titanium sheet	880	924	5	110	4.5	6	5	7	9	6	60
GRP	950	400-1800	<2.0	40	1.95	8	7	8	8	5	8
Carbon fiber composite	1100	1200-2250	<2.0	120-250	1.60-1.90	8	7	8	9	5	50.0+

6.3.1. BEST MATERIAL SELECTION USING QFD

Subsequent to determination of the technical rank for all engineering metric without scarifying the costumer voice, it will be more effectual to prioritize the candidate materials in the material space for each BIW component.

Recall that for each BIW component there is a need to specify the most and least engineering metric, so for each part, the results of corresponding QFD were pulled out and the values of the properties for every candidate material in the material space was recorded, Table 6.3 and Table 6.4 illustrate some of material candidates in the material space with it corresponding properties and the normalized values of its properties, respectively.

Table 6.2: Decision criteria used in AHP.

Criteria	Subcriteria	Definition
Dent resistance	Yield strength (YS), panel thickness and panel stiffness.	It is important to avoid panel damage in-plant and minimize dents and dings on external parts in-service. Poor panel quality in used cars will generally depress resale values and possibly influence the decision to purchase a particular brand.
Ease of manufacturing	Forming Joining Painting	Optimize design, layout, and processing for the BIW panel to reduce variability and improve manufacturing parameters with the aim of increasing production rate and good quality of the end products. The main manufacturing processes for BIW are classified in three groups forming, joining, and painting.
Noise, vibration, harshness (NVH)		The main measure of NVH is the static and dynamic material stiffness. Static and dynamic stiffness are the measures of the ability of a material to withstand elastic deflections under static loading conditions and low-frequency vibrations under dynamic loading conditions.
Fuel economy	Density	The direct performance measure of this selection criterion is density of the chosen material. By doing so, magnesium and CFRP gain the highest rank while steel gets the lowest rank.
Cost	Material cost Manufacturing cost	The designers always look to cost as a major constraints in their selections, however, materials selection, design selection, and manufacturing process selection are important and need to be selected accordingly. In this study, design selection and its associated cost is beyond our goal is it includes many selection parameters.
Temperature performance		Not all materials would perform well at high temperature (e.g. plastic and CFRP), hence it is important to avoid the selection of these materials for high temperature applications like in splash wall. Also temperature performance reflects the performance of the candidate material in terms of thermal distortion and thermal conductivity.
Crashworthiness		The crashworthiness of the BIW structure is measured in terms of its ability to maintain a survivable volume for the passengers and minimization of the loads transmitted to the passenger compartment during potentially accident scenarios. Sometimes, impact toughness is used as a direct measure of this criterion.
Durability	Fatigue strength, Corrosion resistance, and Wear resistance	• Fatigue strength: a measure of the ability of a material to withstand high-cycle alternating loading without failing. • Corrosion resistance: a measure of the ability of a material to withstand the exposure to different chemical substances without suffering property degradation or failure. • Wear resistance: a measure of the ability of the material to resist scratch or material removal upon movement against harder materials
Bending stiffness		The resistance to bending is called the bending stiffness, per unit width, the bending stiffness depends on the modulus of elasticity ***E*** and thickness ***t*** of the panel
Torsional stiffness		The resistance of the panel to twisting, i.e. torsional stiffness which depends on the shear modulus ***G***, area ***A*** and the length ***L*** of the panel.

Table 6.3: Values of material candidates properties in the material space.

Material Properties	**Measurement Unit**	**Steel-BH**	**Steel-DP**	**Steel-HSLA**	**Steel-Martensite**	**Aluminum -5xxx**	**Aluminum -6xxx**	**Magnesium**	**Titanium**	**GFRP**	**HDPE**
Density	g/cc	7.87	7.87	7.87	7.87	2.7	2.7	1.75	4.5	1.9	1.59
Price	$/kg	0.78	0.99	0.82	1.1	3	3.85	3	46	6.24	40
Young's Modulus	Gpa	210	210	210	210	70	70	45	100	25	142
Tensile Strength	Mpa	320	600	524	1200	270	210	240	924	300	1730
Total Elongation	%	39	34	30	7	24	26	6	5	2	2
n value		0.2	0.21	0.14	0.07	0.33	0.3		0.086		
r value		1.7	1	1	0.9	0.8	0.61				
***Formability**		8	6	6	4	6	6	4	6	8	8
***Joinability**		9	8	8	7	5	5	4	5	7	7
***Paintability**		9	9	9	9	8	8	7	7	8	8
****Corrosion**		2	2	2	2	3	3	1	3	3	3
CO_2 Emission		8	8	8	8	9	9	9.5	9	8	9
*****Disposal**		8.5	8.5	8.5	8.5	9	9	6	6	5	5

*range 1=difficult to process, 10=few production problems; **3:Good, 2:Be Careful, 1: Not Useable
***10 = without difficulty, 1 = extensive development required

Table 6.4: Normalized values of material candidates properties in the material space

	Material Properties	**Direction of Improvement**	**Steel-BH**	**Steel-DP**	**Steel-HSLA**	**Steel-Martensite**	**Al-5xxx**	**Al-6xxx**	**Mg**	**Ti**	**GFRP**	**HDPE**
Normalization of Material Properties	Density	**-1**	1.0	1.000	1.000	1.000	0.343	0.343	0.222	0.572	0.241	0.122
	Price	**-1**	0.017	0.02	0.018	0.024	0.065	0.084	0.065	1.000	0.136	0.026
	Young's Modulus	**1**	1.0	1.00	1.000	1.000	0.333	0.333	0.214	0.476	0.119	0.004
	Tensile Strength	**1**	0.267	0.500	0.437	1.000	0.225	0.175	0.200	0.770	0.250	0.013
	Total Elongation	**1**	0.390	0.34	0.300	0.070	0.240	0.260	0.060	0.050	0.020	1.000
	n-value	**1**	0.606	0.64	0.424	0.212	1.000	0.909	===	0.261	===	0.036
	r-value	**1**	1.000	0.59	0.588	0.529	0.471	0.359	===	===	===	===
	Formability	**1**	1.000	0.75	0.750	0.500	0.750	0.750	0.500	0.750	1.000	1.000
	Joinability	**1**	1.000	0.89	0.889	0.778	0.556	0.556	0.444	0.556	0.778	0.778
	Paintability	**1**	1.000	1.00	1.000	1.000	0.889	0.889	0.778	0.778	0.889	0.889
	Corrosion	**1**	0.667	0.67	0.667	0.667	1.000	1.000	0.333	1.000	1.000	1.000
	CO_2 Emission	**1**	0.842	0.84	0.842	0.842	0.947	0.947	1.000	0.947	0.842	0.947
	Disposal	**1**	0.944	0.94	0.944	0.944	1.000	1.000	0.667	0.667	0.556	0.556

Then normalized material properties were multiplied by its relative technical score, the sum products of these multiplications were turned out scores that prioritize all material candidates in the material space for each part. As a final point, the QFD produced the best optimized material choice for each BIW part independently and based on customer demand and other engineering metrics. Table 6.5 illustrates sample calculation for some of such scores for some of the material candidates (the higher the score the better).

Consequently, the material selection table was constructed based on the returned scores from the QFD house for each BIW component as shown in Table 6.6, the first three choices were extracted from the QFD decision, the reason for that, the scoring assignment for both engineering metrics and customer weights may be biased towards one more than the other, which in turn will affect the QFD decision, however, one can manipulate these weights and scores to accommodate the customer demands and/or engineering requirements as will be discussed in the next section.

Relatively; the masses for parts of the new BIW were calculated in addition to the cost, weight, MPG, Added cost per weight saved, break even mileage, % change in demand and light weight index as it will be discussed in the next section.

The previous calculated results were contrasted with those of the base design, it is important to know that the base design was made out of cold rolled steel, and the minimum gage thickness added one more constraint to the process, i.e. if the new calculated thickness is less than the available gage thickness available in the market, then the available gage thickness will be considered in the calculations for the weight and other engineering indices.

Table 6.5: QFD based top three material candidates for the roof.

Engineering Metrics Rank	**1**	**2**	**3**	**Score**	**Rank**
Top 3 Engineering Metrics	Density	Tensile Strength	Young's Modulus		
Technical Targets	13	9.94	8.22		
Direction of Improvement	-1	1	1		
Steel-BH	1	0.267	1	**-0.068**	**10**
Steel-DP	1	0.5	1	**0.0064**	**6**
Steel-HSLA	1	0.437	1	**-0.0138**	**8**
Steel-Martensite	1	1	1	**0.1659**	**1**
Aluminum-5xxx	0.343	0.225	0.33	**0.0167**	**4**
Aluminum-6xxx	0.343	0.175	0.33	**0.0007**	**7**
Magnesium	0.222	0.2	0.21	**0.0276**	**3**
Titanium	0.571	0.77	0.476	**0.1328**	**2**
GFRP	0.241	0.25	0.119	**0.0105**	**5**
HDPE	0.122	0.0125	0.004	**-0.0459**	**9**

Table 6.6: New BIW QFD based design, first three choices

Part	**First Choice**	**Second Choice**	**Third Choice**
Roof	CFRP	Steel-Martensite	Steel-DP
Hood (inner)	CFRP	Steel-Martensite	Steel-DP
Hood (outer)	CFRP	GFRP	Aluminum-6xxx
Trunk (inner)	CFRP	Steel-Martensite	Steel-DP
Trunk (outer)	CFRP	Steel-Martensite	Steel-DP
Trunk Pan	CFRP	Steel-Martensite	Steel-DP
Engine Cradle	Steel-DP	Steel-BH	Steel-HSLA
Shock Towers	Steel-DP	Steel-BH	Steel-HSLA
Quarter Panel	CFRP	Steel-Martensite	Steel-DP
Front Fender	CFRP	GFRP	Aluminum-6xxx
Door (inner)	CFRP	Steel-Martensite	Steel-DP
Door (outer)	CFRP	Steel-Martensite	Steel-DP
Wheel House	CFRP	Steel-Martensite	Magnesium
A B Pillars	Steel-DP	Steel-BH	Steel-HSLA
Floor pan	CFRP	Steel-Martensite	Steel-DP

6.3.2. BEST MATERIAL SELECTION USING AHP

Nowadays, the majority of manufacturers are considering the selection criteria beyond the range of physical and mechanical properties on which old selection method was based (Davies, 2003). However, the legislative requirements concerning, for instance, emissions and end-of-life (ELV) disposal are now influencing the initial choice of material, and increasingly the process chain or successive stages. Manufacturers must consider all mechanical, manufacturing and environment aspects to ensure that minimum disruption is incurred which may have consequences in productivity and quality. By doing so, all materials are considered candidate for a given design if they meet the design requirements in the conceptual design stage. After that screening takes place in the embodiment design stage to remove materials that do not perform well from the selection list.

AHP was used as a decision making tool in the conceptual and embodiment design stages. The most efficient design attributes for different BIW panels have been determined based on the AHP results. Since that the selection decision is a multiattribute problem, AHP was able to rank both the decision criteria and candidate materials as it will be discussed later. The first step in AHP is to identify the problem and determine its goal. The goal was "selecting the best material for a given BIW panel". All major panels were considered in this study. The second hierarchy level contains the main selection criteria, which were developed by expert engineering team. Both the goal and selection criteria should be clearly stated and decision makers have to identify the factors or subcriteria affecting the selection process. The last hierarchy level consists of the candidate materials. Taking the roof as an example, we constructed the complete hierarchy layout using Expert Choice 11.5 software to construct and evaluate the hierarchy as shown in Fig. 6.2. The most critical and time consuming task was the pairwise comparison which begins with comparing relative importance of two selected items at a time and ends with a complete comparison matrix, however, this matrix must be consistent to be used in the next steps. Figure 6.3 shows all of the pairwise comparison values assigned to the selection criteria of roof material. This relative importance was translated into numerical values and incorporated in the AHP.

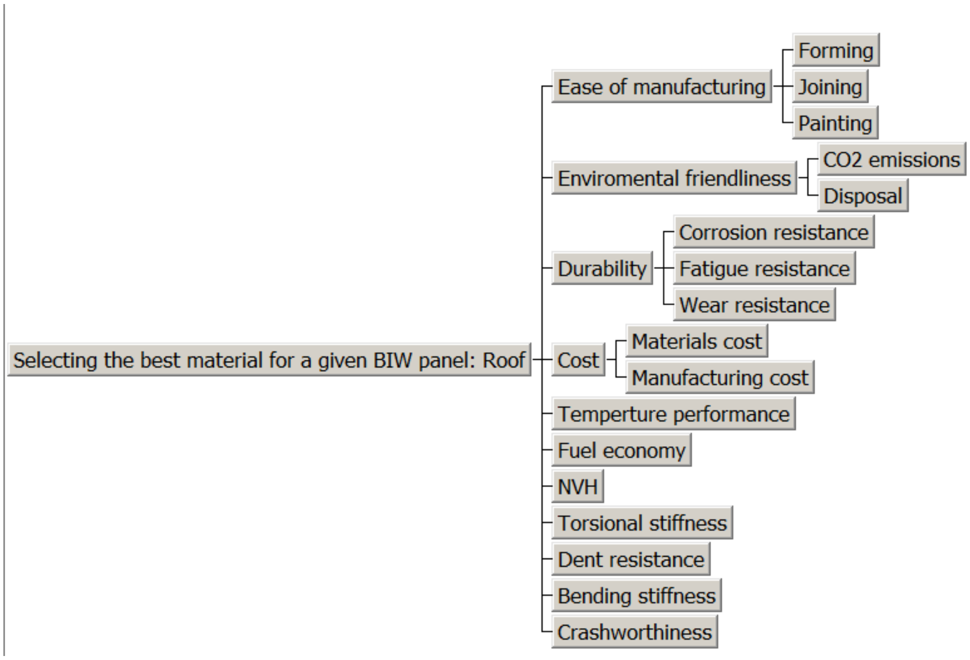
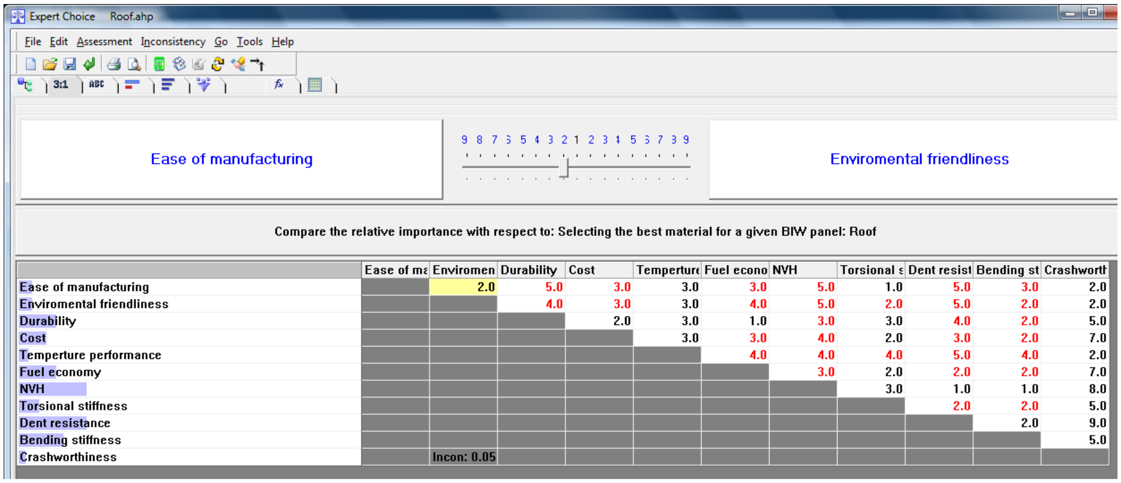


Figure 6.2: Hierarchal layout of the problem



Ease of manufacturing

Enviromental friendliness

Compare the relative importance with respect to: Selecting the best material for a given BIW panel: Roof

	Ease of ma	Enviromen	Durability	Cost	Temperture	Fuel econo	NVH	Torsional s	Dent resist	Bending st	Crashworth
Ease of manufacturing		2.0	5.0	3.0	3.0	3.0	5.0	1.0	5.0	3.0	2.0
Enviromental friendliness			4.0	3.0	3.0	4.0	5.0	2.0	5.0	2.0	2.0
Durability				2.0	3.0	1.0	3.0	3.0	4.0	2.0	5.0
Cost					3.0	3.0	4.0	2.0	3.0	2.0	7.0
Temperture performance						4.0	4.0	4.0	5.0	4.0	2.0
Fuel economy							3.0	2.0	2.0	2.0	7.0
NVH								3.0	1.0	1.0	8.0
Torsional stiffness									2.0	2.0	5.0
Dent resistance										2.0	9.0
Bending stiffness											5.0
Crashworthiness		Incon: 0.05									

Figure 6.3: Piarwise comparison between the main selection criteria.

The judgment values or ratings (Figure 6.3) are based on the authors' experience, experts opinion and materials handbooks. The priority vectors and consistency test for the main criteria with respect to the goal are shown in Figure 6.4. Taking the roof as an example, it can be shown that pairwise comparison shows that dent resistance is the most important selection criteria with priority vector (*p*) of 0.217, followed by NVH with priority vector of 0.179. Other important selection criteria for roof include fuel economy (*p*=0.139), cost (p=0.123), bending stiffness (*p*=0.094), durability (*p*=0.069), cost (*p*=0.077), and torsional stiffness (*p*=0.062). However, other selection criteria have lower relative importance with (*p*≤0.050). This does not mean that factors are not considered in the selection, but they had low contribution levels in the roof selection attributes. The overall inconsistency was 0.05≤0.10, which means acceptable level of inconsistency.

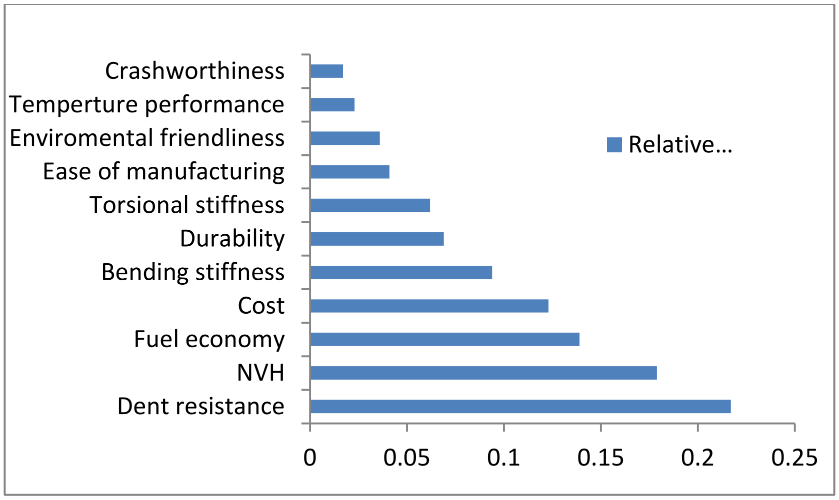


Figure 6.4: Rank of the selection criteria with respect to goal statement (CR=0.05).

Now, going deeper in the hierarchy, i.e. assigning values for subcriteria with respect to the main selection criteria. This process is greatly impact the overall results. For example, the ease of manufacturing has four subcriteria namely: yield strength, ultimate tensile strength, modulus of elasticity and impact strength. The authors assigned these criteria the same weights with respect to the main criteria (mechanical performance) as all of them have the same importance level in the conceptual and embodiment design stages. However, plastic will get the highest rating value in terms of ductility, but it has the lowest values of modulus of elasticity, yield strength and ultimate tensile strength when compared to other metals.

The judgments for all levels are acceptable as CR was always kept less than 0.1. The ranking of the material alternatives for roof is shown in Figure 6.5. It shows that the FRP would be best candidate -with a weight of 0.141 (14.1%)- that achieves the design requirements for roof material. The second choice was Ti with a weight of 0.134

(13.4%)-, and the third choice was martensitic steel -with a weight of only 0.124 (12.4%)- as it has three main advantages: it has low relative cost, it is relatively easy to manufacture and it has good NVH properties. The overall inconsistency was 0.04≤0.10, which means acceptable level of inconsistency.

Now, the following question may arise in this situation, why FRP got higher priority vector compared to Ti and steels? as we mentioned before the following main selection criteria (dent resistance, NVH properties, fuel economy and bending stiffness) shifted the priority vector of FRP and Ti to upper levels. On the other hand, HDPE was ranked sixth as polymers in general tend to have a greater rate of thermal expansion than steel, it is possible to have visual quality problems in terms of buckling, warping or uneven panel gaps. This expansion must be allowed for at the design stage – by appropriate design of the fixing method. Also, HDPE would not perform well in terms of durability as it becomes weak when exposed to UV light.

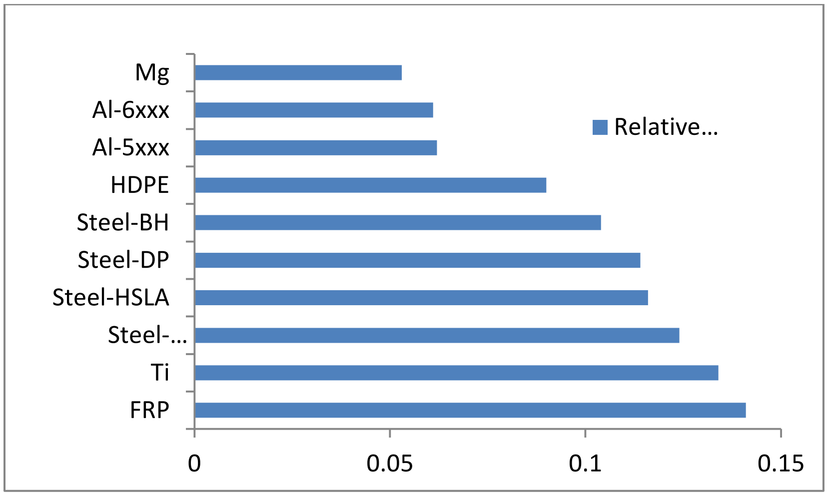


Figure 6.5: Final rank of the alternatives for roof (CR=0.04).

Similarly, all BIW panels have been subjected to the same selection process by keeping all matrices fixed except the ratings of the main criteria with respect to the goal. For example, in fender selection process we assigned more weights to dent resistance and less weight to temperature performance (Fig. 6.4). Table 6.7 summarizes the best three candidate materials for different BIW panels obtained from AHP. Again, different grades of steel remain the best choice for most applications, but other candidates could work.

Even though the new trends in lightweight design suggest using aluminum, magnesium and CFRP, the selection of these materials should take into consideration how to optimize material with regard to the chain of processing operations necessary to produce a functional part. However, most manufacturers are maintaining a conservative steel grade policy, requiring only minimal changes in the processes. Actually, the use of predominantly aluminum structures is only evident by one or two of the more adventurous companies who can absorb the extra supply and manufacturing costs (Davies, 2003). Thus, for the main BIW structure the increasing use of high strength steel will continue to develop and the trend for a typically progressive car manufacturer. However, a weight saving of 10–15% can be achieved from selective parts via thickness reduction (Davies, 2003).

Table 6.7. BIW major panels and the possible material candidates (AHP results)

Part	First Choice	Second Choice	Third Choice
Roof	FRP	Ti	Steel-Martensite
Hood (inner)	Steel-DP	Steel-Martensite	Steel-HSLA
Hood (outer)	FRP	Ti	Steel-Martensite
Trunk (inner)	Steel-DP	Steel-Martensite	Steel-HSLA
Trunk (outer)	FRP	Ti	Steel-Martensite
Trunk Pan	Steel-DP	Steel-Martensite	Steel-HSLA
Engine Cradle	Steel-Martensite	Steel-HSLA	Ti
Shock Towers	Steel-Martensite	Steel-HSLA	Ti
Quarter Panel	FRP	Ti	Steel-Martensite
Front Fender	FRP	Ti	Steel-Martensite
Door (inner)	Steel-DP	Steel-Martensite	Steel-HSLA
Door (outer)	FRP	Ti	Steel-Martensite
Wheel House	FRP	Ti	Steel-Martensite
A B Pillars	Steel-DP	Steel-Martensite	Steel-HSLA
Floor pan	FRP	Ti	Steel-Martensite

6.3.3. COMPARISON BETWEEN QFD AND AHP RESULTS

The comparison between QFD and AHP results shows that both tools work well, but AHP has the ability to adjust the weights if inconsistency found. However, such inconsistency index could be used in QFD, but no established role of this inconsistency is found in the literature. Moreover, AHP basically uses the pairwise comparison between all of the selection criteria and candidate materials among themselves and among each other. The good feature that makes QFD one of the best decisions supporting systems is the ability to translate customer needs into the final product. The ranking results of both tools show that different steel grades are the best choice for replacing the current BIW which is mainly made from forming grade steel. Some deviations in the rank were found as in the material rank, but the main difference was in the rank of the second and third choice. This means that as many candidate materials considered in the selection process, a slight change in rank would arise due to weights assigned by different persons. Another issue in using QFD is that no typical scaling has been established and anyone can use his own scale as in this study where we used a scale between 1-3. However, this will reflect in the results as this limits discriminating power of the QFD. This problem can be avoided by using a wide range scale (e.g. 1-10 scale as that one used in AHP). The bias arises when dealing with such tools can be avoided by establishing a customer-oriented questionnaire.

6.4. SUMMARY

The proposed model for exploiting decision making systems in the design process is an attractive procedure which aids the designers to determine the best alternatives material for the BIW in the early design stages. QFD was found to be a superior tool to decide on material selection for automotive body panel replacement for light weight BIW without scarifying the necessities of other customer needs as well as engineering requirements. As a comprehensive tool QFD was used in order to optimize the BIW designs based on a comprehensive methodology. However, AHP is a decision-making system which provides systematic selection method based on the selection criteria and subcriteria; also it gives numerical priority vectors of the candidates. The AHP analysis reveals that steel is still the best choice for BIW among the other candidates. However, other candidates might work in some cases, but in trade off cost or ease of manufacturing.

CHAPTER SEVEN

KNOWLEDGE BASED SYSTEM, EQUIPPED WITH CLUSTERING ANALYSIS FOR ECO-MATERIAL SELECTION, AN AUTOMOBILE STRUCTURE CASE STUDY

This chapter aims at developing a material selection framework structured around a Knowledge Based System (KBS). Specifically, a Hybrid Data-Mining (H-DM) is employed to extract knowledge from large datasets using clustering analyses techniques; the mind knowledge then serves as the inference logic within the Knowledge-Based System (KBS) designed for material selection purposes. The selection structure employs sustainable material indices. Additionally, the proposed KBS material selection model is purposefully composed of material sustainability, functionality and cost indices. The constructed knowledge is then demonstrated for selecting automobile structural panels.

7.1. INTRODUCTION

Knowledge is the most valuable asset of a manufacturing enterprise. Where it makes a firm differentiate itself from competitors and to be able to deal with all suppliers, competitors and customers in the market. Knowledge exists in almost all stages in manufacturing starting from purchasing materials, marketing, design, production, maintenance and distribution, but knowledge can be notoriously difficult to identify, capture, and manage (Harding et al., 2006).

Knowledge based systems is composed of several approaches and algorithms from database management, machine learning, statistics and artificial intelligence. The accelerated development of KBS motivates its deployment to process data in different fields such as in banking, finance, marketing, insurance, science, and engineering, etc. Specifically in manufacturing, Knowledge based systems are gaining wide acceptance and importance as it can provide significant competitive advantage over traditional analysis methods (Halevi, and Wang, 2007; Shehab and Abdalla, 2002).

The complexity of knowledge based systems is mainly dependent on the manufacturing process itself because it decides on the parameters used in building the database. Spiegler in (2003) differentiated between two models of knowledge; the first model is based on a conventional hierarchy and the transformation of data into information and knowledge with a spiral and a recursive way of knowledge generation; while the second model uses a reverse hierarchy where knowledge can be discovered in the early stages before the data and information processing. Knowledge Discovery from Database (KDD), Knowledge Management (KM), and Knowledge Based Engineering (KBE) are potential tools to accommodate manufacturing-borne data. Their specific benefits from the end users' perspective can include;

- A speed-up of human professional or semi-professional work.
- Major internal cost savings within companies. These cost savings would be direct like cost saving in assembling remote team, or indirect as a result of quality improvement.

- Improving quality and speed of decision making. Using KBS enhances the quality of decision making and reduces the time required to implement the correctness of decisions.
- Facilitate the new product development process. Some good examples of new product development that use KBS and the benefits drawn from KBS will be given in this chapter.

Hence, this chapter is an attempt to provide a framework for developing a knowledge based system designed for selecting materials while taken the sustainability factor – through sustainability indices- into consideration; the specific implementation in this study is focused on eco-material selection for automobile body structures (panels). The paper also discusses the challenges associated with processing large datasets into meaningful knowledge using data mining techniques. Such data mining methods will serve as the basis for building the system inference logic. Thusly, this study integrates the data mining and knowledge based system into one comprehensive intelligent model that can aid designers in the automotive industry in decision-making and when investigating different alternative materials.

7.2. KNOWLEDGE BASED SYSTEMS IN ENGINEERING DESIGN AND MATERIAL SELECTION

Material selection is an important discipline in engineering design. The selection process is usually carried out by designers and material engineers who are tasked with selecting the best material that fits the application in terms of function, shape, and cost.

Sapuan et al (2001) emphasized the importance of the KBS within the context of concurrent engineering, while discussing the role of the materials database in helping designers in rigorous materials selection scenarios. Employing a KBS framework equipped with a material database have been reported by several researchers; Sapuan et al., 2002; Sapuan and Abdalla, 1998; Mohamed and Celik, 1998; Cherian, 2000. The reported research work relied on tabulating the materials and their (mechanical, thermal, electrical, etc.) properties in a database, while logical and graphical user interfaces are created to facilitate accessing such information. Nowadays, the use of KBS in material selection received more acceptances due to its efficient operation especially in the early design stages.

Mok et al. (2001) showed how KBS and graphic modules can be integrated to come up with a useful tool for selecting mold designs for an injection molding process. Tang in (2004) used a collaborative design environment, during the product development phase, to facilitate the die-maker active involvement in developing a sheet-metal stamping die. The author reported that the die-maker should be involved in new product development processes as early as possible to integrate the concurrent engineering practices in metal stamping development. Also, he suggested that using an agent-based approach consists of part design agent, die maker involvement agent, and coordination agent, to integrate die-maker's activities into customer product development process within a collaborative concurrent environment. He illustrated an example where the agent based system was used to involve the die-maker with the part designer to achieve an optimal part design.

In order to use the available data effectively, it should be formulated and stored in a knowledge base, which can be used along with an inference logic engine to form an intelligent search and inference algorithm because the 'Selection' implies 'Making Decision'. Hence a KBS computer system attempts to represent human knowledge or engineers' expertise to provide relatively quick and accessible educated decisions. Additionally, the KBS has the ability to accomplish cognitive tasks that currently still require a human expert by automating the data mining and decision making processes (Sapuan, 2001, Madhusudan et al., 2004).

The study structure starts by addressing the KBS architecture through the proposed sustainability model for material selection, the methodology used for data mining and clustering analyses. The results from the data mining and clustering are presented in section five, while section explains the KBS inner workings. The conclusion section summarizes the manuscript study and present future work directions.

7.3. APPROACH

7.3.1. DATA MINING AND CLUSTERING METHODS

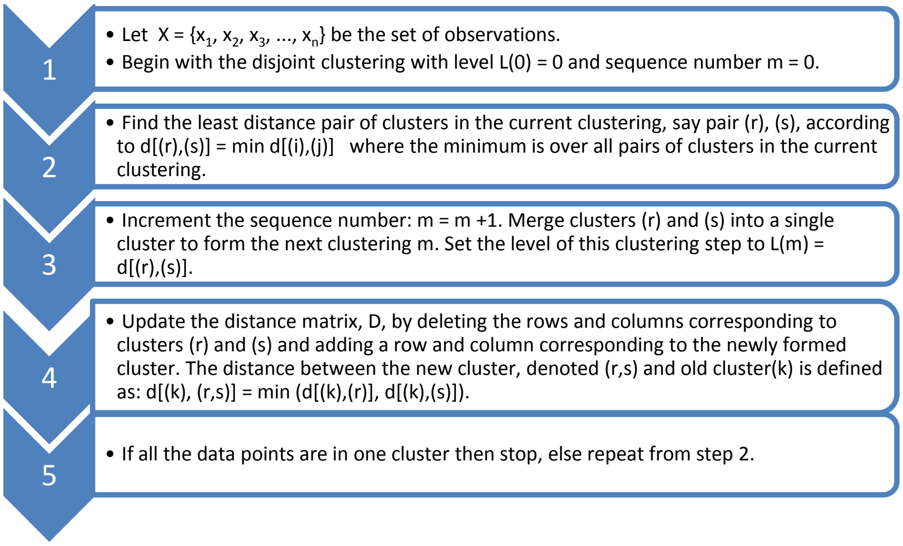
In this chapter, sustainability attributes are represented as points (vectors) in a multi-dimensional space, where each dimension represents a distinct attribute (variable, measurement) describing the object. Thus, a set of objects is represented as an *mXn* matrix, where there are *m* rows, one for each object, and *n* columns, one for each attribute. One quantitative measure of similarity is the distance between cases. Euclidean Distance measures the length of a straight line between two cases. The numeric value of the distance between cases depends on the measurement scale. The data is sometimes transformed before being used for many reasons like the dataset that has different ranges or different measures for different attributes. In cases where the range of values differs widely from attribute to attribute, these differing attribute scales can dominate the results of the cluster analysis and it is common to standardize the data so that all attributes are on the same scale. To avoid any issue of having one attribute dominating the others, the following data standardization method was used to normalize all attributes in a scale of (0–1) (see chapter 4 for more detail). Table 4.1 shows normalized values for all sustainability attributes used in this study.

7.3.2. CLUSTER ANALYSIS

Cluster analysis is an exploratory data analysis tool that is usually used to solve classification problems (Freitas, 2002). Its objective is to sort cases -either quantitative or qualitative- into groups, or clusters, so that the degree of interrelationship is high between members of the same cluster and minimal between members of different clusters or groups. Each cluster thus describes, in terms of the data collected, the class to which its members belong to.

Thusly, Cluster analysis can be considered as a tool of data mining (Abonyi and Feil, 2007), because it has the ability to reveal associations and structures in large datasets where knowledge is not evident in their original shape. The advantage of using cluster analysis comes from the fact that a user doesn't have to make any assumptions about the underlying distribution of the data prior to its analysis (Sharma, 1997).

There are numerous ways in which clusters can be formed. Hierarchical clustering is one of the most straightforward methods (Harding et al., 2006). Most common statistical packages use one of the following hierarchal clustering approaches to determine the distance between observations in the cluster and between different clusters; these methods include: single linkage (nearest neighbor approach), complete linkage (furthest neighbor), average linkage, Ward's method, and centroid method (Sclove, 2012). All of these approaches differ in the method they used to calculate the distance and what defines the distance as being statistically significant or insignificant. Most of the time, the distance is based on Euclidean distance in the sample axes. However; in this study the single linkage approach was used to discover hidden knowledge in data. Some of the important issues to be considered before performing hierarchal cluster analysis are: the user must select a criterion to determine the similarity or the distance between the different cases; also it is important to select a criterion to decide on the number of clusters that are needed to represent data. However, there is not a generally accepted procedure for determining the number of clusters. This decision should be guided by theory and practicality of the results, along with use of the inter-cluster distances at successive steps. When using a criterion such as between-groups sum of squares or likelihood, this can be plotted against the number ***k*** of clusters in a scree diagram (Sclove, 2001). In multivariate data analysis, principal component analysis (PCA) is usually used as a precursor to determine the appropriate number of clusters to be extracted. PCA is considered as a variable reduction procedure, which makes it an efficient statistical method in reducing a complex data set to a lower dimension thus revealing knowledge or patterns that are often hidden in the data. Because the goal of principal components analysis is to reduce the dimension of the dataset, focusing on a few principal components versus many variables, several rules have been proposed for determining how many PCs should be considered and how many can be ignored. One common rule is to ignore principal components at the point at which the next PC offers tiny increase in the total variance explained. A second rule is to only consider all PCs up to a predetermined total percent variance explained, usually 90% is used. A third rule is to ignore components whose variance explained is less than 1 when a correlation matrix is used or less than the average variance explained when a covariance matrix is used, with the idea being that such a PC offers less than one variable’s worth of information. A fourth standard is to ignore the last PCs whose variance explained is all roughly equal (Holand, 2008; Sharma, 1996; Hair et al., 2007). Then, the cluster analysis can be performed accordingly. In this study the hierarchical clustering algorithm was used as shown in Figure 7.1.


1

- Let X = {x_1, x_2, x_3, ..., x_n} be the set of observations.
- Begin with the disjoint clustering with level L(0) = 0 and sequence number m = 0.

2

- Find the least distance pair of clusters in the current clustering, say pair (r), (s), according to d[(r),(s)] = min d[(i),(j)] where the minimum is over all pairs of clusters in the current clustering.

3

- Increment the sequence number: m = m +1. Merge clusters (r) and (s) into a single cluster to form the next clustering m. Set the level of this clustering step to L(m) = d[(r),(s)].

4

- Update the distance matrix, D, by deleting the rows and columns corresponding to clusters (r) and (s) and adding a row and column corresponding to the newly formed cluster. The distance between the new cluster, denoted (r,s) and old cluster(k) is defined as: d[(k), (r,s)] = min (d[(k),(r)], d[(k),(s)]).

5

- If all the data points are in one cluster then stop, else repeat from step 2.

Figure 7.1. Hierarchical clustering algorithm (Naik 2012)

This hierarchical clustering can be formulated in any programming software using the following algorithm:

Given**:** A set X of objects $\{x_1,...,x_n\}$; and the distance function $dis(c_1,c_2)$

```
1.  for $i = 1$ to $n$
        $c_i = \{x_i\}$
    end for
2.  $C = \{c_1,...,c_b\}$
3.  $l = n+1$
4.  while $C$.size > 1 do
```

```
        a) $(c_{min1},c_{min2})$ = minimum $dis(c_i,c_j)$ for all $c_i,c_j$ in $C$
        b) remove $c_{min1}$ and $c_{min2}$ from $C$
        c) add $\{c_{min1},c_{min2}\}$ to $C$
        d) $l = l + 1$
    **end while**
```

7.4. RESULTS AND DISCUSSION

The basic approach used to build the knowledge-based system starts from reducing the dimension of data set into meaningful, smaller components or groups, hence cluster analysis (CA) in association with principal component analysis (PCA) were used to extract the hidden knowledge in data prior to translate this knowledge into usable if-then rules which then can be used as a basis of the knowledge based system. PCA attempts to reduce both the amount of information and complexity in dataset to enable engineer to understand the complex relationships before he or she starts building knowledge based system. Thus, PCA was used as pre-cursor to get the proper number of clusters (groups) that can be extracted upon performing cluster analysis (CA) and hence grouping different materials in their corresponding clusters easily. Upon performing cluster analysis, it was found that five clusters would be enough to capture majority of variability in data as well as their ability to reflect sustainability characteristics into usable classes. Figure 7.2 displays the hierarchical tree diagram (dendogram) of these clusters which permits a convenient graphical display that shows the entire sequence of merging (or splitting). Cluster analysis statistics are shown in Table 7.1, while Table 7.2 shows the distance between different clusters. The interpretation of these clusters into meaningful sustainability aspects is tabulated in Table 7.3. For example cluster 1 has high density, very good technical factors (i.e. formability, joinability and paiantability), good environmental characteristics (medium life cycle impacts (energy and CO_2) and high recycle fraction), low life cycle cost impact, and good mechanical properties for auto-body applications. Similar conclusions can be drawn for other clusters. Remarkably, it was found that High strength carbon fiber (0° unidirectional lamina) composite occupies a single cluster by itself; however, knowing the fact that this material has a modulus of elasticity of 140GPa and yield strength of 1850MPa (same value for ultimate tensile strength) make it very competitive for replacing load bearing structural panels and exceeds other materials like stainless steel.

Table 7.1. Cluster analysis statistics

	Number of observations	Within cluster sum of squares	Average distance from centroid	Maximum distance from centroid
Cluster 1	9	4.54504	0.662112	1.34582
Cluster 2	3	0.04573	0.116778	0.17341
Cluster 3	2	0.01594	0.089281	0.08928
Cluster 4	6	1.25455	0.450751	0.57149
Cluster 5	1	0	0	0

Table 7.2. Distances between cluster centroids

	Cluster1	Cluster2	Cluster3	Cluster4	Cluster5
Cluster 1	0	1.3163	2.09164	2.31558	2.461
Cluster 2	1.3163	0	1.57259	1.91311	2.34125
Cluster 3	2.09164	1.57259	0	1.59156	2.14093
Cluster 4	2.31558	1.91311	1.59156	0	1.31587
Cluster 5	2.461	2.34125	2.14093	1.31587	0

Rule-based reasoning based on CA results was used to construct the KBS framework. However, a basic KBS comprises a knowledge base expressed as if-then rules and an inference mechanism or rule interpreter. Hence, the rule-based reasoning based on cluster's interpretations was used as the basis for building the inference engine of the KBS according to the following structure:

```
If (conditions: $A_1$, $A_2$,……., $A_m$)
Then (conclusions: $X_1$, $X_2$, ….., $X_n$)
ElseIf (conditions: $B_1$, $B_2$,……., $B_m$)
Then (conclusion: $Y_1$, $Y_2$, ….., $Y_n$)
ElseIf (conditions: $C_1$, $C_2$,……., $C_m$)
Then (conclusion: $Z_1$, $Z_2$, ….., $Z_n$)
ElseIf (conditions: $D_1$, $D_2$,……., $D_m$)
Then (conclusion: $U_1$, $U_2$, ….., $U_n$)
Else (conclusions: $V_1$, $V_2$, ….., $V_n$)
EndIf
```

Table 7.3. Clusters and their interpretations

	CA Numerical Results (centroids)						Qualitative Interpretation *,‡				
Variable	**Direction of improvement**	Cluster1	Cluster2	Cluster3	Cluster4	Cluster5	Cluster1	Cluster2	Cluster3	Cluster4	Cluster5
Density	↓	0.211	0.569	0.868	0.941	1.000	H	M	L	L	L
life cycle cost analysis ($/kg)	↓	0.887	0.975	0.826	0.521	0.366	L	L	L	M	H
Modulus of elasticity (GPa)	↑	0.931	0.335	0.215	0.199	0.667	H	L	L	L	M
Yield Strength (MPa)	↑	0.296	0.057	0.071	0.171	1.000	M	L	L	L	H
Ultimate tensile strength (MPa)	↑	0.398	0.091	0.120	0.178	1.000	M	L	L	L	H
Shear modulus (GPa)	↑	0.922	0.323	0.212	0.214	0.061	H	M	M	M	L
Total Elongation (%)	↑	0.631	0.425	0.250	0.039	0.033	H	H	M	L	L
Formability	↑	0.792	0.833	0.500	0.917	1.000	H	H	M	H	H
Joinability	↑	0.852	0.556	0.444	0.778	0.778	H	M	M	H	H
Paintability	↑	0.951	0.889	0.778	0.333	0.333	H	H	H	L	L
Corrosion resistance	↑	0.901	1.000	0.111	0.407	0.556	H	H	L	M	M
Fatigue resistance	↑	0.917	1.000	1.000	0.625	0.625	H	H	H	M	M
Wear resistance	↑	0.926	0.667	0.667	0.778	0.778	H	M	M	M	M
Flammability resistance	↑	1.000	1.000	1.000	0.567	0.800	H	H	H	L	M
Resistance to salt water	↑	0.778	1.000	0.375	1.000	1.000	M	H	L	H	H
Resistance to UV	↑	1.000	1.000	1.000	0.800	0.800	H	H	H	M	M
RDI	↑	0.000	0.008	1.000	1.000	1.000	L	L	H	H	H
Water usage (L/kg)	↓	0.717	0.046	0.011	0.137	0.053	L	H	H	M	H
Recycle fraction, ψ (%)	↑	0.936	1.000	1.000	0.004	0.000	H	H	H	L	L
Life cycle energy assessment (MJ/kg)	↓	0.920	1.000	0.992	0.835	0.775	M	H	M	M	L
Life cycle CO_2 assessment (Kg CO_2/kg)	↓	0.865	0.914	0.883	0.831	0.754	M	H	M	M	L

* H: High; M: Medium; L: Low

‡ If the expectancy is the-larger-the-better (e.g. recycle fraction), then larger values get higher ranks; while if the expectancy is the lower the better (e.g. density), then larger values get lower ranks.

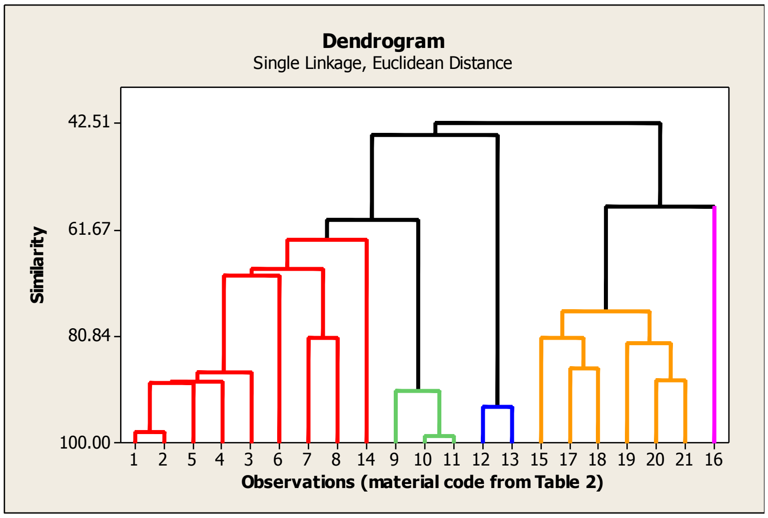


Figure 7.2: Dendogram showing different clusters and materials that fall under these clusters.

7.5. KNOWLEDGE BASED SYSTEM DESCRIPTION

The proposed material selection knowledge-based system for eco-material selection of automobile body-in-white panels consists of a user interface, knowledge acquisition, inference engine, knowledge base and database. Figure 7.3 gives the detailed description and structure of the proposed system used in this research, while Fig. 7.4 internal decision tree structure the KBS which gives users an overview about this KBS and its goals. The database consists of the materials and their properties. The inference engine communicates between the user and the knowledge base, reasons the facts and makes appropriate decisions, and finally gives the solution. A rule-based technique was used for developing the inference engine. The rules describe the conditions and attributes at which the selection procedure is to be made. A user-friendly interface is created to enable non-expert users to work in this system with minimal effort. The user interface incorporates and organizes data that have to be evaluated for further evaluation. In order to use KBS effectively, the user has to select one of material's classes that are stored in database, then he/she has to select type of the material under the selected class (Fig. 7.5 shows an example of such selection). A user friendly interface was designed in such way that when the material of interest is being selected, it invokes the necessary mechanical, economical, environmental and technical characteristics and starts running the inference process to give final sustainability classification (Fig. 7.6). The output of KBS composed of multi-tabs which give the user an idea about the characteristics of this material in terms of mechanical, environmental, technical and sustainability aspects. However, if the user needs to assess a new material that is not stored in the database, then he/she has to tell the KBS some facts about this material, like its mechanical properties, environmental characteristics, and general aspects (i.e. density and cost) (Fig. 7.7). Then the KBS is able to give him/her general sustainability assessment of this material.

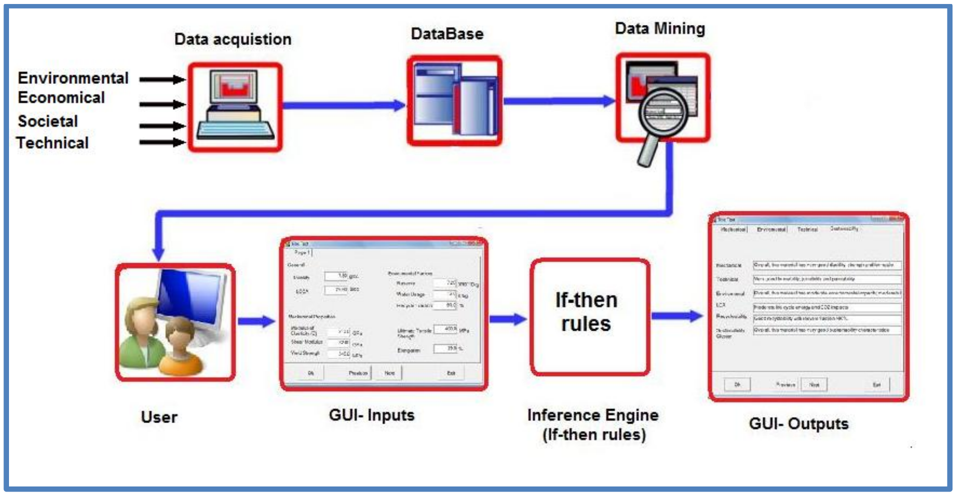


Figure 7.3. Structure of the hybrid data mining- knowledge based system

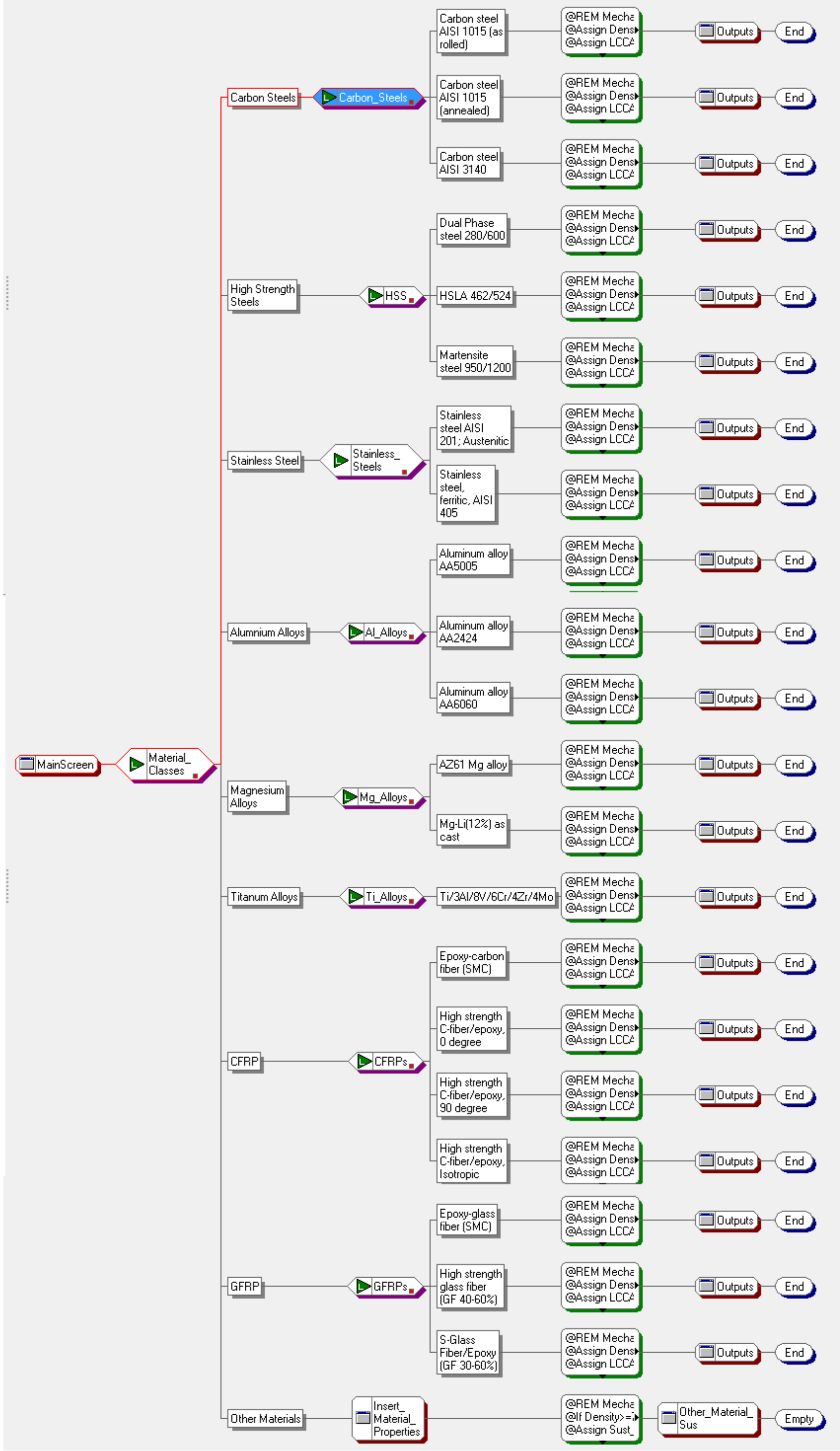


Figure 7.4: Screenshot of the internal structure of the KBS model showing logic flow in the decision tree

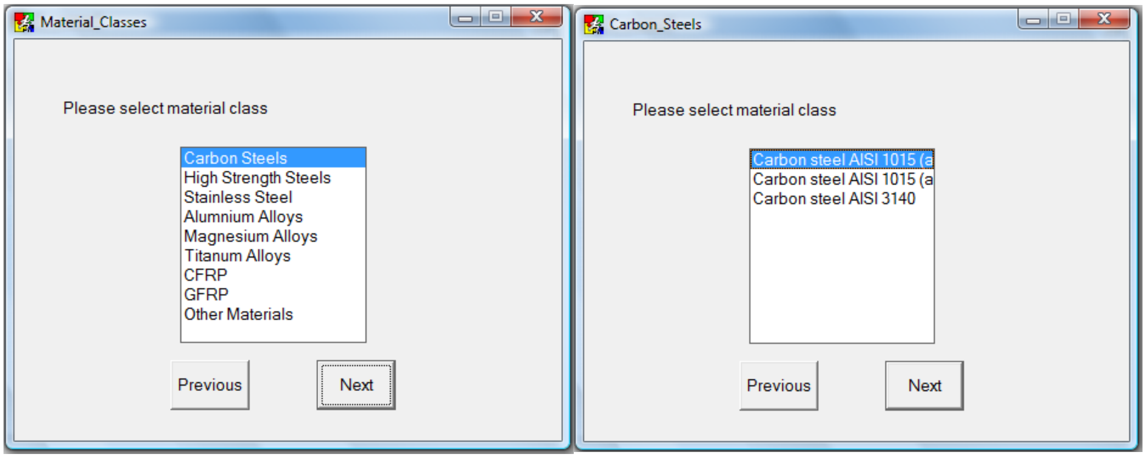
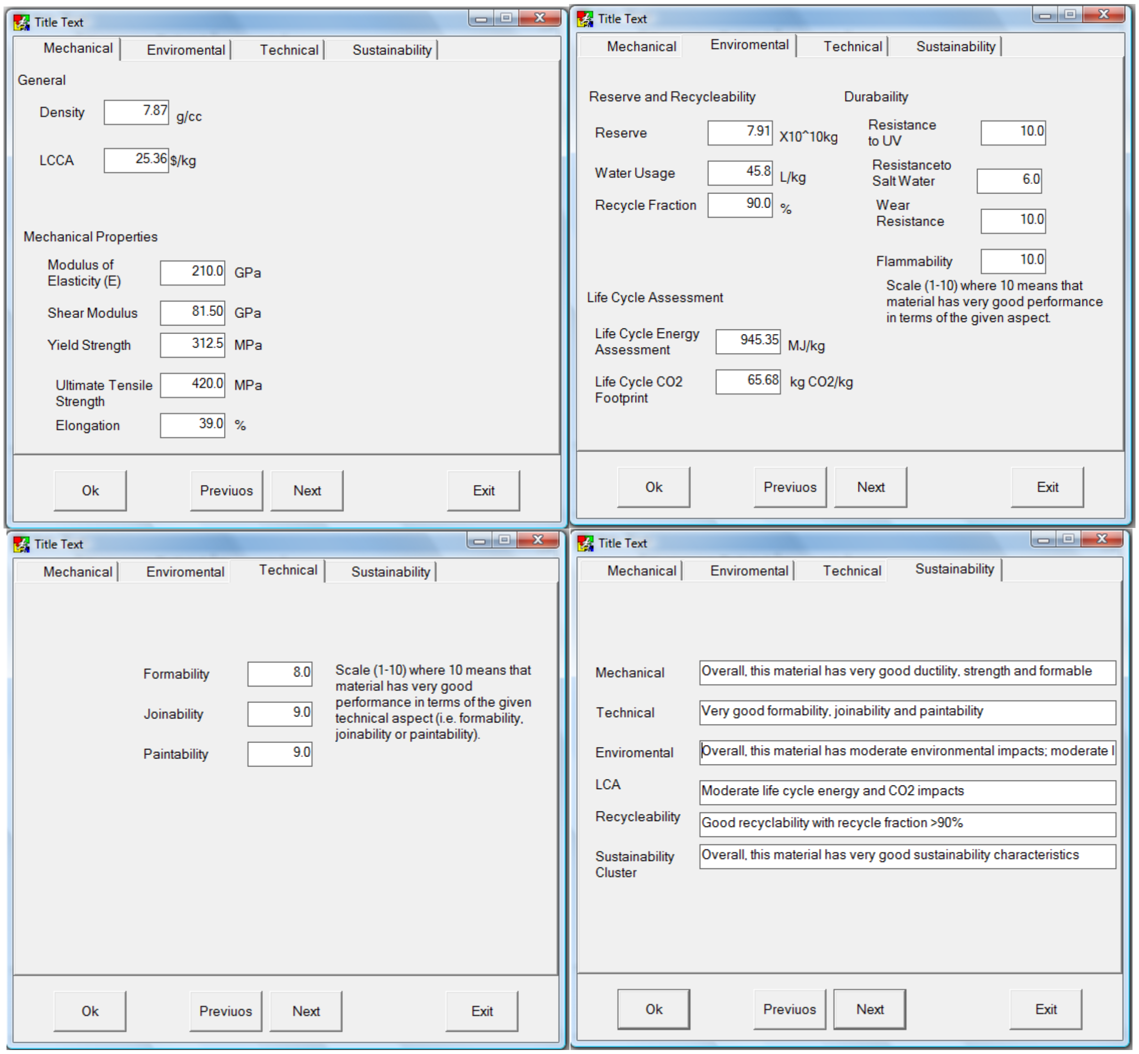


Figure 7.5. Screenshot of the KBS showing the flow of knowledge to aid user in his/her selection among different materials; left: selection of material class; and right: selection of any material under this material's class.



General

Density: 7.87 g/cc

LCCA: 25.36 $/kg

Mechanical Properties

Modulus of Elasticity (E): 210.0 GPa

Shear Modulus: 81.50 GPa

Yield Strength: 312.5 MPa

Ultimate Tensile Strength: 420.0 MPa

Elongation: 39.0 %

Reserve and Recycleability

Reserve: 7.91 X10^10kg

Water Usage: 45.8 L/kg

Recycle Fraction: 90.0 %

Durabaility

Resistance to UV: 10.0

Resistanceto Salt Water: 6.0

Wear Resistance: 10.0

Flammability: 10.0

Scale (1-10) where 10 means that material has very good performance in terms of the given aspect.

Life Cycle Assessment

Life Cycle Energy Assessment: 945.35 MJ/kg

Life Cycle CO2 Footprint: 65.68 kg CO2/kg

Formability: 8.0

Joinability: 9.0

Paintability: 9.0

Scale (1-10) where 10 means that material has very good performance in terms of the given technical aspect (i.e. formability, joinability or paintability).

Mechanical: Overall, this material has very good ductility, strength and formable

Technical: Very good formability, joinability and paintability

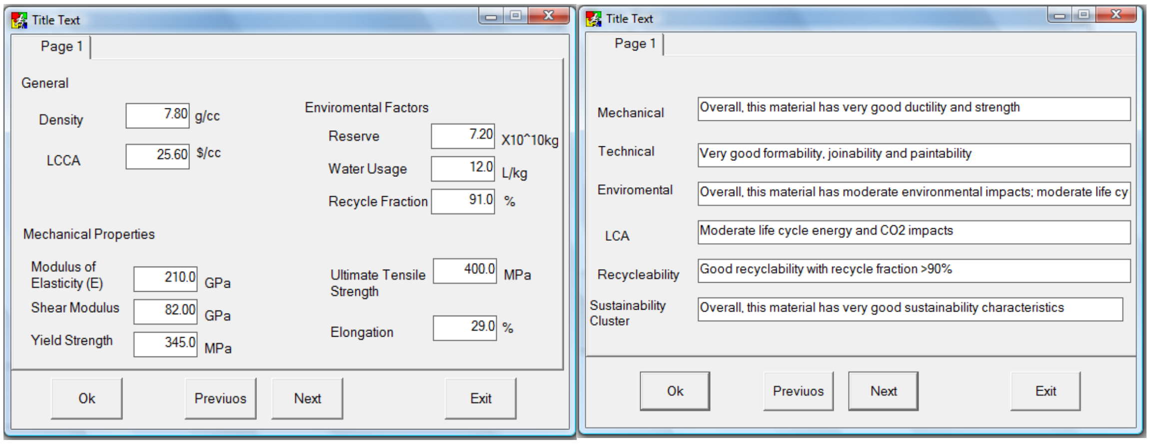
Enviromental: Overall, this material has moderate environmental impacts; moderate l

LCA: Moderate life cycle energy and CO2 impacts

Recycleability: Good recyclability with recycle fraction >90%

Sustainability Cluster: Overall, this material has very good sustainability characteristics

Figure 7.6. Screenshot of the KBS showing the outputs of the KBS for the selected material; top left: mechanical properties; top right: environmental characteristics; bottom left: technical characteristics; and bottom right: expected sustainability aspects of the chosen material.



General

Density 7.80 g/cc

LCCA 25.60 $/cc

Enviromental Factors

Reserve 7.20 X10^10kg

Water Usage 12.0 L/kg

Recycle Fraction 91.0 %

Mechanical Properties

Modulus of Elasticity (E) 210.0 GPa

Shear Modulus 82.00 GPa

Yield Strength 345.0 MPa

Ultimate Tensile Strength 400.0 MPa

Elongation 29.0 %

Mechanical: Overall, this material has very good ductility and strength

Technical: Very good formability, joinability and paintability

Enviromental: Overall, this material has moderate environmental impacts; moderate life cy

LCA: Moderate life cycle energy and CO2 impacts

Recycleability: Good recyclability with recycle fraction >90%

Sustainability Cluster: Overall, this material has very good sustainability characteristics

Figure 7.7. Screenshot of the KBS showing the input and output screens for a new material that does not exist in the database; left: input screen; right: expected sustainability aspects of this material.

7.6. SUMMARY

In this chapter we have discussed the clustering analysis approach and how it can be used to cluster multi-attributes dataset into meaningful groups, thereby affording rules for building knowledge based system. These clusters form a basis for understanding how sustainable materials are (from multiple viewpoints) and can work as a basis of rule-based reasoning in building knowledge based systems. This study also shows that the KBS is a very appropriate tool in eco-material selection process and can save time and effort while designing new products or assessing current or new materials.

From sustainability point of view, the current analysis reveals that different steel grades are still the best choice for BIW panels over other candidates, which explains why the OEMs focus on developing improved steel alloys and grades rather than considering other materials like aluminum or magnesium.

CHAPTER EIGHT

CONCLUSIONS AND FUTURE WORK

8.1. CONCLUSIONS

- In light of escalating fuel prices and ongoing climate change discussions, sustainability is becoming a more prominent role in material selection decisions for automotive applications.
- Selecting material for automotive application in general, and structural body panel in particular, based on the life-cycle assessment method as the only eco-indicator would result in unfair comparison and unfair selection because lightweight material like aluminum and magnesium will win the game.
- Life cycle assessment is still important and it requires an extensive amount of data and it has the ability to quantify the environmental impacts of any product over its life-cycle; however, sustainability aims at developing a comprehensive model to include all the major factors that cover social impacts, economic impacts, environmental impacts manufacturability, functionality, and recyclability has become essential.
- From both economic and environment point of views, aluminum and magnesium prove to be potential alternatives for steels in future automotive applications; however, OEMs need to know that different grades of steels (especially HSS and

AHSS) still attractive not only because they are relatively inexpensive, but because they have excellent formability, weldability and recyclability making them viable options in the future of automotive industry.

- Recycling plays an important role and once take back initiatives will place the responsibility of product disposal on the product manufacturer, designers will be asked to develop products that are reusable, made of recycled materials, and are recyclable.
- Material selection process should be made based on a systematic way in which material X can replace material Y without losing the functionality of the replaced panel, this is the reason behind using material selection indices for lightweight designs instead of considering lighter materials based on their densities only.
- Multi-attribute decision-supporting methods are good tools to assess different materials when two or more objectives need to be considered at the same time.
- Quantifying sustainability is a challenging issue as there is no well-established methods are available today. In this study two scoring methods were used namely: preference selection index and principal component scoring method and both of these methods show that different grades of steel are the best material options that can meet sustainability requirements.
- This study proved the overall benefit of using lighter materials such as advanced high strength steels in auto-body structures with respect to environment, society, economy, manufacturability, functionality and recyclability/re-manufacturability.

8.2. LIMITATIONS AND FUTURE WORK

Based on the current study’s findings, and from the economic and environmental benefits of using lightweight materials, future work should be focused on determining the right combination of materials in automotive structures. This would help to meet sustainability requirements of cost reduction, reduction of environmental impacts over the life-cycle of the vehicle and to improve safety and performance of the auto-bodies. However, some issues might limit this approach such as joining different materials together to get the final body structure, also the disassembly at the end-of-life which needs to be considered for multi-material BIW. More “sustainability” sub-elements might be added to refine the “sustainability” model and some weights might be placed on different sub-elements or influencing factors.

Knowing that ‘sustainability’ is a hot topic in many fields including automotive industry, the future work should focus on the following issues:

- Lack of recognition by both consumers and manufacturers of the value of products have been design for sustainability, so the question that arises here is “how can design for sustainability be promoted more in automotive industry?”
- Integrating sustainability into core business objectives; while some companies have crossed this threshold, many still view ‘sustainability’ as an added cost of doing business, so achieving sustainability goals should be one of the ultimate goals of the product development process.
- Improving design capacity. Designers and their clients need to be more aware of the tools for design for sustainability and the benefits of applying them.

- The real cost accounting procedures have to be instituted for the real cost to be determined. Without the benefit of an accurate cost, an evaluation of the merit of designing for sustainability cannot be established; hence performing complete life cycle cost analysis would be one of the topics that need further analysis.
- Using more of decision supporting tools like decision trees, digital logic, fuzzy logic, etc. would help designers to get better understanding of the sustainability goals and how they can be met.
- Quantifying design for sustainability would be one of the topics that needs more study. Some statistical and optimization tools can aid future work in this particular task.
- Improving knowledge based systems for eco-material selection as well as manufacturing processes selection would enrich the field of design for sustainability for automotive applications.

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