Early Phase of the Cross Car Beam Concept Development

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Design is in everything we make, but it’s also between those things.
It’s a mix of craft, science, storytelling,
propaganda, and philosophy.

Erik Adigard

ABSTRACT

Product development is the process of generating new products or services that intend to meet pre-existent needs. This process is a very powerful tool in the modern world, where competition became global and product life span is shorter than ever. However, its use and implementation may not be entirely straightforward and, if misunderstood can lead to a disastrous business or, ultimately to the company's ruin. The recognition of a new market opportunity is how the whole process starts and goes through many steps until the product is ready to be launched.

This thesis submits an approach for the early phase of this process using an automotive component as a case-study. The intention is to reflect and understand how the process of design and product development can be applied to such complex product as the Cross Car Beam. Within the scope of the project it was established a partnership between a local Tier 1 car component supplier and the Faculty of Engineering, which allowed for a closer and direct contact with most stakeholders.

Being the automotive industry a very challenging industry regarding quality, reliability, safety and price, there was a special emphasis given to the effort of reducing costs and enhancing performances. Working with a zero constraint policy created multiple solutions, which means that each one had to be carefully analysed. From the traditional mild steel single tube, to the highly integrated hybrid, many solutions can be obtained by varying only a few parameters.

The systematic feature of the process allowed to get to the end of the project with clear-cut product specifications for what intends to be and what it has to be done to reach it.

KEYWORDS: Design and Product Development, Automotive Industry, Cross Car Beam, Systematic Process

RESUMO

Desenvolvimento de produto é o processo the geração de novos produtos ou serviços que pretendem responder a necessidades pré-existentes. Este processo é uma ferramenta muito ponderosa no mundo em que vivemos, uma vez que a competição é global e a vida útil de um produto é cada vez mais curta. No entanto, o uso e implementação desta ferramenta não é simples nem direto, se for mal usado pode levar ao falhanço de um projeto e, em casos mais graves à falência da empresa. O reconhecimento de novas oportunidades de mercado é como todo o processo se inicia, depois tem de passar por uma série de etapas até o produto estar pronto a ser lançado.

Esta tese submete uma abordagem à fase inicial deste processo usando um componente automóvel como caso de estudo. A intenção é refletir e perceber como é que o processo de design e desenvolvimento do produto pode ser aplicado num componente tão complexo como é o caso do Cross Car Beam. No âmbito deste projeto, foi estabelecida uma parceria entre um fornecedor de componentes automóveis local e a Faculdade de Engenharia, que permitiu um contacto mais próximo e facilitado com a maioria dos *stakeholders.*

Sendo a indústria automóvel tão exigente no que respeita a qualidade, confiabilidade, segurança e preço, que foi dado ênfase especial ao esforço de redução de custos e melhoria de desempenhos. Trabalhar com uma política de zero restrições criou múltiplas soluções, o que significa que cada uma teve de ser cuidadosamente analisada. Desde o tradicional tubo simples de aço-carbono até a solução híbrida altamente integrada muitas soluções poderiam ser obtidas com apenas uma pequena variação dos parâmetros.

A característica sistemático do processo permitiu chegar ao final do projeto, com especificações claras do que o produto pretende ser e o que tem de fazer para lá chegar.

KEYWORDS: Design e Desenvolvimento do Produto, Indústria Automóvel, Cross Car Beam, Processo Sistemático

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF GRAPHICS

INTRODUCTION

MOTIVATION

Product development is the process of generating new products or services that intend to meet pre-existent needs. This process is a very powerful tool in the modern world, where competition became global and product life span is shorter than ever. However, its use and implementation may not be entirely straightforward and, if misunderstood can lead to a disastrous business and, ultimately to the company's ruin. The recognition of a new market opportunity is how the whole process starts and goes through many steps until the product is ready to be launched. This thesis submits an approach for the early phase of this process using an automotive component as a case-study.

The automotive industry is a very challenging industry regarding quality, reliability, safety and price, thus there is a special emphasis given to the effort of reducing costs and enhancing performances. Working with a zero constraint policy will create multiple solutions, which means that each one has to be carefully analysed. The process can be long depending on the complexity of the problem so setting planning is essential.

Objectives

The goals for this project are firstly to understand the product design and development process and apply that knowledge for the development of an actual product. This assignment intends to be a part of a larger project carried out by the Faculty of Engineering of Porto University (FEUP) in collaboration with a local automotive company, SODECIA S.A., aiming to design and develop a new concept of a cross car beam. This thesis will cover solely the early phase of the product development.

When dealing with systematic design, which it will be the case, Baxter presents in a very cheerful and simple way some ground rules that should be considered, he calls them the "three unwise monkeys rules":

Figure 0-1-1 – Illustration of the three unwise monkeys, from the left to the right: speak no evil, see no evil and hear no evil (Huckfinne 2009) /

- **See no evil:** setting clear and realistic targets for the product/project is a way of assuring that everyone knows the point of destination and consequently it gets easier to verify if you are on the right track;
- **Hear no evil:** it is worthless to have specific targets if the development process is not kept under supervise, i.e., if no-one pays attention to the little deviations of the original plan, then it is impossible to guarantee the success of the project;
- **Speak no evil:** Thomas Edison once said, "creativity is one percent inspiration and ninety-nine percent of perspiration"; this means that only after having a multitude of solutions you can be certain that your solution is the best possible one. It is convenient to remember that if you have a single solution you can't attest that it is the optimum one, besides wrong paths lead many times to breakthroughs.

Our main concern will be the first rule, seeing that, as said before, this thesis will be focused on the early phase of the process, the establishment of the product design targets is the desired output.

The paramount goal of this thesis is to be able to contribute to a new concept for a Cross Car Beam, which integrates the cockpit system. By using the acquired knowledge of design methodologies to help the creation of a solution that best meets the duality performance vs. innovation.

THESIS STRUCTURE

The remainder of this thesis is split into 6 chapters.

The two first chapters are dedicated to the product development process as well as the some particularities of the automotive industry. So, the chapter 1 will be focused on the product development process, i.e., it will be explained in detail all steps and stages that concern product design and development. Notwithstanding, one can already say that describing these targets is the end of the early phase of development, right before beginning concept generation. Of course that there is no line to define the beginning and finish of a stage but one can assume some gates along the process. The chapter 2 gives an overview of the automotive industry as the case study we are presenting is based on a specific product, integrated in this economic field, pointing out the industry evolution.

Then chapter 3 will continue with reflexions on the specific product we aim to study. This section is intended for disclosing all there is to know about the cross car beam, what is it and how does it behave. In fact, it intends to give different perspectives of the state of art of the CCB.

Chapter 4 will introduce the methodology, i.e., it will hand us the description of the project and of some analysis tools that it will be of use. As the project in hands is part of a larger one, which has the collaboration of a local automotive manufacturer, this section it will also briefly introduce SODECIA, S.A.

The chapter 5 will present main findings and discuss their implications in defining the specifications of the cross car beam. It will comprise the study and analysis of existing cross car beams, the different choice of materials, configurations and other relevant features.

Finally, in chapter 6 it will be disclosed the main conclusions, followed by the contributions of this work and some recommendations for future work.

1 PRODUCT DEVELOPMENT PROCESS

Throughout human existence we can find at least one crucial characteristic that defines us as specie, the ability to make all sort of tools and artifacts to suit our needs. Since the beginning of times, human beings have created new objects, or have simply improved the ones they already had, so they could continue to serve the ever-changing needs. However, the traditional craftsmanship is in many ways far from using the design process “per-se” (Cross 2008), at this point different meanings of the design concept start to appear.

The notion of what design is has been evolving from its very beginning, nonetheless, it is usually defined as the “art or action of conceiving and producing a plan or drawing of something before it is made” (Oxford Dictionaries). The word design is believed to come from “disegno”, which means drawing in Italian but from the previous definition it should be translated as a draft, that is, as something that requires more advance planning as opposed to hands on. Notwithstanding of its large variety of meanings, design has become over the recent years a very popular subject covering our daily lives (Hauffe 1998). The preoccupation with aesthetics (the form), probably the first feature to be assessed by a layman, and usefulness (the function) are no longer the only characteristics of design, its systematic methodology helps companies to foresee future problems, saving time and money in the long run (Cross 2008).

The industrial revolution in the 19th century brought a whole new dimension to design, from concept generation to actual production of the product, a process that was till then usually carried by one man only, became responsibility of a large team with diversified knowledge. The creation and the execution were separated in two parts of the same process but the goal was preserved, responding to the society needs. That is how industrial design appeared and since then it has been the mediator between the necessity and the necessary, it is only fair to admit that it plays an extremely important part in today’s society as a social and economical phenomenon. One of the many definitions for industrial design assumes that the objects are formulated to be industrially manufactured, i.e., this definition excludes all craftsmanship work and applied art objects as they are not obtained neither by using machines nor from series production. This concept has also evolved greatly until the beginning of the 60‘s, when it was proposed a more complete definition with wide acceptance that included all process phases of producing a new product, from planning to design, including all the necessary research and testing (Maldonado 2009).

In that way, the development of a new product became a complex multi-phase process of answering to client demands, studying the competition, understanding the physics involved, choosing the most suited materials, knowing the regulations, etc. That being the case and as it will be referred forward, some defend that the design and product development can only reach its full potential if combines social science (marketing), technology (engineering) and applied arts (design) in the use of systematic methods, which of course cannot be considered an easy task (Baxter 1995).

The industrialization of design called for larger teams and the addition of other expertise to the process, inevitably brought different approaches to what the design process used to be. The Figure 1-1 represents a schematization of the new perspectives brought into the design process.

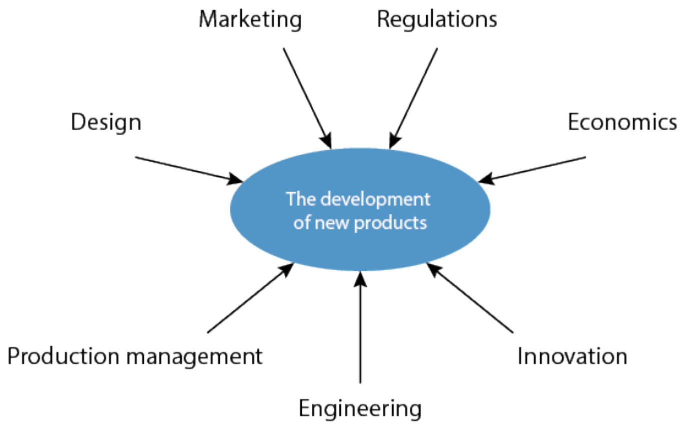


Figure 1-1 – Different perspectives to take into account in the product design and development process (adapted from (Trott 2005)

1.1 The Innovation Role

Nowadays, it is clearer than ever that innovation is a crucial part of business success. With increasing pressures from competition and with shorter average life span of products the solution for most companies has to be the continuous innovation. Nevertheless, new product development is not as simple or even as straightforward as we would hope it would be, there are some trade-offs that have to be made in order to meet the different, and sometimes, incompatible requirements of the product.

After the Second World War, US economists promoted the linear models of innovation, which, due to its uncomplicated characteristics, managed to endure for 40 years in the fields of science and industrial policy. The breakthrough achieved took place by the recognition that innovation emerges through the interconnection of the scientific and technological development when attending the needs of the market. This same basis supports the current models of innovation (Trott 2005).

Pursuing innovation is very close to what identifying the product opportunity gap is, that is, they are both based on the idea of ascertaining the margin between what already exists in terms of products or services and what can be created that will respond to the prevailing needs or trends. To reach the product opportunity gap, one should constantly and simultaneously consider three major factors: economical, technological and social (see Figure 1-2).

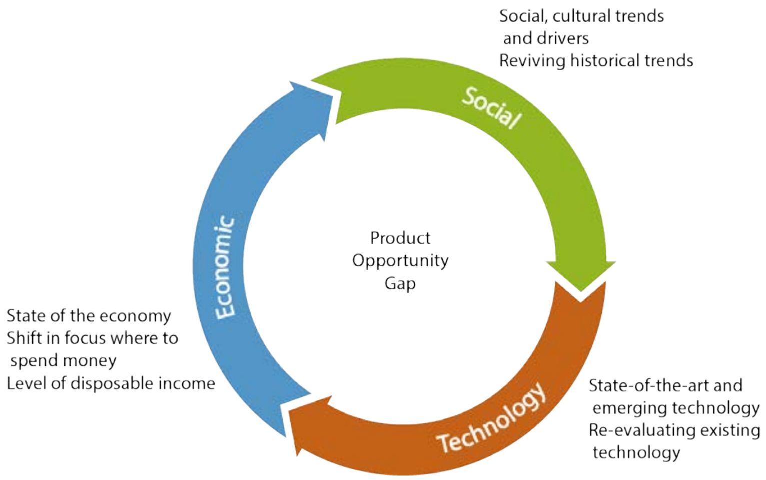


Figure 1-2 - Meeting the Product Opportunity Gap (Cagan and Vogel 2002)

If well studied, these three areas together can give the necessary information to meet or even exceed the customer desires and expectations:

- The economical factor evaluates the purchasing power people perceive they have that will allow them to buy more products or services without even having the real necessity. The consciousness of who has the means, who is going to spend it and for whom is also of great importance since it will undeniably influence the course of action.

- The social factor alludes to the apprehension of the environment people live in, there has to be a good understanding of today's society to easily pick up the social and cultural tendencies. Societies are persistently injected with potential new trends, most of them created by the entertainment industry, from television to magazines or outdoors, but only a few manage to enchant and triumph.

- The technology factor is probably the most intuitive of them all, it deals with the expertise on the available technology. The technology evolution has been continuous whether regarding new materials or new manufacturing processes, furthermore, the volume and speed with which a computer processes information has also suffered exceptional growth, ergo allowing significant lifestyle changes (Cagan and Vogel 2002).

Reinforcing this idea, the managing director of McCain Foods states that 'Its only by understanding what the customer wants that we can identify the innovative opportunities. Then we see if there's technology that we can bring to bear on the opportunities that exist'. He is also of the opinion that bringing innovation into a product can be easy however, that is not the same as having a commercially viable product (Trott 2005).

Although many external and internal circumstances may influence innovation, it is believed that the way these three areas are connected is the key to succeed, see Figure 1-3. For instance, the "technology push" model, where a technology is assumed and only then marketing and sales work their "magic" to the potential consumer, was a very popular innovation model after the Second World War but nowadays it is mostly seen in pharmaceutical industry (Trott 2005). The generic model, "market pull", is based on the opposite assumption, i.e., the marketplace is no longer a passive component of the process but a crucial one instead. The marketing finds a market opportunity by keeping close relationships with customers and users, then the designers and engineers search for the design and the (available) technology that best suits the market needs (Ulrich 2012).

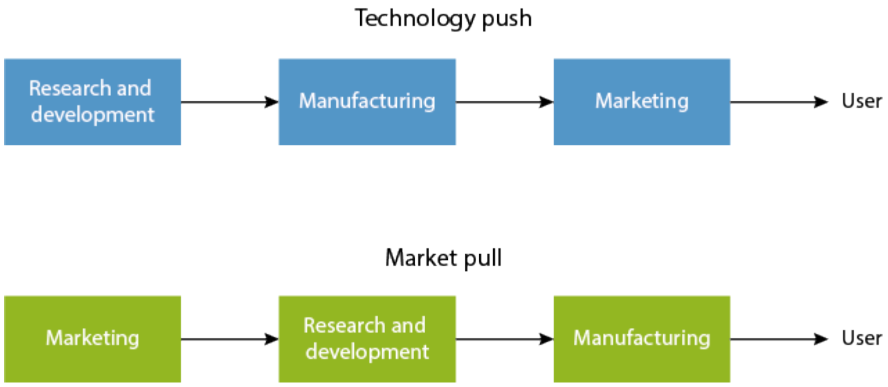


Figure 1-3 - Linear models of innovation (Trott 2005)

1.2 The Design Method

Traditionally any procedure, technique or tool used for designing, could be called design method but there has been a boom of new and groundbreaking procedures that are more suitable for the existent complex problems. Sometimes these new methods may seem to be nothing more than elaborate names for common-sense techniques. For instance, the "design-by-drawing" method refers to the use of drawing as being almost the sole task to design. But, going beyond the time of the Renaissance it is possible to observe, though on a smaller scale, the use of drawings and sketches already then at the service of design. Nowadays, designers, like architects, keep using this method as basis for their work, not only to represent the overall layout but also its critical details (Cross 2008).

The idea that a product concept is expected to be converted into a manufacturable, saleable and profitable product is quite simple but, on top of these characteristics, producibility is also implicit. This means that the easiness with which a design can be manufactured in good time maintaining the high quality at a low cost that can and should be controlled (Magrab 1997a). That is why industrial design has embedded on its basis the serial production nature, where at anytime of the product manufacture there can be a tight control of the overall performance, and by doing so, deviations can be kept to a minimum (Dorfles 1991).

It is well accepted that in the design process you should have the design first and its materialization later, i.e., only after having the project completed you can produce the product. Although we make this process partition, in the end, they both have to exist, seeing that the product development can only be successful if the product is indeed manufactured and sold.

Nowadays, within some industries it is common to refer to design as a small part of the product development process, that is, the design can be seen just as an exercise to create new concepts. The automotive and aerospace industries are good examples of such since they deal with problems of great complexity where the development process has to be wider in order to comprise all factors involved. In other business areas like fashion, product design has practically the same meaning as product development ; (Trott 2005; Cross 2008).

1.3 Product Development Process

Product development is the process of generating new products or services that intend to meet pre-existent necessities. The process is quite extent and it can take from a few weeks to several years to be completed depending on the complexity of the problem. The initiation of the process is set by the recognition of a new market opportunity and goes all the way to the product launch and its sale.

A process can be portrayed as a recipe, i.e., simply a sequence of instructions or steps that transform inputs into outputs. And as a recipe, the steps can be manipulated to create a new process that is more efficient given the problem at hands and the company's organization. However, there are certain rules that have to be met for the product to be successful. The following figure illustrates a generic development process with its six corresponding phases. Remember that there can be several different models of the process depending on the complexity of the product, the industry or the available resources, but generally speaking, they all meet the basic steps depicted in this figure.

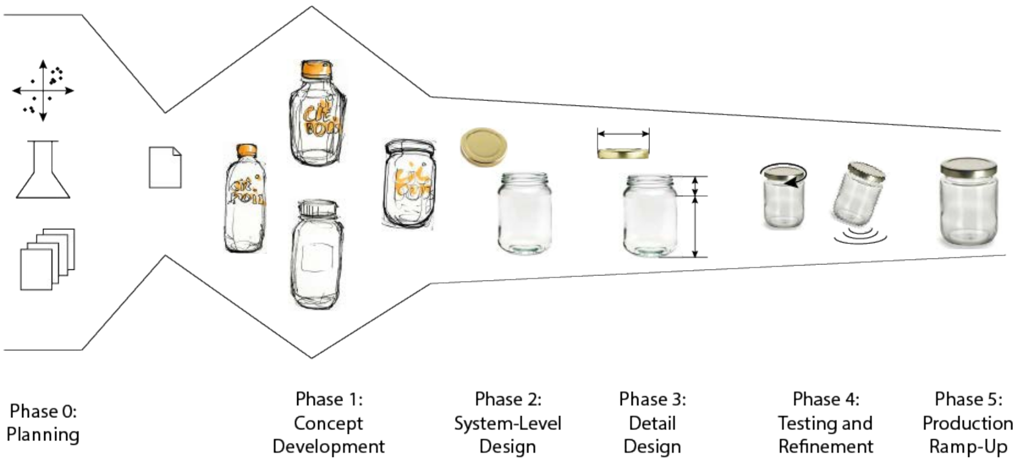


Figure 1-4 – A scheme of the generic development process formed by six phases (adapted from (Ulrich 2012)

It is easy to understand that the early steps of the process are crucial and one should want to spend enough time on them since, the time and money spent on it should minimize the probability of failure. By the end of the early steps, major decisions regarding how the product will be done will have already been taken and a considerably large part of the funds will be committed by then. And for this reason, the sooner you make changes in the project the less expensive it gets to do it (Magrab 1997a). Nonetheless, as tempting as it sounds, one does not have all the time in the world to complete these first steps, just the enough time. That is to say, if one does not intend to meet the established deadlines then, there is no point on having them in the first place, and ultimately, will never be able to produce any product.

In the development process, the decisions are made by constantly having to weigh and choose between different options. These processes have many challenges that have to be exceeded thereby the team have to be confident of the path chosen because there are many detailed decisions that have to be made along the way. It is also important to be aware that there are deadlines to be met and that the team not only have to master the technology to be used but also to be cautious to produce the lowest cost product possible without sacrificing the quality (Ulrich 2012).

A successful product development can make the difference between having a competitive company or endanger the entire business. As a consequence, the literature available on the topic is endless. However, despite the great number of product development processes available, in the end they all have similar guidelines that help managing the process and consequently the risks involved.

Assessing product profitability is not a remotely immediate task but is one of the easiest ways to evaluate the product development success. For all that, there are other five dimensions that, in the end, will affect profit and, are more expeditious for analysing the performance of the product development plan (Ulrich 2012). They are:

- Product cost, which includes equipment and tooling, and is reflected on the balance between the investment and the sales;
- Product quality that is usually used to set the product value;
- Development time, that is directly related to the time the product becomes available in the market;
- Development cost as part of the initial investment;
- Development capability, which indicates if the team has the capability to do future development projects more efficiently and economically;

In the following paragraphs there will be made an attempt to explain and describe all the steps of the generic development process depicted in Figure 1-4.

A - PLANNING

Planning the product development is essential to the overall project schedule. Naturally it corresponds to a stage prior to project approval and launch of the product development process, and is therefore often considered the “phase zero”. The main goal of the Product Planning is to find the products to be created/developed under a given organization, and establish the time period under which it will be introduced on the market. Therefore it implies the need of a structured step-by-step process, and the key steps are as follows:

- Opportunities Identification
- Evaluation and Prioritization
- Allocation and Timing
- Pre-project Planning
- Results and Process Analysis

An opportunity is an idea for a new product or, simply, the characterization of a solution for a new need. Opportunities are identified through analysis of market trends as well as technological developments. This means that to identify an opportunity, both the technology and the market must be known, as it implies to search for a wide range of alternatives and filter them to identify those that are really promising. To identify opportunities is essential to rule out the ones that might not create value so that the most promising ideas can be developed. These would be the ones that are worthy of future investment. However, this selection should be done carefully, you can not know for sure in advance which ones are going to successful. And because, excellent opportunities are rare, ideas should initially be generated in large numbers without ever being sacrificed their average quality. It may also be interesting to create absurd notions to widen diversity and increase the chance of emerging an exceptional good opportunity.

To skip to the next step it is necessary to perform a mission statement, which intends to disclose the proposal, objectives, target markets and the stakeholder.

B - CONCEPT DEVELOPMENT

Typically a concept is best defined by the effort to designate the form, function and features of a product. It is usually accompanied by a full list of specifications, together with a study of the "status quo" on the market and the correspondent economical validation.

In the Concept Development phase, one tries, after defining the necessities found in the market to which the product is aimed, to create and assess alternate product ideas. Among these, a few are chosen for further development and analysis.

The steps within this phase are generally composed by:

1. **Identifying customer needs** - one key factor in Product Design and Development is to start with a set of well-defined needs to respond to. It is of major importance to manage to enable an accurate and assertive link between the customers and those who will develop the product.

2. **Product Specifications** - in Product Specifications there is no place for subjectivity, on the contrary, they seek to describe in measurably detail the requirements of a product. A target-value is defined for each characteristic, which should answer one or more needs. To achieve this correlation it is necessary to know the customer needs, collect information of competitive products, set final specifications and finally, establish target-values.

3. **Concept Generation** - this must be the step where a description of form, technology and working principles starts to appear. It should be noted that with a good concept it might be hard to carry out effectively the remaining development phases but with a weak concept that is almost impossible. The good part is that this step is quite inexpensive and rapid comparing to the whole process. As this is a stage, for creative excellence, several concepts should be generated. Though, they should not all be considered and that is where structured methods can be helpful.

4. **Concept selection** - Is an assessing process, which is used to compare and choose one or more concepts that would best fit customer's needs. One must be aware that selection of concepts is applied throughout all the development phases.

5. **Concept testing** - This phase will depend on the answer given by potential consumers, more than the one given by the development team itself. The idea is to take the concepts from the previous step and test them among the customers in order to understand which are the ones that should be pursued. This test can also contribute to make sales forecasts.

C - SYSTEM LEVEL DESIGN

System level design is the stage, within the process, where the product starts to gain "character" because only at this stage the product architecture can be properly defined, by deconstructing the product into several sets of smaller components. These are shaped individually but their assembly is also included in this phase.

A product must be thought of in a formal and functional level. The functional elements correspond to the individual operations that the physical elements execute enabling the good performance of the product. The architecture of a product is seen as the plan that translates the function into the form and that it establishes the interactions between them. Decisions taken in this phase of development will have serious implications at various levels afterwards, including performance, manufacturing, product replication and all the logistics involved in the standardization of the product.

In short, this phase should stipulate the overall product geometry, the functional specifications and an early description of the assembly process.

D - DETAIL DESIGN

As the designation suggests, is where specifications of all elements composing the product are designed in detail. All the documentation necessary is gathered in order to create a manual of rules that establish measures, geometry, tolerances, etc. to be sent to the production. The parts to be acquired from suppliers must be listed and inventoried. Material's selection, production costs and physical strength will be the most relevant aspects at this stage.

E - TESTING AND REFINEMENT

In this stage, the product will be tested in order to verify the compliance of the objectives proposed, but this stage may also imply an analysis in which assessment may result in product adjustments.

Several models have to be built to evaluate different aspects. Sometimes, the models are alike regarding geometry and materials but they might vary in fabrication or assembly process. The goal of such prototypes is to assess the suitability of the product to its function and user needs, that is, to evaluate the overall design and performance. There are also models or prototypes made through the real process of production that serve to test the performance and dynamics of the product. This assessment can result in changes in the engineering of the product itself. That is to say that for the various types of prototypes, there are different types of technologies.

It must be emphasized that this phase of product development, although very valuable, entails very high costs, mainly because it is often necessary to produce various models for different test types and, also because it is quite lengthy. Since this is a very important phase for product validation, these two factors often represent an obstacle. And, in order to greatly reduce the cost and time associated with prototyping this is commonly preceded by numerical simulations. Numerical models intend to reproduce the actual product and, these should also be tested by simulating different service conditions or accidental events. Having said that, the physical prototypes should only be designed after the virtual models pass the tests.

F - PRODUCTION RAMP-UP

This is the last phase of product development, preceding the product distribution to the market. Before releasing the product, the complete production system must be tested and the ramp-up is designed to simulate and fix problems that might still exist in the production process. Apart from the technical perspective, this approach enables an assessment of the commercial perspective, allowing identification of failures and subsequent development of improvements.

2
NEW PRODUCT DEVELOPMENT IN THE AUTOMOTIVE INDUSTRY

2.1 Corporate Strategy

Automotive industry is a particular business, which surpassed numerous challenges over the years and that, without any doubt, greatly influenced modern society. Europe's economy, for instance, relies on a solid and innovative industrial base, being the automotive industry one of the prime contributors to its economic output. Together, the European vehicle manufacturers represent the largest private investor in European Research and Development (R&D), investing an average of 5% of turnover each year on R&D activities, amounting to an annual investment of over 20 billion Euros (The Automotive Industry - Focus on the future R&D Challenges 2009; ACEA - European Automobile Manufacturers' Association 2010) ; . The U.S. automotive industry also corroborates this idea of great weight in today's society by being responsible for 1,7 million direct jobs and 8 million indirect jobs nationwide. Its R&D investment is close to 17 billion dollars a year from which 99% is generated by the auto industry itself. If not that, then the fact that all but one (Saudi Arabia) of the G-20 countries, the world's prime economies, have automotive production should confirm that it is indeed an industry of great importance to the economy and development of a country (Alliance 2012).

There has been a continuous search for differentiation strategies to produce passenger cars from the beginning. In 1913, Ford was the first automotive company to break with the conventional by adopting a strategy of manufacturing standardized products in high volumes with low production costs. A few years later, around 1920, General Motors was turning to another direction, Alfred P. Sloan gave customers more than a cheap car, he invested on style, power and prestige without neglecting the significance of cost. There are other examples throughout automotive history that can attest that both technology and market changes can create the right circumstances for new strategies to emerge (Ibusuki and Kaminski 2007).

The classical arrangement of a supply chain in the automotive industry as seen in Figure 2-1 is composed of distinct layers that may sometimes overlap. On the top of the chain are the Original Equipment Manufacturers (OEMs). These are vehicle manufacturers that do not only produce the greatest part of the car components (around 70%) but are also responsible for the entire design and development work. These are followed by the "Tier-1" suppliers, which are major suppliers that sell finished components to the OEMs. Subsequently there are the "Tier-2" companies, which represent key suppliers to Tier-1 firms and, do not supply directly the OEM. The following suppliers, the "Tier-3" or "Tier-4", are firms that supply the Tier-2 companies and, usually provide the basic raw materials. In spite of all that, a company may be a Tier-1 supplier to one OEM and also a Tier-2 to another or even, a Tier-1 supplier for one product and a Tier-2 supplier for a different product for the same OEM.

Since the beginning, the automotive industry has been evolving towards a more efficient business, always looking for new ways to improve its supply-chain, reduce time-to-market and integrate global operations. This evolution co-occurred with several mergers between key OEMs over the years, thus reducing considerably the number of nameplates. These major dealers were offering products and brands from many different automotive manufacturers (Davenport, Leibold, and Voelpel 2007).

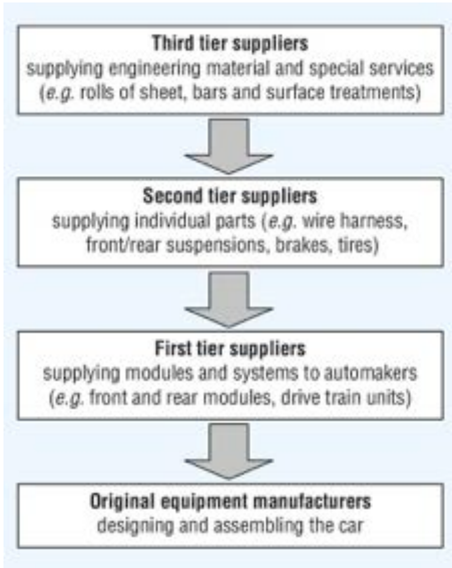


Figure 2-1 - Scheme for the Automotive Industry Supply chain

It was in the 70's that this business model began to experience some changes. More and more products were being purchased from external suppliers, maintaining however the vehicle assembly and the majority of engineering and product design work being carried out in-house (Miller 2005). The following section will cover some of these changes, attempting to explain its source, reflect on its consequences and, also, trying to depict today's reality.

2.1.1 Change of Paradigm: OEMs vs VBOs

In the more recent decades, the automotive industry has been suffering another drastic change, a paradigm shift due to the political and economic circumstances of today's world. What used to be a well-structured supply-chain with the OEM at the top followed by a few thousand Tier-1 suppliers is disappearing to make place for a new business model, the Vehicle Brand Owner (VBO). The latter is mostly about managing, marketing and sustaining the nameplates thus, entrusting most of the responsibility and the manufacture work to outsourced companies (PriceWaterhouseCoopers 2000).

In the OEM business model, all the development and engineering was a secret kept under locked keys by the OEMs. They would only advance a detailed design of the product to be manufactured to potential suppliers so they could vie between them to get the contract. Usually the supplier that presented the lowest price got the contract, agreeing with a specific fixed price, production volume and period of time. Apart from price, suppliers would also be evaluated regarding manufacturing capability, capacity, reputation, reliability and, in a lower degree by product quality. Recurrently, the OEMs could hold legal ownership of all the tool sets, moulds and stamping dies. The supplier's role was mostly limited to engineer the best way to manufacture the product at the lowest cost and with an acceptable gain (Miller 2005).

With this inverted pyramid model, the OEM's hand over most of the power and responsibility relieving a substantial part of their costs and, in some extent, empowering the most ambitious Tier-1 suppliers, which readily embraced the opportunity to upgrade their "status" to "Tier one-half systems integrators" (Tier-0,5). This means that they cover part of the responsibility formerly assumed by the OEMs, namely product design and development and, supply chain management. (Davenport, Leibold, and Voelpel 2007; OTM 2005; Harrington 2007). This kind of responsibility will bring the biggest challenge of them all, how to maintain confidentiality within different relationships with VBOs while assuming the best practices. The relationships between mega-suppliers and VBOs are key to success. In this new business model, suppliers are assessed more judiciously. VBOs should no longer focus so much on short-term price to be equally able to equate corporate stability, product design and production engineering capabilities. Subsequent levels of the supply chain should also receive attention, particularly on the degree of reliability, availability to locate the plants near OEMs and participation in the assembly process (Miller 2005). This means that the OEMs/VBOs now expect their Tier-1 suppliers to submit ideas on how their products and systems should evolve, and make proposals on how these would fit the OEM product line-up. The early and final steps of design and development process may be performed in a partnership relationship, but the steps in between should be fully borne by the suppliers. Such shifts of roles will inevitable have consequences throughout the entire supply-chain. (Willem van der Wiel 2012; Mehta 2000) ; .

This tendency transpires the state at which the automotive industry reached; today the sale of vehicles by itself does not bring much profit for OEMs but, on the other hand, services such as assistance and repair or, aftermarket and car finance proved to be very lucrative. The VBOs would become a kind of relationship manager: they would be in charge of the creation and maintenance of new alliances, the enrichment of the supply chain networks and the direct communication with customers. Because of all that, the progression from one business model to another seems only to be expected (Davenport, Leibold, and Voelpel 2007).

The suppliers that assume the Tier-0,5 category will have to make substantial efforts in order to meet with its new expectations, only the best production practices will be considered. Complying with just-in-time requirements to diminish inventory exposure and offering only the best manufacturing practices should be the way to go. This means that not all suppliers will want or will have the conditions to take this path. After all, the ones who actually decide to give that step will have to seriously invest in technology development, either by developing it themselves or by acquiring/merging with other firms that have the proper know-how. There are studies suggesting that companies that remain in the same category may be more lucrative in the short-run but will eventually struggle with the fierce competition if they do not present differentiation factors. The two world leading Tier-0,5 companies regarding parts production are Delphi and Visteon, both good examples of companies formed from the divorce of small businesses with their parent-company, GM in 1999 and Ford in 2000 respectively (Miller 2005).

VBO model is very much based on a consumer centred model, or at least it is believed to be true in the future. The companies will no longer be the sole dictators of the rules but instead, they will be closer than ever to the customers in order to better understand their needs, and to rapidly answer to their demands. A new customer interface will emerge using alternative channels and a fresher message. The cost of maintaining a distribution network, such is the case of the dealerships, will eventually become superfluous in many markets. Today’s reality shows us that a customer who has better access to information, easily acquired in the borderless world of technology, will be a more demanding customer. Ergo, a relationship based on a simple “one-to-one” approach should be much more effective than a “one size fits all” (PriceWaterhouseCoopers 2000).

2.2 GLOBALIZATION

Transportation is a synonym for both freedom and proximity, making it a key element of the globalized world. Nowadays, information, products and people travel across the world quite easily, resulting in an unparalleled increase of competitiveness, because the market is now global.

In the automotive industry, the pressure to keep the costs down is higher than before, and the use of common parts throughout different models is a predictable procedure for multi-country platforms of global OEMs. However, this approach needs to be pondered and must have into consideration the local market. From regulations to climate conditions or material availability, there are many factors that must be evaluated locally in order to avoid an "over-designed" and "over-costly" product, which happens if one tries to satisfy the higher common denominator for each specification. For the most part, this broad approach has the advantage of achieving the intentioned costs savings, insofar as it benefit from scale economy, shorter development times, proven designs and fewer tests (ICRA 2011).

As the automotive industry is a very challenging industry regarding quality, reliability, safety and price, a special emphasis is given to the effort of reducing costs and enhancing efficiency. As previously stated, in order to reduce the overall cost it is necessary to take into account that if one plans carefully in advance it will diminish the probability of having to make changes in the future, thereby avoiding not accounted costs.

From its inception, the automotive industry seeks to reduce production time and costs and, despite Henry Ford’s assembly line, which reduced time by 90% revolutionizing the sector, this is still a concern. We live in a world more and more global that promotes the competitiveness along with a greater productivity, thus, every manufacturer that wants to endure and prosper has to reduce the production and development times while reducing the components costs and maintaining its performance and quality standards. On the other hand, the manufacturers need to add value to their products by redesigning functionality or by reducing its complexity (SODECIA 2012).

2.3 SAFETY AND SECURITY

Another serious concern derived from globalization is the awareness that one should ensure greater safety and comfort as the traffic increases. Investment in R&D and in transport policies is continually growing to ensure a future with less road accidents and a greener industry.

Road safety is a pivot concern for all stakeholders as it may dictate the sustainability of the industry itself. By becoming an affordable asset to all families, the automobile became a repeated sight in cities all over the world. This phenomenon led to a serious road traffic growth that forced governments, both central and local, to rethink town planning. This new machine has the power to bring communities together but also has the power to take lives and, although the number of casualties keeps on dropping every year, automobiles are still responsible for thousands of deaths all over the world. Every player related to this industry will have to continuously contribute to the efforts of diminishing this affliction; from auto-companies and research centers to large governmental institutions all have a role to play in this fight for safety. As examples of such measures we have on the political field: better communication routes, better planning, more regulation, more investment in education and awareness and; on the technological field: better materials and strengthening of active and passive safety systems (European Council for Automotive R&D 2011).

The massive extension of regulation and laws surrounding the automotive industry can be explained by the fact that a car is the most hazardous way of transportation of today's society. In fact, the automobile is responsible for some thousands of deaths every year in Europe alone (SODECIA 2012) but, in the US the numbers are not far off, in 2008 almost six million car accidents were registered from which resulted 37.000 deaths (NHTSA 2013). And although human error is the most frequent cause for car accidents, there is a general concern for this issue. OEMs keep on improving their automobiles safety, at the same time that governments and other international institutions are campaigning for greater awareness and sensitisation in the hope for a more responsible behaviour by both drivers and pedestrians. As a consequence, consumers became more informed and safety became an essential and valued aspect when buying a car. Therefore, it is necessary that accurate information regarding safety performances for each individual car is made available. In 1997, was created an international independent entity that has been the catalyst for the continuous and rapid improvement on the car safety issue, the European New Car Assessment Program (Euro-NCAP) as it is called. This entity has the purpose of assessing vehicles performance in crash simulations, that is, they carry out several tests simulating the most serious and fatal car accidents and, rate them with the maximum of five stars according to four different areas: adult protection, child protection, pedestrian protection and safety assist. European legislation dictates a minimum statutory criterion of safety for new cars, Euro NCAP however pushes manufactures to overcome these minimum requirements (Euro NCAP 2012).

Safety is an issue that will never be entirely resolved because of the industry dynamic nature, which enables continuous improvements. As long as new materials and new designs keep emerging, safety measures have to keep up and evolve accordingly. To ensure proper performance, durability and reliability tests have to be performed in compliance with the circumstances. This requires a deep knowledge of the materials to use and a comfortable mastery of the manufacturing processes and joining techniques. The ones that have this know-how will be capable of predicting the behaviour of products in specific environments more easily. In truth, the growth of computer-aided tools that are widely used in this industry was only possible due to the great understanding of these domains (Center for Automotive Research 2011).

2.4 ENVIRONMENTAL CONCERNS

Studies show that despite being a major concern, environmental issues have little room for improvements due to the costs, manufacturing and performances requirements, among others. At this point, innovation in this field does not happen quickly as it used nor does it happen as a whole. That is, it is indisputable that great strides have been made since the beginning with regard for the environment, but today we have reached a level of steady evolution. Improvements like lightweighting or material complexity reduction, although crucial, they should be applied to entire systems instead of parts.

The automotive industry has come a long way towards the new challenges posed by today's society. In one hand, there are the general demands concerning the environment preservation and better safety solutions, i.e., the industry's R&D teams have been working to reduce energy consumption, to improve energy efficiency, and to carefully analyse components life-cycle and materials recyclability. All this without disregarding occupants safety and comfort.

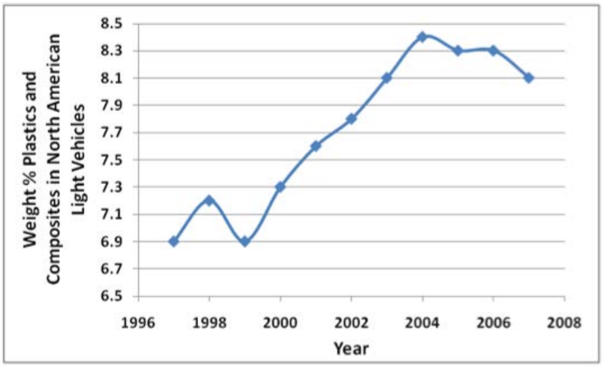
Environmental concerns have become a global issue with growing relevance that led to the creation of special regulation, for instance, the control of CO^2 emissions. The efforts made in energy efficiency and automotive technologies are scarce to offset the growth in traffic. Notwithstanding, the weight reduction appears to be the more efficient way to reduce the emissions as it reduces the fuel consumption. Regulation was also created to encourage the investment in renewable energies as a viable alternative to fossil fuels, and to pressure a cautious analysis of the components life-cycle and their recyclability.

2.4.1 END-OF-LIFE VEHICLE RECYCLING

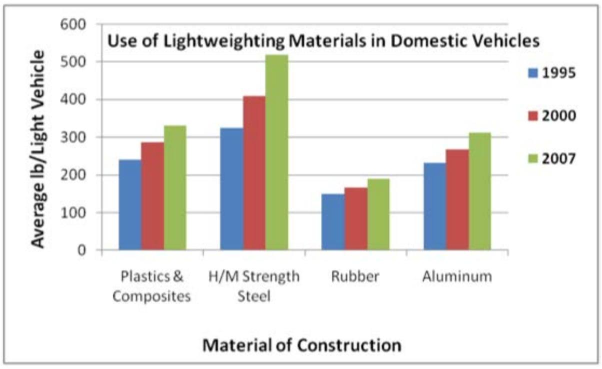
The automotive industry is one of the largest consumers of materials. In 2007, between cars and trucks there were 246 millions of vehicles on US roads with an average weight of 4,076 lb (1,849 kg). The math is quite simple, between metals, plastics, composites, rubber and glass there were about 1 million tons of materials among these vehicles. The energy needed to produce just 32 million tons of materials (regarding the amount used in the domestic US automotive industry in 1999, including passenger cars, truck, buses and replacement parts) is equivalent to about 250 million barrels of oil. And because this industry is the largest consumer of materials it is only natural that it also represents the largest source of recycled materials (Jody et al. 2010).

Over the last decades, great efforts were dedicated to improve the recycling rate of end-of-life vehicles, giving the main focus to the separation and recover of non-metallic materials from the shredder residue. The increase of lightweight materials for more energy efficient vehicles will give rise to a growth of the percentage of shredder residue that must be disposed of, compared with the percentage of metals recovered. This means that, as materials evolve new technologies must be developed to ensure the system sustainability. Without a viable shredder industry behind, the amount of scrap available will diminish and, therefore the companies will be obliged to turn to primary ores for production of finish metals. Of course this would have a severe impact on environment, energy consumptions would increase and greenhouse emissions too.

The average weight of vehicles has increased but also has the percentage of lightweight materials (see Graphic 2-1 and Graphic 2-2), which may result in more waste in the landfill unless, new technologies are developed to enhance the recyclability of these materials.



Graphic 2-1 - Presence of Plastics and Composites in North American Light Vehicles (Jody et al. 2010)



Graphic 2-2 - Use of Lightweighting Materials in Vehicles (Jody et al. 2010)

2.4.2 Automotive Material Recyclers

To achieve a level of vehicles recyclability that is sustainable and economic it is necessary that all stakeholders work together. Only with a comprehensive approach will be possible to develop the needed processes to efficiently and in accordance with the regulations, meet the market needs.

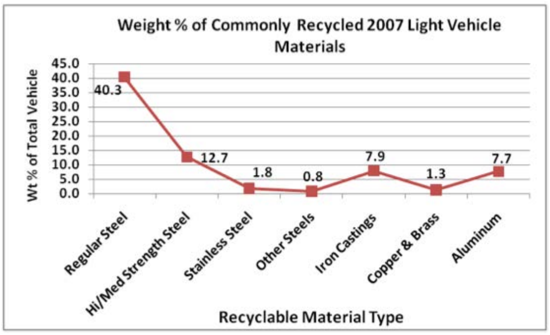
End-of-life vehicles usually go to the automotive dismantlers first, where they are processed and useable parts are recovered from the vehicle. This procedure provides a low-cost replacement parts to repair shops, parts brokers and individual customers. Some of these recovered parts must be remanufactured, that is, some parts must be torn down, inspected and the faulty components replaced. In truth, many automotive components are remanufactured, as this is a way to provide low-cost repair and to reduce replacement parts cost. Only then comes the stage of recover recyclable materials. The auto hulk and other materials are processed in a shredder, which consists of a large hammer mill tearing up the auto hulk into small blocks of materials. Afterwards, the materials are separated to be then recycled into new products. However, not all the materials are recyclable so the remaining scrap, the shredder residue, will be disposed either by throwing it to landfills or by incineration, being the first the most used practice (Jody et al. 2010).

2.4.3 Regulations

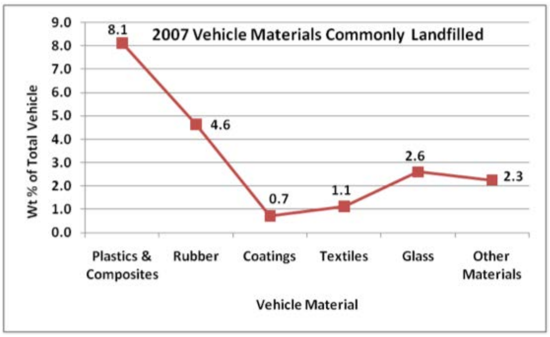
“For an activity to be sustainable it must be economically attractive and environmentally friendly and provide a beneficial service to society in a safe and responsible manner.” Given the challenges of materials shortages, increase costs and tighter regulations, one of the goals of modern industry is achieve sustainability.

There might be different regulations for different countries throughout the world but the European Union regulations are probably the strictest ones. In September of 2000, the EU issued a directive that included several rigorous provisions on the disposal of end-of-life vehicles, including provisions relating to product accountability attributed to the vehicle manufacturers besides, also mentioning the need for the increase of the reuse and recovery to at least 95% by 2015 (Jody et al. 2010).

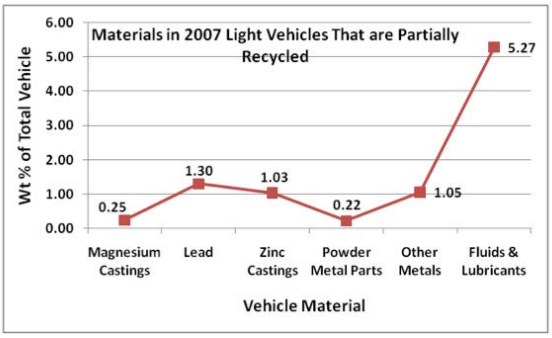
The graphics below show the materials that are presently recycled, the ones that are partially recycled and the ones that are not recycled at all. About 75% of vehicle weight is metals (see Graphic 2-3), which are profitable recycled via parts reuse and remanufacturing, and by shredding. The non-metals (see Graphic 2-4), which add up to 20% of vehicle weight are not recycled and, the remaining materials (see Graphic 2-5) are only partially recycled.



Graphic 2-3 - Recyclable Materials in an Average Light Vehicle (Jody et al. 2010)



Graphic 2-4 - Landfilled Materials in an Average Light Vehicle (Jody et al. 2010)



Graphic 2-5 – Partially Recycled Materials in an Average Light Vehicle (Jody et al. 2010)

2.5 Design Drivers

2.5.1 Lightweighting

Wanting to make a car lighter is not news, Henry Ford was one of the biggest promoters of such idea, but only in the last 50 years was developed the technology that was needed to make great progress in that direction. Even now, using lightweight materials is not a matter of just replacing the ones being used. Factors like existing infrastructure, material cost, and high volume capacity become of great importance for mass production vehicles.

The benefits of automotive lighweighting are many, as can be seen below (Center for Automotive Research 2011):

- The first benefit should be the obvious impact on fuel-consumption; if a vehicle is lighter then it takes less work to move it. It is estimated that a 10% reduction in mass results in a 3 to 7 % reduction in fuel consumption.

- The use of lightweight materials has also the advantage of reducing the overall CO_2 emissions generation of the vehicle. Even for the use cycle of the vehicle, which is responsible for the larger part of the emissions during vehicle lifecycle (see Graphic 2-6).

- Performance can also increase with the use of lightweight materials. A mass reduction of the parts that are not supported by the suspension has a good impact on noise, vibration and handling of the vehicle. Also, lowering the center of gravity, by reducing the weight at the top, reduces the risk of rollover.

- At last, by reducing the overall vehicle weight it is possible to introduce new systems into the car without significant impairment of performance. There are always new systems to be installed, whether it is equipment to give more comfort to the occupants, or electrical batteries, thus this weight reduction must really be something to conquer.

Graphic 2-6- Comparison of Greenhouse Gas Emissions for different materials throughout the Vehicle Lifecycle (Center for Automotive Research 2011)

These advantages show that despite the changes of needs that may happen or the evolution in technology that will continue to occur, the vehicle lightweighting will inevitably continue to be a concern due to the increase of overall performance it allows.

There are essentially three ways to accomplish that weight reduction:

1. **Reduce Size -**in order to reduce mass, the most straightforward method is to reduce the overall size. However, this is not really an option, especially in the US where large cars, like the Sport Utility Vehicle (SUV), is continuingly gaining admirers. This can be a viable solution for specific niche markets; the Smart for Two is a good example.

2. **Redesign and Reduce Content -**If reducing the overall size can turn out to be a difficult product to sell then, to redesign and/or reduce the number of parts can be an alternative method of lighweihting. Redesign would be something like changing the body construction, which can be problematic as it results in volume variations and, most likely in complex solutions hard to produce and assembly. Reduce the number of non-structural parts goes in the opposite direction of the future trends, customers will demand more and more equipment to be made available for their comfort or safety.

3. **Material Selection** -Lightweighting through material substitution is probably the best method once it is the only that does not affect directly the end-user. The challenge is to find a material that can give the same performance without having to change the overall vehicle size. The traditional mild steel, with its low-cost, high-strength and capacity for high volumes production, is being replaced for compatible lightweight materials.

2.5.2 Numerical Simulation

The use of numerical simulation emerges from the need to reduce costs and development times at the same time as it helps to select more suited solutions regarding design, materials, etc. for the problem at hands. Numerical simulation is not however an expeditious procedure, the creation of the right environment, like for example, the creation of the boundary conditions that best simulate reality can turn out to be rather onerous. But once achieved, one can simulate various scenarios without much sweat. Nowadays, numerical simulation is expected to be consistently used in the development process by automotive industry, notwithstanding the traditional experimental testing can not be entirely forgotten, after all, the computational calculations have to be validated. The major advantage of computational simulations should be the significant shortening of time for testing and, inevitably, the costs reduction (Tabacu, Tabacu, and Hadar 2011)

Experimental testing is still a valuable method of assessing product performance despite they are very costly and time-consuming. Additionally to the time it takes to build the required prototypes, it is a procedure that also requires sophisticated instrumentation and certain amount of manpower. And in the end, this kind of technique is not flawless, the results may reflect localized phenomena and if not carefully analysed may cause to under- or over-evaluate the overall response. On the other hand, there are the numerical methods, which allow a much in-depth analysis of the structures. In this case, the problem is divided into small parts, the finite elements, and each one obeys to known rules and equations according to their mathematical and material model. (Tabacu, Tabacu, and Hadar 2011)

The major challenge of numerical simulation is to correctly describe reality through equations, that is, this method is only as good as the numerical representation of reality is.

2.5.3 Prototyping

Prototyping is a mandatory step of the experimental testing. But in spite of that, prototyping can be very costly and time consuming because most of the times several copies of the same component must be built in order to do all testing necessary and if the design does not pass, then several other prototypes must be build again. For this reason, numerical simulation technologies are used today in a large-scale and with very successful results. Prototyping continues to be extremely important, but due to the abovementioned reasons should only be performed on a stage where the design is already optimized, i.e., if the results are not good enough during the simulation, testing the physical component will be a waste of time and resources. Numerical simulations are pretty complete nowadays, with a typical simulation including a static analysis to assess the stress distribution and deformation, modal analysis to verify NVH performance and, of course, an impact analysis to evaluate the crashworthiness performance.

2.5.4 Costs

The oil crisis of the 70’s awoke the OEM’s for the need to increase vehicle fuel economy. Along with more efficient powertrains, it also brought an urgent search for mass reduction. From those days on, there has been a globalized effort to develop lighter car. This task has proved to be a rather difficult one as the safety and comfort features have substantially increased since then. It is a constant juggling of priorities between regulations to meet, performances to guarantee and costs to expect, and fortunately, the technology, that allows creating new materials, upgrade existing ones or improve processes, keeps booming. The search for light, smart and innovative materials is believed to be one of the ways to accomplish a successful future for the automotive industry.

The automotive industry is essentially a mass-market production business, that is, affordability, diversity and competitiveness are prime concerns for this industry. The development of better materials and more suitable manufacturing techniques will allow for an increase of production efficiency, which consequently will enable the creation of competitive and affordable products. (European Council for Automotive R&D 2011)

The cost issue can be a bit tricky to assess because it involves a handful of variables and the optimal solution comes from seeing the big picture, that is, being always aware of all the factors involved regardless it is a product designed from scratch or not. One of the overall cost components is the infrastructure. So, it is crucial to understand if one will need to invest in new equipment, or if it is possible to use the ones that already exist. Both machine tools and assembly equipment count as company investment and, because they are evaluated according to their working lifespan whenever it is possible to take advantage of this existing equipment there will be room for lowering the costs and thus gain in competitiveness. The material cost is itself another fraction of the total expenses. Since the price is usually associated with weight ($/lb. or €/kg), when it comes to high production volumes this issue gains greater relevance. Niche markets may present an unique opportunity for both infrastructure investment and the use of expensive materials seeing that these vehicles typify low production volumes and may not justify mass production. Still with regard to the material cost, it should also be taken into account the issue of supply chain volatility, i.e., since most materials used in automotive applications are mined, there is necessarily a dependence upon the countries that have the raw material. The political instability lived in some countries may be responsible for fluctuations in both supply and cost of a particular material. But, on the other hand, the introduction of new materials, like the plastics and composites have their risks as well. Any new material has to endure years of testing to ensure that it has the structural and long-term capability to meet the rigorous automotive demands. This can be a lengthy process and will definitely be expensive, being that in the end there is not even the certainty of success. But if there is, it will result in a significant edge for the company (Center for Automotive Research 2011).

2.5.5 Material Selection Processes

Nowadays, engineers are confronted with a spectrum of thousands of different materials from which they have to choose the most suited one along with the best manufacturing process for the problem at hands. The succeeding screenings from all available materials till the top 10 that best meets the application demands is what the material selection process is all about.

The increase in the industry competitiveness has given a great power to materials, designers are forced to understand better than ever the material selection process. Despite the technical data (physical, mechanical, chemical, etc) they must also be aware of the materials intangible aspects because they might want to take advantage of them in order to provoke certain emotions.

Material Selection is a very complex and time-consuming process because beyond all that was mentioned before, there are many variables to consider and their relative importance is not clearly set. In fact, the numerous objectives and constraints can only be outlined according to each problem because variables may differ from one problem to another. The problem must be understood very well in order to be possible to make better choices. On that account, the use of quantitative and systematic methods can be of utmost help. This field is becoming more and more relevant receiving recognition as one of the top branches within the materials science and engineering discipline (Karana, Hekkert, and Kandachar 2008).

2.6 MATERIALS FOR STRUCTURE APPLICATIONS

Material selection is a process that has always been present throughout Man’s history with design and craftsmanship. While some materials may be found in nature, others are produced by a few processing techniques which allows to shape the material with the desired properties. Only with the continual increase of knowledge and the development of specific tools it was possible to leave the era of stone, bronze and iron behind and enter into today’s world, where there is a huge selection of materials and "sub-materials". However, this progression turn out to be quite steady till the beginning of the 20th century, where the primary materials used were mainly timber, concrete, steel and copper since they were enough to fulfil the engineering requirements at that time. It was not until the second half of that same century that scientists began to understand the relationships between material structure and its properties. This set in motion a particularly important growth for new solutions; the need for innovative and more adequate solutions led to a more active and dynamic attitude. Regardless the business sector, the materials were constantly being altered or replaced so that they could meet the latest demands, whether they were higher services temperatures, lighter structures or more reliable components. The result was often the introduction of newer and better materials (Farag 1989; Callister 2003) ; .

It should be noted that there are industries more risk sensitive than others and, that explains why the evolution of materials used may take different paths depending on the industry. And, if at first the empirical experience was enough, nowadays one can no longer say the same, particularly in the automotive industry. New materials can take several years to be accepted and widely adopted, since a pile of data on their "DNA" and their performance must accompany them in order to reduce the risk involved. This data should ensure and confirm the reliability of these materials according to their purpose. What one finds is that industries less sensitive to risk usually turn out to be the most innovative and the ones who make way for other industries to move forward with greater confidence and lesser risk.

Selecting a material that best suits a particular purpose can be, like in many other decisions during design and product development, an expensive and time-consuming process, involving a constant juggling of priorities. Many compromises have to be made along the way since the ideal material does not actually exist, despite our continuous efforts to achieve it. On another hand, since every problem has its own constraints, whether intrinsic or acquired, the path to follow is not clear-cut. The search criteria for the optimum material can vary according to different factors, like the type of industry, target-market, regulations, timing, properties, manufacturing, etc. and there is no consensus in which ones are truly effective in the material selection process. Different authors suggest different approaches to this problem by assuming that there are material aspects more important than others or simply by choosing some of them over others. However, all these theories arise within a given context and it is interesting to note that they have evolved towards becoming both more complex and complete as the materials themselves multiply and the regulations become more restricted. Despite all that, they all agree that not only mechanical properties but also cost are of the utmost importance. These are obvious factors to consider when choosing a material. In fact, the first has to do with the requirements established in the primary steps of the design process, that assure that the component will bear out its purpose and will serve as basis. The second aspect is a compulsory and an unavoidable factor which ultimately decides which direction to follow, i.e., it limits to some extent the range of potential materials to be used (Karana, Hekkert, and Kandachar 2008).

Regardless the exhaustive amount of material data available on handbooks, suppliers or others, there is still a general frustration among designers with respect to non-measurable aspects of materials. Although physical and tangible aspects represent the most expeditious approach and are traditionally the primary aspects to consider, product designers do not base their choice of materials solely on these aspects. Budinski, for instance, recalls that it may be decisive to also analyse the available size, shape, finish and tolerances of materials (Karana, Hekkert, and Kandachar 2008).

Generally speaking, all aspects to consider in the material selection process, whatever the weight given to each, can be placed in one of these groups:

Table 2-1 - Aspects to consider in material selection

GENERAL ATTRIBUTES		Physical and Chemical Properties Metallurgy Considerations Product Size and Shape
MECHANICAL PROPERTIES	Service Demands	Strength Rigidity Heat Resistance Electric Conductivity
	Production Demands	Dimension Stability Ability to be Shaped Ability to be Joined Tolerances Production Cost
BUSINESS ISSUES	Economic Factors	Price Availability Machine Tools
	Policies and Regulations	Industry Regulations Country Restrictions Political Goals Health and Safety Regulations
	Environmental Factors	Material / Product Life-Cycle
OTHERS	Aesthetic Attributes	Touch Smell Visual
	Perception	Quality

When looking into materials mechanical properties it is almost always necessary to study the requirements for service and for fabrication/production separately. According to Patton (Karana, Hekkert, and Kandachar 2008), the service demands are pivotal as the component has to fulfil its purpose otherwise it becomes useless and superfluous. But the material's ability to be shaped and joined with other materials is of major importance as well. The more limited these abilities are, the more complicated and expensive it gets to work the material, having no use in the end. Patton also states that a designer has the responsibility to search for the most economical solution, it is of little use to have a more costly material that may even not require machining, when a simpler and cheaper material which may require extra machining does the trick for a better overall cost.

Within the business issues one must watch out for the economic factors, already mentioned in chapter 2.5.4, policies and regulations that might apply and, finally the environmental factors. The latter may be included in the regulations group but due to its importance may also be considered separately. The economic factors consist mostly in the duality of costs and availability. With this regard, Budinski emphasizes the designer responsibility of selecting a material that can be obtained within a certain time frame, if this matter is overlooked it may cause a serious setback to the process and, the costs may rise exponentially. As to the regulations and policies, these have the power to outlaw specific materials and manufacturing process if they believe them to be prejudicial to health. Besides, these regulatory agencies also indicate special guides that each industry should follow, which may not be directly related to the choice of material but it will affect it. In the case of the automotive industry there are specific safety parameters to fulfil and, also, environmental targets to meet. The environmental concern should cover the impact of production, manufacturing, use, reuse and finally the material disposal. Mangonon (Karana, Hekkert, and Kandachar 2008) believes that the cost of including these concerns during product development can be a significant impediment and so, most companies only do it if required by law.

While the primary focus of most authors is confined to the materials technical aspects, Ashby and Johnson also include issues like perception and sensorial properties. These intangible aspects of materials, or “indefinable characteristics” as Lindbeck (Karana, Hekkert, and Kandachar 2008) says, are the features that give personality to a product, that is, they stir our senses and emotions. This field of materials science is gaining ground with the marketing strategies wanting to use these features as differentiators. Patton suggests that the market is prepared to economically value more this type of feature than the rigidity or dimensional stability, for example.

2.6.1 Material Classification

Solid materials have been grouped primarily according to their chemical composition and atomic structure, originating the big three: metal, ceramics and polymers. However, there are other materials that may not fit into one particular group but instead may overlap between two of them. These are the composites, semi-conductors and biomaterials. In the following paragraphs it will be given a small description of the major aspects of each material group, excluding ceramics, semi-conductors and biomaterials once they are not essential for the purpose of this study (Callister 2003).

A - METALLIC MATERIALS

Metals were the dominant material in the past for structural applications and to some extent continue to be the most obvious ones, as these constitute the most studied materials and of which there is more available and corroborated information.

Metallic materials are combinations of metallic elements, which means they have a large number of free electrons that are responsible for their good conductivity to heat and electricity and, also because of the metallic bonding characteristics, they exhibit a type of deformation mechanism that enables a relatively high strength and toughness. Within this group there are the pure metals like iron, aluminium, magnesium, lead, etc and the mixtures commonly known as alloys that are more frequently used in structural applications due to their better properties.

The ferrous alloys that represent the largest portion of engineering materials world production have iron as the base metal and, because of their low-cost solution and their versatility they are the favourite option for a wide spectrum of applications. In this category there are alloys with so much as 98% of iron and alloys that can go up to 50% of other alloy elements. The remaining metallic materials such as aluminium, magnesium, titanium, etc. fit in the category of non-ferrous alloys. Although, the comparatively higher cost, they become appealing when searching for specific properties like high electrical conductivity, lightweight or corrosion resistance. Within each group of alloys it is customary to do a differentiation in relation to its chemical composition, finished method or product form but other common and useful division for the metallic materials is according to their production method, i.e., they may be classified as cast alloys which means they are cast directly into shape, as wrought alloys when they are shaped by hot or cold work into semi-finished products like plates, sheets, etc. or even as powder metals which are compacted and sintered to produce ready-to-use components (Farag 1989).

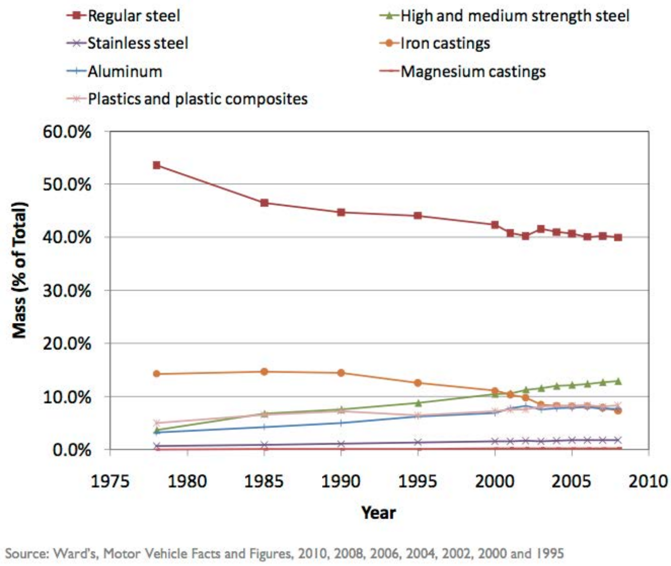
Metallic materials are a typical and predictable selection for most engineering applications due to their good mechanical properties. By having greater strength it allows smaller thicknesses/sections, which may result in lighter components and by having higher toughness is less prone to sudden failures during service. However, these two properties are usually inversely proportional so, one should seek the balance that best meets the demands of use. Another important property is the modulus of elasticity, a property that gives an insight of the material elastic behaviour by disclosing its stiffness. As a valuable design parameter is to be noted that for most steels this value is approximately 210 GPa and for Aluminium is around 70 GPa. (Farag 1989)

As said before, in order to design and select the appropriate material for a given component, one should consider carefully different aspects; all chemical and mechanical properties are undeniably important but the material manufacturing process and, the material ability to be welded and/or machined are also of crucial significance. For instance, wrought microstructures are stronger and more ductile than cast microstructures, this fact along with the ease of obtaining various shapes and tolerances makes the first to be preferred. However, the shape requirements may restrict the number of materials available. On the one hand, for hot-worked products tolerances may be quite wide causing complications in additional processing and, on the other hand, for cold-worked products the tolerances are smaller but the presence of residual stresses can also create problems during the additional processing. Weldability and machinability should be considered in light of each case nevertheless, these abilities could be improved by adding some alloying elements, but not without sacrificing the material strength and toughness. (Farag 1989)

The elasticity modulus as stated before is a measure of the material elastic behaviour but contrary to other mechanical properties it is not markedly influenced by alloying or heat treatment. Exceeding the elastic range, metals present a plastic response, that is, they start to deform permanently, which is a result of slip deformation. Plastic parameters namely yield and tensile strength, are influenced by the easiness with which these dislocation movements may occur. In other words, mechanical strength is measured by the resistance to deformation since, the more difficult it is to move dislocations in the lattice the greater the forces will have to be to initiate plastic deformation. Hardness is also a plastic parameter although it deals with localized deformation and so it will follow the same principle. By obstructing or limiting the dislocation motion the material will be harder and stronger. Strengthening techniques may include reduction of grain size since grain boundaries serve as barriers, creation of solid-solutions because they impose lattice strains on surrounding host atoms, cold-working seeing that by increasing the number of dislocations they are actually being tampered with, among others (Farag 1989; Callister 2003).

Because failure is sometimes unavoidable the least to be done in such situations is to understand and try to predict in what conditions and when it might happen. Having this in mind, there is at least one more mechanical parameter worth mentioning, especially when designing structural components, and that is the fracture mode. Fracture is when a body splits in two or more pieces in response to an imposed stress at relatively low temperature; in other words, this phenomenon is about the initiation and propagation of cracks in response to stress. There are basically two fractures modes possible, ductile and brittle, and the distinction is in the material ability to deform plastically. Ductile fractures present evidence of significant plastic deformation, after the cracks are formed the propagation progresses slowly, in fact, if there is no increase in the applied stress then the crack length stops advancing. This fracture mode is traditionally more desirable because by not occurring so abruptly, it gives time to take preventive measures. Brittle fractures, on the other hand, exhibit little to no plastic deformation with low energy absorption. Contrary to ductile fracture they present unstable cracks, which means that once the propagation starts it wont stop even with no increase of the applied stress. Metallic materials are commonly known for their ductile behaviour however there are some alloys that present both behaviours by varying the temperature. Materials that undergo the ductile-to-brittle transition are materials that may be ductile at room temperature but at lower temperatures they become brittle, which can be disastrous. Metallic materials having Body-Centered Cubic (BCC) or Hexagonal Close-Packed (HCP) crystal structures are the ones to watch out for. These present both fracture modes by varying the temperature of service so, they are advised to be used at temperatures above the transition range. Metal alloys having Face-Centered Cubic (FCC) crystal structures like Aluminium based alloys, remain ductile even at low temperatures (Callister 2003).

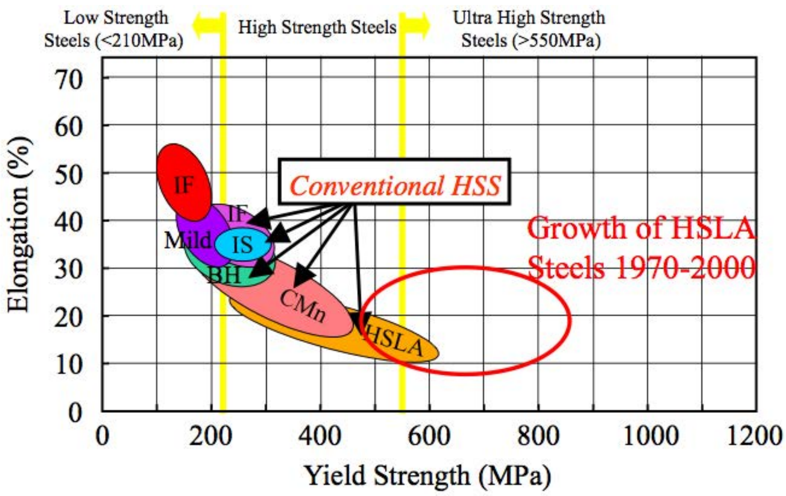
Graphic 2-7, shows the evolution of vehicle material composition over the last decades, where it is visible a steady decrease in the use of regular and mild steel in opposition to the increase of lighter materials with comparable mechanical strength, as is the case of high-strength steels, aluminium and magnesium.



Graphic 2-7 - Vehicle material composition over the last decades (Center for Automotive Research 2011)

- ### Iron and Steels

Due to a great technology development over the past decades iron and steel continue to be the most common materials used, especially for structural purposes but not limited to it. In an automotive, for instance, these materials can be seen applied in vehicle bodies, engine, chassis, wheels, etc. Although the number of materials within this group has multiplied, with the introduction of stainless steels, new compositions of iron and high strength steels, they manage to maintain the crucial aspects that make them so attractive, like reliability, strength, stiffness and low-cost. In addition to altering its composition to get more suited materials, their manufacturing abilities were also reviewed and improved to better respond to production demands. The graphic below shows the different types of steel that are used today in automotive applications.



Graphic 2-8 – Schematization of steels distribution according to total elongation and yield strength

Today’s popular high strength steels may include dual-phase, martensitic and boron steel.

Dual Phase Steels

The Dual phase steels are serious alternatives for reducing weight in structural components because of their strain hardening capacity and their strong bake hardening effect.

Dual phase steels present a hard martensitic or bainitic phase dispersed in a soft ferritic matrix, which is the reason for its exceptional combination of strength and ductility. While the ferritic phase, which is usually continuous, gives rise to excellent ductility, the martensitic phase, in the form of islands, lead to the high tensile strengths. These steels also present high strain hardenability, i.e., when deforming these steels, strain is concentrated in the ferrite phase creating high work-hardening rate. This property is of great importance because together with the high ductility it allows for higher tensile strengths when compared to steels with the same yield strength. Their yield strength can be increased by means of bake hardening process. Bake hardening is a process of increasing the yield strength by elevating the temperature aging after pre-straining. These Dual phase steels also have excellent fatigue strength and good energy absorption capacity (WorldAutoSteel 2013).

These steels are produced by controlled cooling from the austenitic phase or from two-phase ferrite plus austenite phase to transform some austenite to ferrite before a rapid cooling transforms the remaining austenite to martensite.

Martensitic Steels

Martensitic steels are used in applications where HSLA and dual phase steels are not enough regarding strength. This material allows thinner sections for the same mechanical resistance.

The martensitic steels are, as the name says, steels comprised essentially of a martensitic matrix. These are usually obtained by hot-stamping, that is, the steel may be formed at 950º C while is soft and then is quenched while inside the closed die to transform the austenite into martensite.

Martensite is the hardest microstructure of steels but it can be said that these steels become stronger as the carbon content increases. The down side of increasing the carbon content is the decrease of toughness and the decrease of martensitic transformation temperature. However, by means of thermal processes or by adding various key-alloying elements it can be increased the ductility, toughness and delayed cracking resistance of such materials (Mohrbacher 2013).

There are good solutions presenting an excellent toughness at a yield strength of about 1000MPa. These values can be obtained in low carbon steels that are not subjected to further tempering treatments.

Boron Steels

Boron steels belong to the ultra high-strength steels grade with its yield strength of about 1350 MPa. Boron alloying helps delaying the ferrite and pearlite formation, thus promoting martensite. This element is used to improve steel hardenability but its effect is reduced by the increase of carbon content, so these are usually low carbon steels (Association and Liverpool 2012).

Boron steels, like the previously mentioned ultra high strength steels have the inconvenience of having low formability and a striking springback at room temperature. The solution to overcome this difficulty to form with cold stamping is hot-stamping just like for martensitic steels.

- ### Light Metal Alloys

Aluminium is a less dense material if compared to steel so, it is a popular choice when searching for lighter structures particularly for Body-in-White. However, this material entails some challenges like its expressly complex forming capabilities, its low Modulus of Elasticity (1/3 that of steel), its higher cost when comparing to mild steel but, lately, its greater challenge has to do with the development of new steels grades with higher strengths and the ability to design thinner walls allowing for weight savings (Mayyas et al. 2011).

Magnesium is even less dense than aluminium and it is mostly used in thin-wall die castings. Its disadvantages include material cost, durability constraints, and limited availability of stock material (Center for Automotive Research 2011).

B - Polymers

Natural polymers derived from plants or animals, such as wood, wool, silk, leather, rubber and cotton have been used for thousands of years, however, only with modern research tools, it was possible to determinate their molecular structure. This knowledge allowed the development of synthetic polymers, which consequently led to a boom of plastics, rubbers and fibers after the World War II. The synthetic polymers can be produced inexpensively and, their properties can be controlled so that they can be superior to their natural analogue. Just as with metallic and ceramic materials, polymeric materials cover a wide range of properties depending mainly on their structural elements (Callister 2003).

Most of these materials are organic compounds that are chemically based on carbon, hydrogen and other non-metallic elements. They are formed by a large number of molecular chains that gives them an unique ability to bend, twist, curl and entangle. They are typically recognized for their low densities and exceptional flexibility. However, their ability to reduce the finishing processes, noise and vibration and, in some applications, the need of lubrication makes this material very appealing for engineering applications.

This type of materials can be divided into two groups, one being the plastics, which present a very diverse and broad spectrum of synthetic solutions and, the other group being the rubbers that are known for their extraordinary ability to deform elastically. Within the group of plastics there is an important subdivision according with its response to mechanical forces at high temperatures, these are the thermosetting polymers and the thermoplastic polymers. The thermoplastics need heat to be shaped into the desired form and, after cooling, that form is maintained. These polymers have the particularity of being able to reverse the process and be formed again and again without jeopardizing much the material properties. On the other hand, there are the thermosettings, which due to a hardening chemical reaction they are not recyclable. After the thermosettings are shaped and cured they become hard and they do not soften upon subsequent heating. Despite the fact that additional heating would cause loss and degradation of properties these materials withstand relatively high service temperatures (Smith 1998).

This type of material have been around within the automotive industry for quite some time now, the first car using polymers was the Corvette in 1953. Polymers present very compelling features to the automotive industry as the possibility of weight reduction, greater parts consolidation, increased design flexibility and corrosion resistance plus, they also present an anisotropic character and a satisfactory mechanical behaviour. However, polymers are not used in large-scale products since most of their limitations have not yet been overcome.

Among these drawbacks are the high material cost and the slow production rates in addition to the concern for crash energy absorption and for recycling goals (Ghassemieh 2011).

The greatest advantage of plastics is obviously its low density compared to metallic materials, but its mechanical properties are not as high. This kind of material is also not appropriate for applications that require high service temperatures. Since the thermoplastics can be "re-formed" over again, its service temperature should generally be lower than in comparison with thermosetting polymers. What happens is that as temperature increases the secondary bonds between the molecular chains get weaker and consequently there is a decrease in mechanical properties. Although the thermoset material withstands higher service temperatures they also get weaker when the temperature is increased. Typically, these are more stable at elevated temperatures, but there are also exceptions of thermoplastic polymers that resist high temperatures (between 100ºC and 200ºC) (Smith 1998).

Plastics fracture strength is usually lower if compared to metals and ceramics. Typically, a thermosetting polymer is brittle and a thermoplastic polymer can present both fracture modes. Brittle mode can be favoured by reducing the temperature or increasing the strain rate, or even by the presence of a sharp notch and greater thickness. Glassy thermoplastics become ductil as the temperature is increased and around the area of their glass transition temperatures they experience plastic yielding prior to fracture.

Polymers may be modified in order to improve their mechanical, chemical and/or physical properties. And that is accomplished by introducing additives, which include fillers, plasticizers, stabilizers, colorants and flame-retardants.

Plastics can be bought in multiple forms: sheets, rods, pellets and granules. And, they can be formed into near-net-shape or net-shape parts. Because of the good surface finishing characteristic, this material allows to eliminate the superfluous machining operations, and because it has a low melting temperature, this material is easier to process than steel, although is also more time-consuming (Mazumdar 2001).

- **Thermoplastic Polymers**

The deformation of these materials can be elastic, plastic or both. The glass transition temperature defines exactly that. Above this temperature the thermoplastic material will deform plastically whereas below this temperature the material will deform elastically. In other words, the glass transition defines when the material stops being brittle and become ductile and vice-versa. There are several factors responsible for the material mechanical properties.

The most common thermoplastic manufacturing processes are injection moulding, extrusion and blow moulding.

- **Thermosetting Polymers**

Thermosetting polymers are often used in the form of a mixture, that is, they may consist of two components: a resin that facilitates the cure and, a filler. Regarding their properties it can be said, that they tend to have higher densities and lower tensile strength comparing to other plastics. However, if these thermosettings are glass reinforced then their tensile strength and impact resistance are greatly improved.

Generally speaking these materials have one or more of the following advantages:

- high thermal stability;
- high rigidity;
- high dimensional stability;
- resistance to creep and deformation under load;
- low density;
- good thermal and electric insulation properties;

Compression moulding or transfer moulding are the most common manufacturing process for these types of plastics but in some cases, injection moulding may also be applied in order to reduce costs.

C - COMPOSITES

Composites is not a singular group, is more like a category between or within groups as it consists of more than one material type. The multiple materials within this group have been engineered so that they could comprise a combination of the best properties of each material type used.

The firsts composites to be developed were mostly used for cosmetic purposes but soon scientists and engineers realized their potential for structural applications, and after much study and refinement so it happened. Nowadays, composites represent 50 percent of the total vehicle by volume, being glass and carbon fiber the most popular ones. The glass fiber may have some shortcomings regarding strength but it is more often used than carbon fiber, which has exceptional mechanical properties. The critical disadvantages of composites are the overall material cost, its availability and the recycling limitations. (Center for Automotive Research 2011; Ghassemieh 2011)

Composites growth is explained by the need to create competitive product with good performance and lightweight. Among all materials, some people believe that this is the most promising replacement for steel and aluminium, being that sometimes it can even perform better.

Composites currently represent a considerably part of the total vehicle by volume, of which the majority is glass reinforced thermoplastic. Lately there has been an increase of carbon reinforced thermoplastic as it provides for additional strength. Among their disadvantages are the overall material cost (the CFRP can be 10 times more costly than steel), the limited availability and the recycling (Center for Automotive Research 2011). These materials are often used for applications with low production volumes because of their shortened lead times.

• Fiber-Reinforced Composites

This type of composite probably constitutes the most important composites as they are usually designed to obtain improved strength and/or stiffness on a weight basis. Its properties will be affected by the fiber length, the fiber orientation and concentration, the fiber phase and the matrix phase.

Fiber-reinforced composite mechanical properties depend upon the fiber itself, and the bond there is between the fiber and the matrix. When there is an applied stress the transmission of force between matrix and fiber only occurs where there is fiber. That is why there is a minimum length for each fiber depending on its diameter, its tensile strength and shear yield strength. The longer the fiber the greater it will be the reinforcement and the stronger it will be the composite. Better and more controlled overall composite properties are obtained when the fiber distribution is uniform. However, by changing the fiber arrangement, concentration and/or distribution one can manipulate the composite mechanical properties.

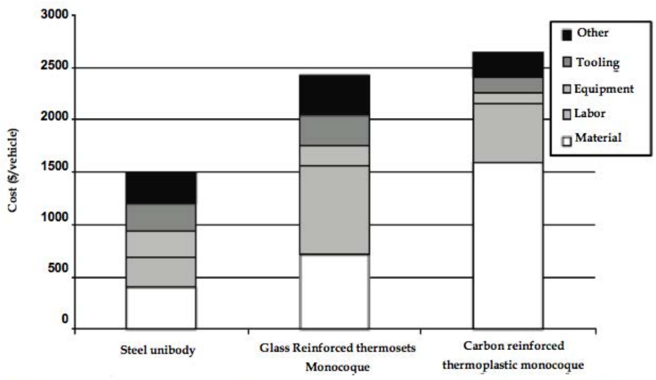
2.6.2 Overview Of Lightweight Materials

These materials are selected based on mechanical, physical and chemical properties, metallurgy, processing ability, product shape, finishing potential, cost and availability. Further on, the most relevant aspects of some common automotive materials will be presented so that is possible to assess and choose more responsibly (Farag 1989).

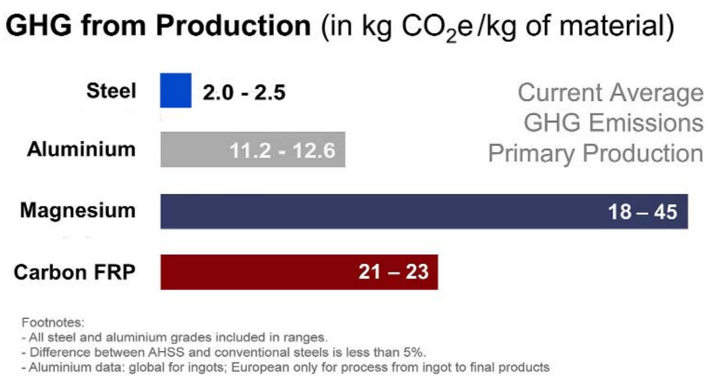
Table 2-2 - Main Properties of Lightweight Materials

	Melting Temp (ºC)	Density (g/cm^3)	Young's Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Approximate production energies (MJ/kg)
Cast Irons	1130	7,05-7,25	165-180	215-790	350-100	16,4-18,2
Low carbon steels	1480	7,8-7,9	200-215	250-395	345-580	22,4-24,8
High Carbon Steels	1289	7,8-7,9	200-215	400-1155	550-1640	24,3-26,9
Aluminium alloys	475	2,5-2,9	68-82	30-500	58-550	184-203
Magnesium alloys	447	1,74-1,95	42-47	70-400	185-475	356-394
PP	175	0,90-0,91	1,14-1,55	31,0-37,2	31,0-41,4	-
ABS	105	1,05-1,07	1,79-3,2	36,13-52,54	41	-
PC	265	1,20	2,38	62,1	62,8-72,4	-
ABS/PC	n.a.	1,1	1,83	-	34,8	-
CFRP	n.a.	1,5-1,6	69-150	550-1050	550-1050	259-286
GFRP	n.a.	1,75	15-28	110-192	138-241	107-118

One of the first things to note is the large difference between melting temperatures. Both polymers and composites do not withstand such high temperatures as metals do. Regarding density is clear that metals are heavier, although aluminium and magnesium present very attractive values as well. In terms of mechanical resistance steels are by far the best materials followed by the non-ferrous metals but, the carbon fiber reinforcement polymer can be very competitive, presenting a elasticity modulus close to the aluminium's with a better yield strength. Regarding costs, this table in addition to the Graphic 2-9 shows us, as would be expected, that the effort to produce light-metals and composites is greater than to produce steel.



Graphic 2-9 – Cost comparison of BIW designs (Ghassemieh 2011)



Graphic 2-10 –Material production greenhouse gas emission (WorldAutoSteel 2013)

Much more could be said about this subject but so as to conclude this review, the following table presents a selection of advantages and disadvantages of some key materials for structural application.

Table 2-3 -Comparison of Lightweight Automotive Materials (Center for Automotive Research 2011)

MATERIAL	BENEFITS	CONSTRAINTS	COST (PER LB.)
Aluminium	• Recyclable • Casting technology is well established • Consolidation of parts	• Corrosion • Difficult to form • Bonding is more challenging than steel	$0.90 to $1.00
High-Strength Steel	• Infrastructure is well established • Good working relationship with automotive • Material properties are well known	• Lower strength to weight ratio than other alternatives • Reducing thickness reduces material stiffness	$0.35 to $0.40
Magnesium	• Low density • Consolidation of parts • Highly recyclable	• Limited production of stock material for manufacturing • High cost • Limited familiarity within the industry	$1.70 to $2.00
Glass Fiber-Reinforced Plastic	• Consolidation of parts • Handles harsh chemical environments • Excellent damping capabilities • Accommodates complex designs	• Slow cycle times • Not recyclable • Limited strength	$0.50 to $5.00
Carbon Fiber-Reinforced Plastic	• Highest strength to weight ratio of all materials • Greatest potential for weight reduction	• Slow cycle times • High cost • Limited familiarity within the industry	$6.00 to $10.00

3
CROSS CAR BEAM

3.1 PRODUCT DESCRIPTION

An ordinary automotive vehicle frame include three pairs of vertical pillars as it is pictured in the top scheme of Figure 3-1, but depending on the class of the vehicle there may be some automobiles that have only two pairs and others that may have four. Notwithstanding, this study focuses on the front end of the vehicle, i.e., the only concern will be with the A-pillars, which are located on opposite sides of the body, between the engine compartment and the passenger compartment, typically enclosing the windshield. As part of the main body structure, the A-pillars are extremely critical for occupant protection especially in case of rollover accidents. Nonetheless, in case of a side-impact crash is the cross car beam, the element linking both A-pillars that will provide the desirable stiffness to protect the passengers.

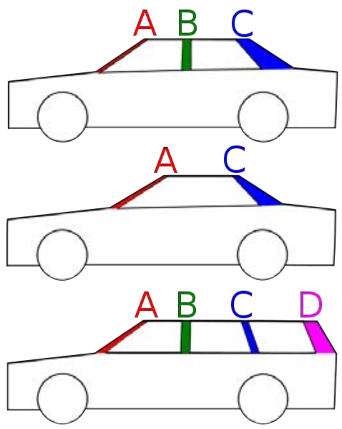


Figure 3-1 - Automotive Vehicle Pillars

The Cross Car Beam (CCB) is a component found in the front part of the vehicle, under the instrument panel (IP) and, is usually designed to support the steering column, the airbags, the instrument panel, and it can also support other systems depending on the complexity of the car in question (see Figure 3-5). Apart from the support role, this component is also instrumental in the absorption of impact-energy, minimisation of the steering wheel displacement in case of a collision, reduction of the overall cockpit vibration and, in providing a greater strength and control of the steering wheel.

The figures below (Figure 3-2, Figure 3-3, Figure 3-4) illustrate where the CCB fits within the cockpit while confirming the possibility of having with different solutions for its design. Because even though the CCB may have a structural function and thus being very important to the overall performance of the vehicle, its design is not predetermined. In fact, when thinking of designing a CCB it is important to understand that this component is intended to take the minimum space or rather merely occupy the space that is left after placing all subsystems that have to be on the front area of the cockpit, for instance: the glove box, the HVAC system, the electric wiring, and so on. This means that regarding shape itself there is no layout to follow, it will mostly depend on the type of vehicle and, the amount and type of subsystems that will constitute the cockpit. In a diminished way, one can say that the only transversal design criterion is that it must have the length of the car width, other than that, the focus should be mainly on the functional requirements.

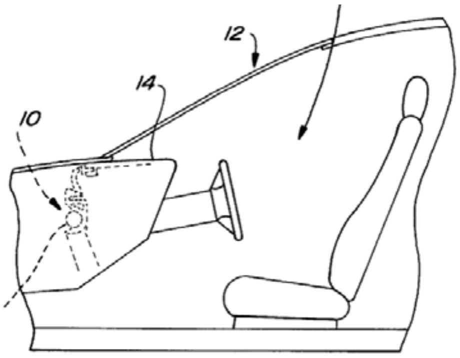


Figure 3-2 – a side view of the passenger compartment showing where the CCB is placed (Bittinger, Ozga, and Lepley 1999)

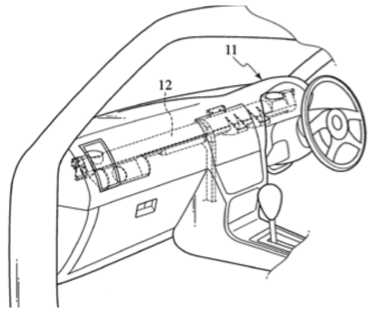


Figure 3-3 – CCB position inside the Instrument Panel in a right-hand drive vehicle (Matsutani 2006)

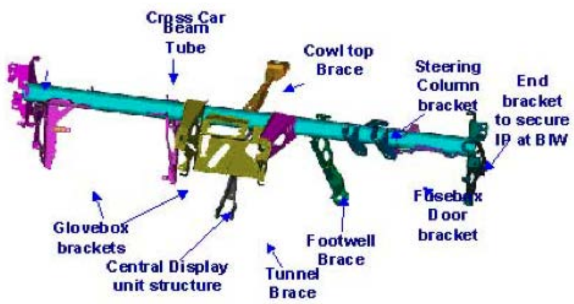


Figure 3-4 – A Standard CCB with multiple brackets attached (Jahn et al. 2004)

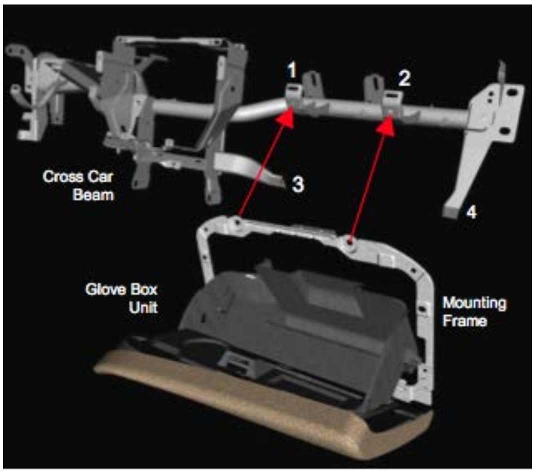


Figure 3-5 – A Standard CCB with an illustration of how adjacent components are attached (Maxfield et al. 2003)

This is a component that has suffered a considerable evolution, and it is expected to continue to do it so, by always searching for new solutions in order to keep following industry demands regarding reliability, safety and quality at the same time it maintains its production cost effectiveness as the Original Equipment Manufacturers desires. In the following paragraphs there will be described some contrasting solutions regarding architecture and material along with a overview of the influence of design in the CCB performance.

3.2 ARCHITECTURE

The architecture of a product results from the exercise of putting together function and form. In every product there will be functional elements that dictates the action and the physical elements that allows for the function to be achieved, a chunk. The architecture of a product is simply a plan that enables the organization of functional elements into physical blocks displaying their interaction.

The architecture is usually evaluated according to its degree of modularity. An utterly modular architecture is characterized as having each physical chunk assigned to a single functional element and, as having a small number of interactions between the blocks. In contrast, an integral architecture presents a scheme where functional elements may be accomplished by a couple of different chunks and a single chunk may comprise multiple functional elements. All the same, the interactions between blocks are no longer well defined as they were with modular architecture but, instead, they are blurry and may be accessory (Ulrich 2012).

The choice of architecture type has important repercussions, for example:

- Whether it is to upgrade the product or to substitute some component due to deterioration, the decision of how much modular the product will be is essential in the event of needing to redesign the product. A more modular approach allows each block to be design independently and, as a consequence a design modification can be done separately to any single block. As can be anticipated, an integral structure entails a greater effort and work to redesign a particular component because it is joined and interlinked with other components.

- Regarding product variety, the degree of modularity is also relevant because a product that may be made available in different models, will have to be produced in a certain time frame if the market demands it. And, a more modular product will facilitate this diversity of supply in a shorter timeframe without complicating the production or making it more expensive to produce.

- The argument made above is also pertinent in the case of using standardize components. A standardize component is a component that can be used in a variety of products, which can come from an internal or external source. Internal source if the company that produces the product also produces the standard component, and external source if different manufacturers use the same component from a particular supplier. Either way, the component should be though as modular so that it is less prone to conflicts. The advantages of standardization can be the possibility to reduce costs and improve quality due to the higher production volumes it allows.

- In the case of assessing product performance, the less modular the product is, the better. Since product performance has to do with the degree to which the product meets the desired function(s), if thinking in the product as a whole, an integral approach enables a reduced functional redundancy and a minimized space occupancy, thus optimizing the product and possibly reducing material and/or weight as well as lowering production costs.

- Another factor to take into consideration when deciding the product architecture is its manufacturing implications, and although smaller and less complicated components should be easier to produce actually, the Design for Manufacturing strategy entails a reduction in the number of parts by means of integration in order to achieve low cost products.

- Regarding product development management is rather easy to acknowledge that each kind of architecture requires a different approach and management style. In one hand, there is the modular architecture, which demands more planning in the initial stages, but because it deals with simple and limited problems the following stages are quite smoother. On the other hand, there is the integral architecture that does not entail such effort in the initial planning but instead it can be more challenging in the succeeding stages due to the complexity of the designs. The recognition that the modular architecture requires less coordination during the detail design phase since each chunk has its design specifications divided in a well-defined way is the reason for most companies who have to deal with dispersed teams to choose this type of architecture.

Ultimately, it can be said that the type of architecture is not an intrinsic property because most products end up presenting both traits, that is, they are more or less modular when compared to other products of the same category (Ulrich 2012).

3.2.1 MODULARITY VS. INTEGRALITY

Something is considered modular when it involves one or more modules as the basis of construction (Oxford Dictionaries) and therefore it makes sense that the degree of modularity depends on what is considered as being the product as a whole. Reviewing the CCB case, this problem can be viewed from two different perspectives, one in which the CCB is the complete product, comprising several blocks, and another in which the CCB is a block itself belonging to a larger set, a set that also includes the IP, for instance. Having said that, the next paragraphs will present an overview for both levels of modularity, first considering the CCB as the whole product and secondly, having the CCB as a component of a larger set.

A very good example of a modular CCB is depicted in the Figure 3-8. The invention (Mani 2011) aims to reduce the weight of the CCB by using light metals as opposed to steel and by adopting a configuration that allows a less costly solution, which materializes as coupling in a linear array a series of thin walled open ended sections (see Figure 3-6). The different sections that can be formed by extrusion, casting or other are attached to each other by connecting the respective opposite ends of the intermediate plates, which in turn are placed at the end of the adjacent sections (see Figure 3-7).

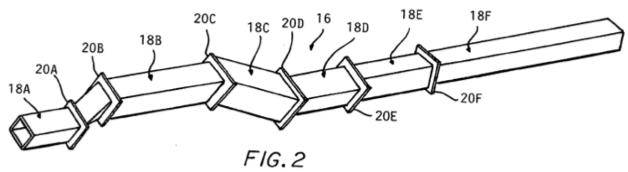


FIG. 2

Figure 3-6 – by attaching linearly a series of thin walled sections is possible to build many structural members (Mani 2011)

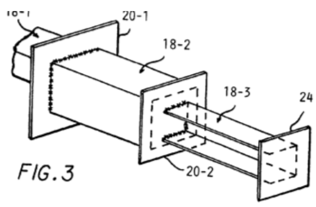


Figure 3-7 - the adjacent ends of sections are welded to the intermediate plates (Mani 2011)

The intermediate plates serve not only as joining elements for the adjacent sections but also as reinforcing elements of strength and rigidity for the whole structure. These plates would be welded or adhesive bonded to the adjacent sections by programmed robots so one may get exceptional joints at reasonable cost. This kind of configuration may also lead to a saving in tooling costs when compared to the traditional steel CCB, formed by welding together a stamped sheet and a tubular piece, because individual sections are smaller and it is easier and cheaper to extend the member length, if needed.

The picture below (Figure 3-8) shows a cross car beam build with the kind of modularity described in this particular invention, which is, a beam created by connecting different chunks, each one having an optimized design to support the additional components.

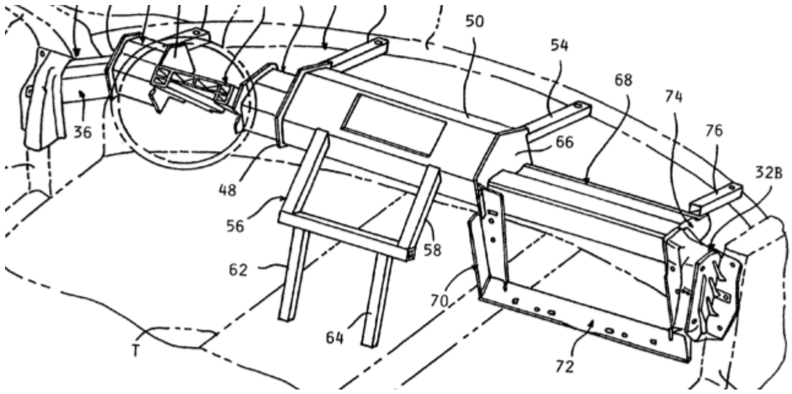


Figure 3-8 – A Cross Car Beam built by linearly attaching different thin walled hollowed sections (Mani 2011)

An integrated cockpit structural assembly can also be quite attractive, besides reducing mass and cost it also improves design flexibility. But, because the IP cockpit is one of the most complex vehicle systems due to the large number of components and the multitude of possible solutions, it requires a large cross functional team to develop it. Between, OEM, Tier-1 and Tier-2 companies, resources are allocated to optimize supplier integration and reach cost reduction in materials, labour and parts integration, enhanced quality and shorter develop times. The example presented next, is an IP cockpit assembled as a module by a Tier-1 company to be later shipped to the OEM where it would be installed into the vehicle. The module includes a two piece cross car structure, which are injection moulded from PC/ABS, the HVAC center stack that is injection moulded from glass filled modified Polyphenylene oxide (PPO), the steering column, wiring harness, energy absorber brackets, etc (see Figure 3-9 and Figure 3-10).

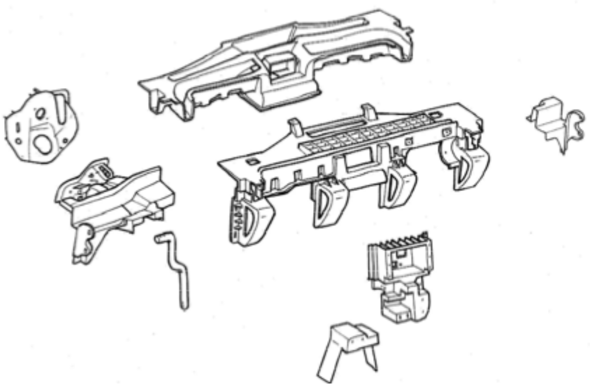


Figure 3-9- An exploded view of the Integrated Structural HVAC System (Kovacic, Lanka, and Marks 2002)

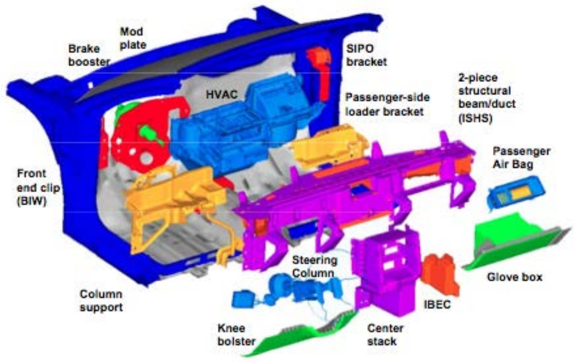


Figure 3-10- An exploded view of the cockpit including the Integrated Structural HVAC System (Kovacic, Lanka, and Marks 2002)

The cockpit assembly consists of joining together the upper beam piece with the lower beam piece and then fasten the steering column support bracket and the passenger side end bracket to it. The HVAC case is mounted directly to the beam structure followed by other mechanical components, such as the steering column, pedals, brake booster, passenger airbag, and center stack. The electrical components and wiring harness are added just before the instrument panel retainer and trim components, which finalize the assembly. Afterwards, the cockpit module should be ready to be shipped.

This project, conducted by a joint venture between GE Plastics, Dephi Automotive Systems and General Motors, concluded that it is possible not only to develop a cockpit module with reduced weight, satisfactory performance and compact packaging as it is also possible to benefit from volume buying by using a the IP structure across multiple vehicle lines (Kovacic, Lanka, and Marks 2002).

3.2.2 Basic Element Profile

Considering the basic element as the primary structural element of the transverse beam which crosses the entire width of the vehicle and whose main function is to protect the occupants in the event of an accident then, one may expect that the shape of this basic element can assume different configurations according to the materials used, the selected production process and, obviously the intended performance. Next it will be presented a few examples of such diversity.

The patent (Kelman and Gray 1994) deals with an invention of a cross car beam that includes an integrated duct cluster, that is, besides the structural role these kind of CCBs also give housing to the HVAC system and the wiring harness, allowing a two-in-one solution. In addition to the creation of a more compacted solution for the cross car ducts, the invention also intends to provide a strong cross car beam by manufacturing it with a composite of steel and moulded thermoplastic material such as polypropylene (PP) or polycarbonate/ABS (PC/ABS). In the next pictures it can be seen five configurations that fit well the previous description even though they assume utterly different fabrication and assembly processes.

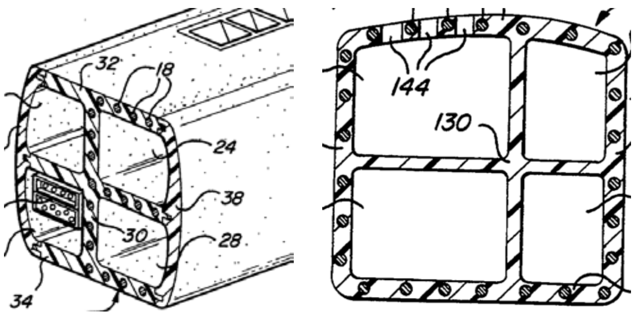


Figure 3-11 – Sectioned perspective view of the Integrated Cross Car Structural Duct Cluster: the embodiment comprises of steel rods embedded in a molded plastic body (Kelman and Gray 1994)

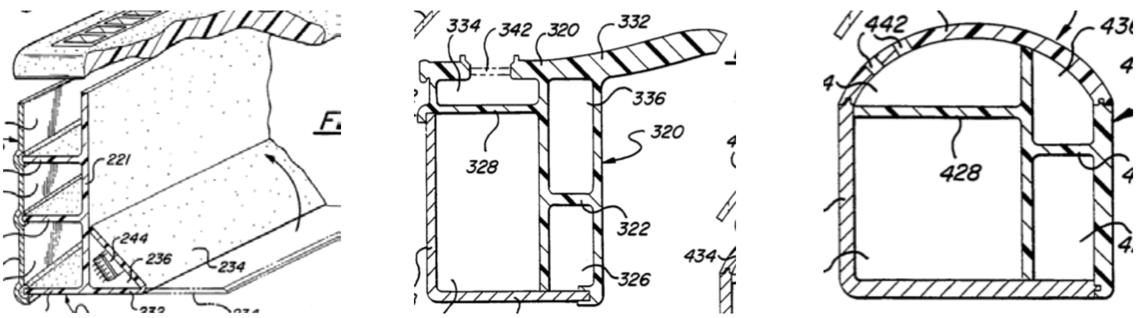


Figure 3-12 - Sectioned perspective view of the Integrated Cross Car Structural Duct Cluster: the embodiment comprises of steel plates that are attached to a molded plastic body (Kelman and Gray 1994)

All five embodiments presented above represent an integrated cross car structural duct cluster that stretches across the entire width of the car from one A-pillar to the other, and all of them are comprised by four distinct ducts, which also span throughout the vehicle width. The duct located at the upper corner was strategically chosen to be the windshield defrost duct since this should be placed adjacent to the lower edge of the windshield so that the heating is done through outlets in the top pad. The other three ducts may switch place given the solution chosen. Of those three remaining ducts one is for delivering treated or ambient air to the passenger compartment, other is for the wiring harness and the last is for the side window defrost duct, which should deliver the warmth through outlets at the end of the duct. Both embodiments in Figure 3-11 present the advantage of a strategic location for the ducts and a great strength for the cross car beam. The rods are for tensile strength and stiffness, while the thermoplastic material provides resistance to buckling and shear forces, in its entirety this combination will also have a good performance with respect to bending forces. The illustration on the left shows three pieces put together: one has walls shaped like a cross with integral flanges, and the other two are closure panels, which should be attached by means of a snap fit, for instance, to the horizontal part of the cross-shaped walls and both flanges. The cross-shaped piece with the flanges is moulded directly with the steel rods embedded, while both duct closure panels are moulded separately. The illustration on the right depicts a thermoplastic body made of a single chunk that has the steel rods embedded in the rectangular periphery. This design is more flexible than the previous regarding the manufacturing process, but let’s take a look, the thermoplastic body can be moulded in one go with a single extrusion or pultrusion process, with the steel rods being embedded at the same time or, an alternate method that involves the outer walls and the steel rods to be moulded in a similar way, and the inner walls, which are cross-shaped, to be moulded separately for subsequently attachments. Figure 3-12 features three potential solutions for the same invention that differ from the Figure 3-11 by having the metal element in the form of a plate rather than rods. The first leftmost has a steel plate that is fixed to three counterbalanced walls from the moulded plastic body thus closing three vertically aligned ducts, and it also has a fourth duct that lies parallel to the lowest of the aligned ducts, which consists of a moulded plastic cantilever that is folded up towards the vertical wall to form a triangular duct. This layout presents two significant bonuses, on the one hand the triangular duct is extremely convenient to house the wiring harness as this can be placed over the cantilever before it is folded and, on the other hand because the ducts are vertically aligned and placed behind the instrument panel, they won’t interfere with each other to gain access to the IP. The other two solutions presented in Figure 3-12, the ones on the right, allow greater stiffness for the cross car beam due to the right-angled steel plate, in other words, both solutions depict a stronger integral cross car structural duct cluster. These two last solutions comprise a composite that in addition to the L-shaped steel plate have a moulded plastic body made of PP, PC/ABS or even thermosetting plastics. Besides the obvious difference of the transverse section implying that a solution is more compacted than the other, the solutions also differ in the number of parts that composes the plastic body, nonetheless and even though the plastic body may have a rather complex shape with a H-shaped portion, cantilevers and asymmetric crosses, in the end, to completely form the four ducts it will be necessary to attach the moulded plastic to the metal plate.

Patent (Derleth et al. 2001) discloses an invention based on a German one whose purpose is not only to eliminate some of the resulting problems of integrating the cross beam into the cockpit and air-conditioning system as well as to improve the subassembly of a cockpit in order to be able to produce it in a simple and cost-effective way. The proposed solution allows the construction of a cockpit subset with a low number of parts and, despite the HVAC system being included this solution is quite flexible, that is, this invention proposes a solution that without having to make major changes is possible to adapt it to almost any vehicle. This factor is an advantage having into consideration that most solutions that integrate the HVAC system consist of complicated aerodynamic shapes and consequently have less freedom to change. To be able to produce a more integral subset in a simple and cost-effective way, it is suggested that the structural unit T-shaped, which will accommodate all the functional modules of the cockpit, be done in a single part by plastic injection moulding (see Figure 3-13). This T-shaped unit has the HVAC system in the area of the center console and includes a series of parts like a fan, a few air mixing flaps, an evaporator and a radiator allowing the distribution of temperature controlled air to the many outlets. There are two parallel air ducts that extend along the vehicle width, which are formed by two parts: the part below is the T-shaped unit, which its top is a shell-like duct component with a wall in the middle to separate the air duct from the defrost duct, and the cover is also a shell-like piece that although usually has a more decorative function it will be the part that closes the shell-like duct component and forms the air ducts (see Figure 3-14).

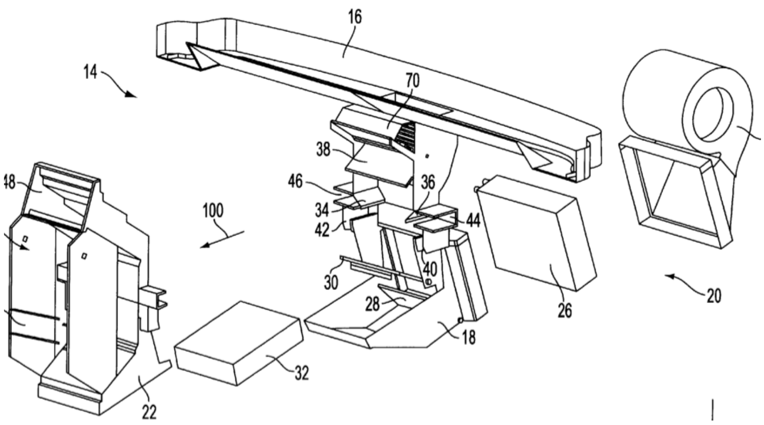


Figure 3-13 – (Derleth et al. 2001)

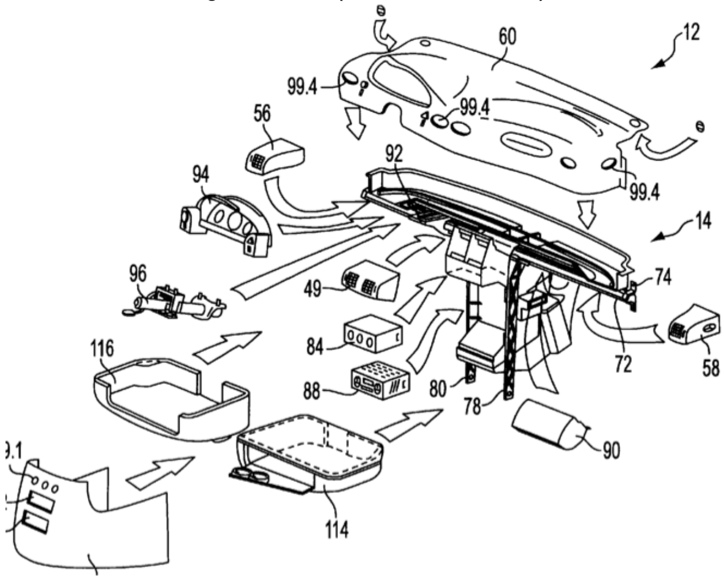


Figure 3-14 – (Derleth et al. 2001)

This cockpit subassembly is attached to the vehicle structure by means of a cross member that passes through the center of the T-shaped unit, and extends to the air duct extremities where it is fixed to the door pillars by fastening shoes, and by means of two anti-vibration struts that are attached to both sides of the HVAC system, positioned in the central area of the cockpit, and to the vehicle floor.

3.2.3 Assembly Solutions

It was mentioned before that the level of modularity could be seen from two different perspectives and the same applies to the assembly construction. A cross car beam becomes part of the structural frame by connecting both A-pillars but it is also its responsibility to support the components that are placed at the cockpit front, hence the two levels of construction: assembling the CCB to the frame and assembling the other components to the CCB. Either case, the assembly needs to be carefully thought due to the part functional requirements and also due to the time and labour it takes.

There is a very useful patent (Jungert and Muller 2010) that explores the first “mission” in a quite insightful way, because it describes a couple of solutions for an adjusting element that can be placed between the A-pillars and the basic member of the cross car beam in order to absorb to some extent the impact energy during a side crash. The invention emerged from the necessity to reduce the overall weight by replacing the conventional steel basic member with a light-metal one, which entails some limitations regarding plastic deformation and rigidity. In the case of a crash it is desirable to have a structure that dissipates the energy from the exerted forces by deforming plastically and/or that absorbs it due to the material rigidity and, because light-metal cast structure are weaker and have a lower modulus of elasticity then the solution must be to rethink the design. The focus concerns the desire to avoid an uncontrolled or unstable fracture, which may occur when using a light-metal cast structure. This particular invention depicts a simple solution, where a mere adjusting element placed between the frame and the light-metal cross beam is intended to absorb a great amount of the impact energy from a side crash by means of elastic, plastic and/or collapsing deformation. Because of the chosen layout, the adjusting element is the first to experience the forces exerted in a lateral crash, reliably securing the light-metal cast structure against brittle fracture and/or buckling. The configuration may be thought so that the adjusting element can absorb all the energy sparing the cross car beam basic element or, that this basic element absorbs as much energy as possible without reaching the fracture limit, and the adjusting element absorbs the remaining impact energy. In the end, it is possible to have a lighter structure with a comfortable degree of reliability. To achieve a compact solution for the cross car beam it is preferable to have the adjusting element entering the basic element (see Figure 3-15, Figure 3-16 and Figure 3-17), that is, the CCB would have a hollow section in both ends and the adjusting element would fit inside. In the figures below are illustrated some viable examples given the description but, it must be kept in mind that other solutions are possible, including combinations of the ones presented in the figures, what matters is that the adjusting element be able to absorb energy through elastic or plastic deformation, or even collapse.

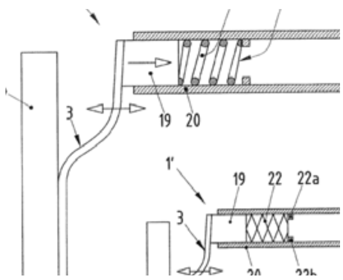


Figure 3-15 - An adjusting element consisting of a spring element to elastically deform (Jungert and Muller 2010)

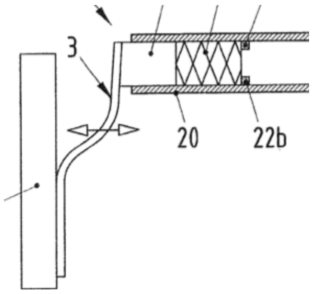


Figure 3-16 – An adjusting element comprising a honeycomb structure to plastically deform (Jungert and Muller 2010)

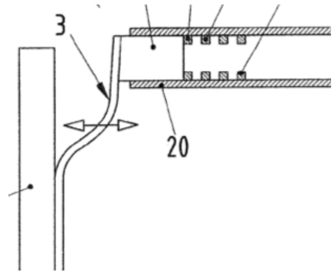


Figure 3-17 - An adjusting element containing several lug structures that should break (Jungert and Muller 2010)

It was already mentioned that the cross car beam works as a backbone for the instrument panel by supporting the different components positioned at the front end of the passenger compartment. Usually these systems or subsystems are mounted with resource to mounting brackets, which are traditionally fastened or welded to the main member of the cross car beam but there exist other solutions as well, like the modular solution presented earlier in this chapter (see Figure 3-8). Regarding the issue of assembling adjacent components to the CCB itself it is important to realize that some of them will be in direct contact with the passenger as it happens with the instrument panel and the steering wheel, and therefore comfort requisites must also be taken into account.

Consumers are quite demanding in respect to comfort expectations meaning that besides the interest in aesthetics and performance, consumers also value that the vibration and noise levels be kept to a minimum. To this end, the invention described in patent (Bittinger, Ozga, and Lepley 1999) concerns a way to securely fasten the IP to the CCB eliminating potential sources of instrument panel vibrations (see Figure 3-18). The invention consists of an apparatus where the upper part fits in the IP and the C-shaped lower part embraces the CCB securing it by friction (see Figure 3-19). The apparatus should absorb the vibrational forces since it should be build from rubber obtained by conventional extrusion. This solution presents a rather interesting and useful feature as regards to the installation process, the assembly between the IP and the appliance may be done during a pre-assembly phase and the assembly between the appliance and the CCB, which is done in a later assembly phase, may be done blindly due to the apparatus configuration.

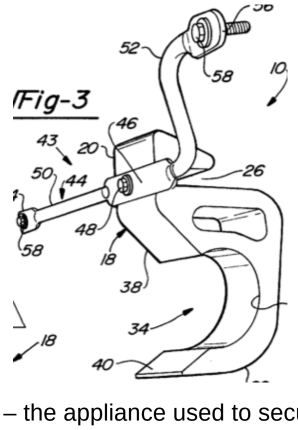


Figure 3-18 – the appliance used to secure the IP to the CCB (Bittinger, Ozga, and Lepley 1999)

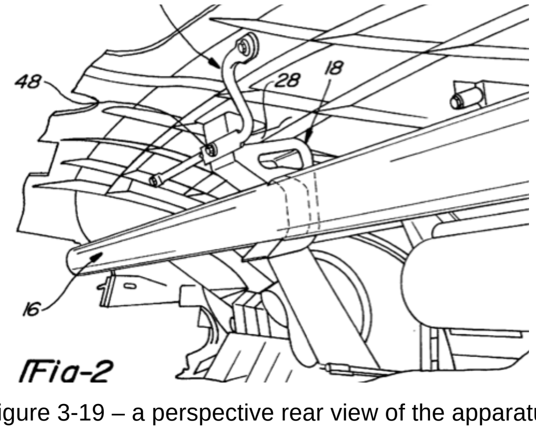


Figure 3-19 – a perspective rear view of the apparatus set in place (Bittinger, Ozga, and Lepley 1999)

Considering the same topic, that is, ways of assembling adjacent components to the CCB, it should be pointed out that, since the CCB supports the various components that occupy the front end of the cockpit then its configuration must be necessarily different if made for a right hand or a left hand drive. When designing a car is natural that the area corresponding to the driver is greater then if compared to the passenger side, and the type of components attached would vary as well. The direct consequence of this is that there won’t be any symmetry about the central plan. Having this problem in mind, both inventions described in patents (Manwarning 1999) and (Jr and O'Brien 2000) show a similar solution where a single extruded aluminium profile will receive the various component brackets (see Figure 3-20) and/or component modules (see Figure 3-24) through existing grooves.

The first patent reports that the extruded component brackets should be mounted by moving them along the longitudinally extending grooves (see Figure 3-21 and Figure 3-22) and that the CCB should be attached to the A-pillars by means of interlocking adapted end caps, which are preferably die cast elements manufactured from either aluminium or magnesium (see Figure 3-23). Components can now be placed in the convenient side without much change in the production scheme once they are easily moved to the desired position. The beam grooves that support the weight and rotational load from the different components also enables an IP with almost no vibration, squeaks or rattles. During assembly of the instrument panel structure the adjacent components are mounted on their respective brackets, which in turn are mounted on the cross car beam by sliding one after the other. The beam grooves together with the bracket tabs allow to correctly orientate the brackets spatial wise, while location marks help the operator during the process of positioning the component along the beam. Finally, these brackets are fixed by a small number of mechanical fasteners.

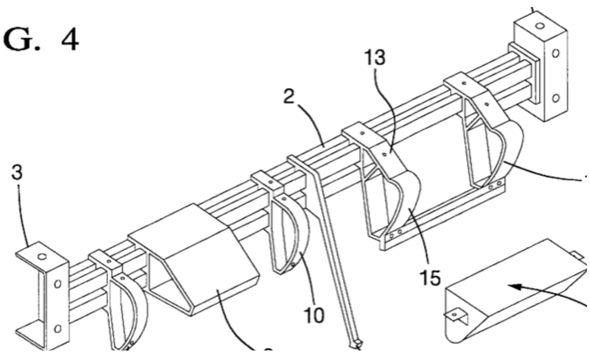


Figure 3-20 – a left hand drive extruded cross car beam where it is visible the grooves that will receive the various component brackets (Manwarning 1999)

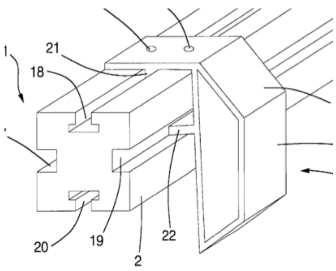


Figure 3-21 – a partial view of the extruded CCB with an adjustable bracket placed in the appropriate grooves (Manwarning 1999)

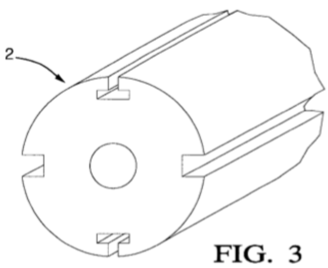


Figure 3-22 – a partial view of an alternative profile for the extruded cross car beam (Manwarning 1999)

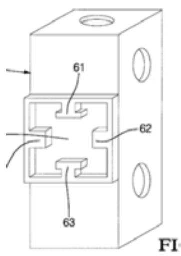


Figure 3-23 – the end cap showing the cavity where it will receive the cross car beam (Manwarning 1999)

The second patent (Jr and O'Brien 2000) discloses a cross car beam with longitudinal channels instead of grooves but whose function is identical. These channels act as mounting locations for the different components (see Figure 3-24). Energy absorption members like the knee bolster, which are positioned so as to protect the driver's and/or passenger's legs, and the airbag module are mounted in one of those channels, and can be welded or screwed at any point of the beam length. The extruded cross car beam is most likely secured to the door pillars by welding.

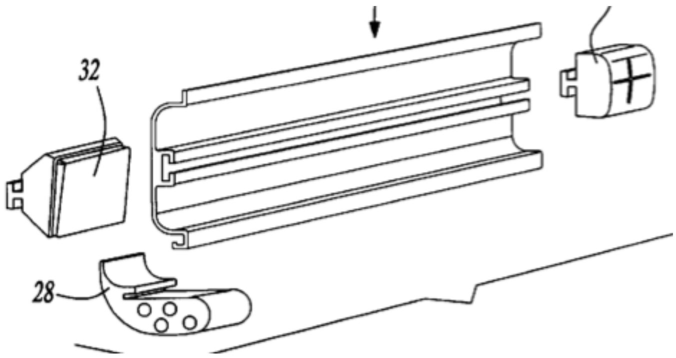


Figure 3-24 – isometric view of the extruded cross car beam with some of the adjustable modules (Jr and O'Brien 2000)

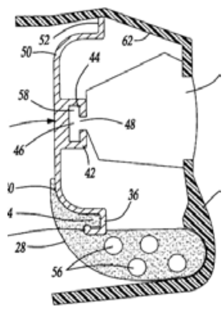


Figure 3-25 – cross sectional view of cross car beam mounting several components (Jr and O'Brien 2000)

The main advantage of such inventions is their flexibility. It is quite easy to vary the length of the cross car beam according to the vehicle width, and to place the component brackets which side (right-hand or left-hand) is more convenient. But, the fact that it is rather simple to develop and replace different support brackets with minimum waste also contributes to its desirability. However, this same design flexibility also has a downside, the freedom to slide the brackets along the grooves is done at expense of losing tight tolerances once, the brackets will necessarily have to be fixed independently. Another disadvantage of this kind of flexible design is its inability to allow an optimum solution with regard to space occupied.

3.3 MECHANICAL PARAMETERS

The Cross Car Beam must have sufficient strength and stiffness to support static and dynamic loads created by the supported items as well as to absorb impact loading which may be transferred from the steering column, knee bolsters and the passenger air bag. It must also control vibration of the mounted and associated items to meet criteria limiting noise, vibration and harshness (NVH) to acceptable levels for passenger satisfaction. (Jergens and Pitrof 1999)

It was already mentioned that a product like the CCB has room to grow as long as demand continues to exist and technology continues to evolve. By this time, the automotive trend and need to reduce weight in both structural elements and other components have been extensively referred and explained. So, one should already know that this evolution can not happen at all costs since the guarantee that the structural performance and safety are not jeopardized is paramount. Also, associated technologies, whether related to new materials production or new manufacturing processes, must be sufficiently developed and reliable so they are not too expensive. After all, one wants this industry to be profitable and its products affordable. This section will try to briefly explain what and why some parameters are essential when designing a CCB and to disclose some of the relationships there are between different parameters. And because steel is the material with more tradition, with an unquestionable performance, it will act as a reference for most examples when studying alternative materials.

3.3.1 SAFETY

Automotive safety standards intend to reduce the occurrence and consequences of automobile accidents. The quality of the product design in terms of compliance with the security requirements for driver, passengers and pedestrians, is evaluated through several component/system tests. Most commonly, to assess a security rating a number of crash tests are performed, such as the standardized New Car Assessment Program NCAP, the Federal Motor Vehicle Safety Standards (FMVSS) or one of their variations. (Lin and Pitrof 2004)

A correct understanding of the regulatory requirements will help to build robust designs, which can achieve high classifications in the performed assessments. Furthermore, meeting the regulation from the start of the design process can help to reduce the costs of later stage product fixes. (Lin and Pitrof 2004)

The cockpit module is one of the most important systems in terms of safety performance of a vehicle. It is the major human-machine interface and it carries occupant protection devices such as the airbags and energy absorbing components. Therefore, the attribution of superior performance has to be achieved by means of the optimization of the entire restraint system, including the Driver Air-Bag (DAB), Passenger Air-Bag (PAB), collapsible steering column/wheel, lower torso energy absorption systems (knee bolster and glove box assemblies) and seat belts.

Crash tests comprise a number of separate tests to components and/or systems, which are divided into categories. Relevant to the cockpit module are the FMVSS201 and 208 regulations, which respectively evaluate interior impact protection and the occupant crash protection. Furthermore, the FMVSS214 specifies performance requirements for protection of occupants in side impact crashes. In the case of the FMVSS208 it is required a collision at 25 mph and unbelted anthropomorphic dummies, while a NCAP test uses belted dummies at a 35 mph collision. Additionally, the FMVSS214 specifies an impact at 33.5 mph, in opposition to the 38.5 mph defined in the corresponding NCAP test.

In order to reduce the forces sustained by the occupants in the event of a crash, it is necessary to ensure that the vehicle absorbs as much energy as possible by means of programmed deformation, but the passengers cabin should be stiff in order to protect the passengers inside. Regarding energy absorption, it is necessary to consider two different cases of collision, frontal and side, because both can affect the CCB integrity.

In the case of a frontal collision, both the driver and the passenger should have their head and chest protected by the airbag deployment and the driver's legs by a knee bolster, placed just below the steering wheel. The airbag and the knee bolster are not enough to absorb all impact energy, so the remainder should be absorbed by axial deformation or collapse of the steering column. All these absorbing energy elements are directly or indirectly attached to the CCB. Let's see, the driver's airbag is integrated in the steering wheel that is attached to the steering column, which in turn is connected to the CCB through a support bracket and, the side-passenger's airbag is integrated in the instrument panel that is also connected to the CCB through support brackets. The correct deployment of the driver's airbag is only possible if the steering column is not subjected to displacement or rotation. The minimization of the steering column vertical displacement can be achieved through appropriate design of the respective support brackets and, the steering column rotation can be avoided if elements like the knee bolster are sufficiently tough not to interfere with the steering column. This last interaction has the potential to compromise the efficiency of the airbag besides causing a serious knee injury.

The appearance of low cost computational power and new computational modelling tools has led to the optimization of safety performance in early development stages. One of these examples is the knee impact model, which simulates the femoral loads of the occupants in the event of a crash. As can be seen in Figure 3-26, there are two main variants of knee impact models, one modelling solely the knees (left) and the other considering the lower torsos (right). These types of analysis can have a very important role in the product development process, especially in early stages, when subsystems are still being developed, usually in parallel, and any design changes will have a much lower impact upon other subsystems.

Figure 3-26- Cockpit-level knee impact models (Lin and Pitrof 2004)

In a study conducted by Lam, Behdinan, and Cleghorn (Lam, Behdinan, and Cleghorn 2003), it was analysed the effect of different materials and thicknesses on the crashworthiness performance. With the help of non-linear finite element crash analysis it was possible to examine the crash behaviour and energy absorption capability of the structure under different conditions. In the crash simulation a Mild Steel model was used to act as baseline, whereas the other models were built using Aluminium with different thicknesses (+20%, +30% and +40%). The Aluminium models consisted of two different alloys: Aluminium AA6111-T4 was chosen for the extruded parts and Aluminium AA5754-O was chosen for the stamped parts.

There are two sets of results due to the two types of crash that were analysed, side impact and frontal impact. The side impact was simulated with a rigid wall hitting the structure on both ends (driver's and passenger's) and, as can be seen in the figures below the main mode to deform in a side impact (same result for both sides) is bending, which is not the preferred mode to absorb impact energy but it can be explained by the lack of support in the central area and the curvature of the central tubular beam.

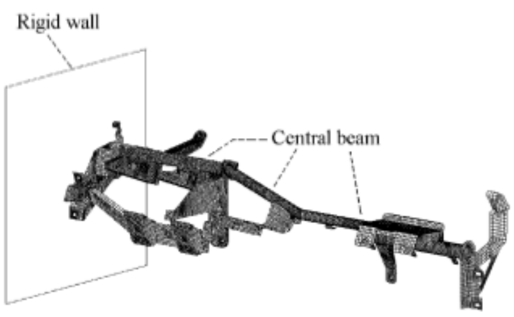


Figure 3-27 - FE model for driver side collision (Lam, Behdinan, and Cleghorn 2003)

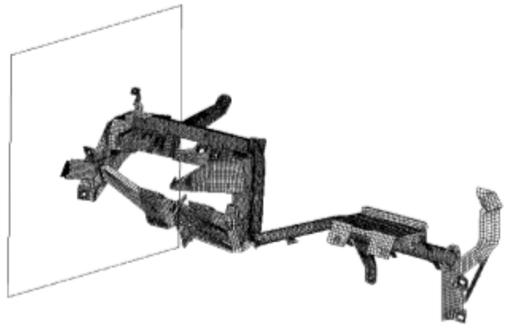


Figure 3-28 – deformed FE model after driver side collision (Lam, Behdinan, and Cleghorn 2003)

Regarding the axial crushing distance, that is, how much the wall displaced after impact, the results (see Table 3-1) indicate that regardless the change in material or thickness there is no significant variation considering the impact on either side. But regarding the energy absorption capability, the results (see Table 3-1) show that for a driver-side impact, the Aluminium model must have a 40% increase in wall thickness to reach near the baseline model performance, but at the same time, for the passenger-side impact, only a 30% increase is sufficient to overcome the baseline model. As a matter of fact, for the passenger-side impact the structure energy absorption capability is about 10% greater for the Al model with 30% thicker walls than for the mild steel model, and is also lighter. Still, this option is not a good alternative since its driver-side impact performance is beneath the desirable.

Table 3-1 - Simulation results for Side Impact

		Wall Displacement (mm)		Energy Absorption (J)	
		Driver-Side Impact	Passenger-Side Impact	Driver-Side Impact	Passenger-Side Impact
Mild Steel	0%	223,74	224,64	1597	916,34
Aluminium (increase in thickness)	20%	+0,32%	+0,2%	-20%	-4,0%
	30%	+0,23%	+0,12%	-12%	+9,4%
	40%	+0,11%	+0,10%	-2,4%	+12,6%

The frontal impact simulation was accomplished by hitting the driver's knees, in the form of two rigid hemispherical thin-shells, into the knee bolster support system (see Figure 3-29). This simulation, allows for a deformation analysis of the knee bolster support system by measuring the travelled distance of the knees after the collision and, it also allows the analysis of the forces acting on the knees. Do not forget that the knees can only withstand up to 10kN of maximum force in a 48km/h frontal barrier.

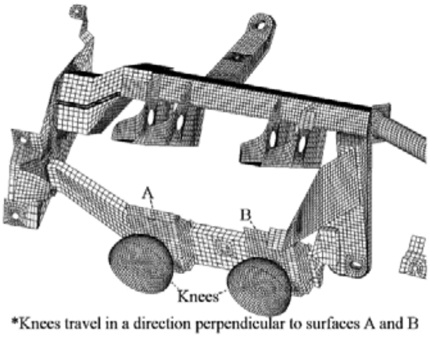


Figure 3-29 - FE model of the knee impact (Lam, Behdinan, and Cleghorn 2003)

The following table (see Table 3-2) reveals the results of this simulation, where it can be verified that the thicker Aluminium model (+40%) presents the best overall results. Concerning the knee displacement, the thicker Aluminium model has the best performance after the baseline model, presenting a modest 7,6% increase in displacement. For the maximum load acting on the knees, the result was that the thicker the walls are, the greater these forces will be, although the Aluminium model that presents the higher value (Al with +40% thickness) is still lower that the baseline model. In other words, this frontal crash analysis demonstrate that the thicker Aluminium model is probably the best option for achieving the best performance despite the slightly increase of displacement, which it is believed to have low effect on the structure performance.

Table 3-2 - Knee impact simulation results

		Left Knee		Right Knee	
		Force (N)	Displacement (mm)	Force (N)	Displacement (mm)
Mild Steel	0%	8,73	95,11	7,74	110,69
Aluminium (increase in thickness)	20%	4,63	107,60	4,27	119,32
	30%	5,27	104,91	4,58	117,33
	40%	6,27	102,33	4,72	115,87

The increasing concern of the automotive industry regarding the safety standards related to integrity of the passenger compartment, along with demand for lower costs and tighter performance requirements, has contributed to the development of new production technologies and to the use of new materials. Therefore, while new technologies continue to emerge there will always be space for product evolution (Derleth et al. 2001).

3.3.2 COMFORT

The concept of comfort relates to the sense of physical and psychological well being, which reflects into a condition of mind that expresses satisfaction with the environment conditions. In the perspective of an automobile occupant, the main sources of discomfort are the oscillations (e.g. roadway, powertrain) which reach the passengers compartment and cause vibration and/or noise.

Thus, the comfort inside a vehicle compartment can be evaluated through three factors (Lin and Pitrof 2004):

- Stability of steering column and wheels, and I/P trim components while driving and/or idling;
- Low inside vehicle noise (e.g. suspension noise, wind noise, engine noise);
- Efficient and effective control of cockpit climate.

Since, most of the sources of oscillations occur outside the vehicle (Heifling 2011), the cockpit module can be designed in order to minimize the transmission and perpetuation of noise/vibration inside the passenger compartment. A number of analytical tools have been developed to evaluate comfort performance. Some of the most relevant methods used in the industry are as follows:

A - BUZZ, SQUEAK AND RATTLE (BSR)

The Buzz, Squeak and Rattle are in-vehicle noises, caused mostly by low frequency vibration excitation. The squeak noises refer to all the noises, which result from the relative unstable motion between two contact surfaces. Buzz and rattle noises are generated by the impact of two surfaces, either originally in contact or not.

The BSR testing process consists mainly in a modal analysis for the identification of critical noise points, and in mapping the noise progression with respect to vehicle life and the environmental conditions (e.g. vibration, temperature) (Chen and Trapp 2012).

B - COMPUTATIONAL FLUID DYNAMICS (CFD)

This analysis consists in the simulation of fluid flows through the use of numerical methods and algorithms. In the automotive perspective it can be used to solve complex engineering problems regarding fluid/air flow and heat transfer, for example, it can be used to predict occupant thermal comfort to support automotive climate control systems. This can have a great impact in the design of various structures, such as, the HVAC system or even the passenger compartment (Kovacic 2002).

C - NOISE, VIBRATION AND HARSHNESS (NVH)

The NVH is a modal and frequency analysis based on Eigen-values, which intends to integrate the customer expectations regarding comfort with the vehicle design and development process. Therefore, such analysis involves the definition of the subjective costumer expectations and their conversion to suitable objective measures. (Duncan, Su, and Wolf 1996) The process consists in measuring and analyzing the oscillations and their sources, the effects of these oscillations onto vehicle occupants (acoustic and tactile criteria) and the impact of the design alternatives upon the perception of the riding experience. These three steps will be discussed in the following paragraphs.

• Vibration and Oscillation Sources

Designing the different vehicle components for NVH performance, including the cockpit module, involves understanding the solicitations that cause the different oscillatory phenomena. The major mechanical oscillations are road induced (e.g. uneven road), tire induced (e.g. unbalance tire/wheel) and powertrain induced (e.g. engine idle shake, driveline unbalanced). These solicitations are transmitted through the chassis to the passenger compartment, generating a wide range of coupled oscillation modes, which in turn are amplified (resonance) or reduced (damped), depending on the natural frequencies of each of the vehicle components (see Table 3-3).

Table 3-3 –Source and Frequency range of the different oscillatory movements (Heifling 2011)

Oscillatory movement	Frequency range (Hz)	Solicitations		
		Roadway	Imbalance	Engine
Body vibrations	0.5 - 5	**		
Freeway hop	2 - 5	**		
Body bucking	4 - 10			**
Stutter, shake	7 - 15	**	*	
Axle oscillation	10 - 15	**	*	
Ferraria effect (jerk)	8 - 20			**
Wheelfight, nibble	10 - 20		**	
Wheel shimmy, wobble			**	
Chatter	7 - 25			
Brake judder	15 - 25		**	
Shiver, jitter	15 - 40			**
Body drone	30 - 70	**	*	**
Axle harshness	30 - 80	**		
Rolling	30 - 300	**		
Powertrain noise	70 - 1000			**

• Subjective and Objective Requirements

The frequency levels, which are usually associated with noise, vibration and harshness, are depicted in Figure 3-30. Several studies have been conducted to evaluate the effects of these frequencies on the human body. However, these studies are mostly concerned with the effects of vibration and noise on human health and less focused on the impact of these two factors in comfort. Thus, the characterization of the impact of oscillation/vibration on the passengers presents a great challenge. To overcome this problem the usual approach consists in designing the cockpit module using the oscillation profile tuned for a targeted costumer group (Heifling 2011).

The different vehicle market segments have requirements according to the preferences of its customers. Depending of the segment, a vehicle can be designed for sportiness/agility, comfort, or general smoothness. (Heifling 2011) However, handling requirements usually conflict with comfort requirements, which should be weighted according to the desired market positioning.

The NVH analysis should be done as a whole however specific requirements can be defined for each of the composing subsystems. The standard followed procedure defines that the individual structural components should be stiff to maximize handling performance, to minimize the noise and vibration of body structure and to provide a feeling of robustness. The stiffness of these individual structural components should take advantage of the mounts and bushings, which will be in turn responsible for the isolation and damping. As a rule of thumb the stiffness of the structural components should be 5-10 times the stiffness of the mounts/bushings, otherwise, the body structure becomes part of the mounting system (Duncan, Su, and Wolf 1996).

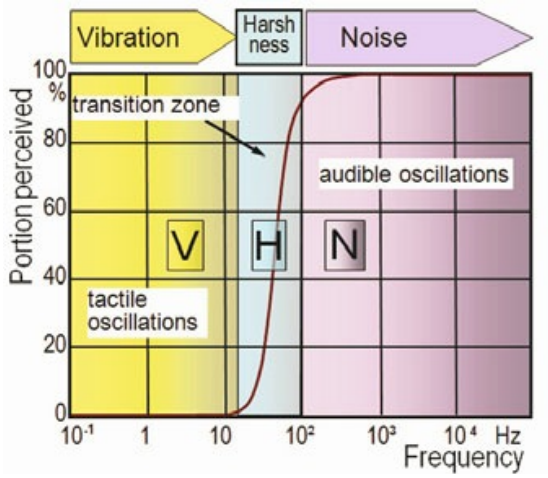


Figure 3-30 –Oscillation frequency ranges associated with NVH (Heifling 2011)

For cockpit modules the most important structural part is beyond dispute, the cross-car-beam (CCB). Thus, in order for the cockpit module have a good NVH performance, one of the commonly OEM imposed requirements, is for the natural frequencies of the CCB to be different from the excitation frequencies generated by neighbouring structures, otherwise the CCB may experience vibrations with large amplitudes. The vibration of the CCB not only can cause noise inside the instrument panel subassembly as, can also transmit this vibration to the steering column, and consequently causing discomfort to the driver. For that reason, the OEMs usually require a target natural frequency for the CCB.

- ### C - Component Modeling and Modal Analysis

The Finite-element (FE) analysis as mentioned in a previous chapter (chapter 2.5.2) is a very common procedure these days to test the structural performance of components before testing the physical prototypes. And, a modal analysis for NVH performance is part of those simulations.

In a previously mentioned study conducted by Lam, et al (Lam, Behdinan, and Cleghorn 2003), different materials and gauge thickness were analysed with the help of finite element normal mode analysis, to understand its effect on natural frequencies and mode shapes. The chosen materials for this experiment were the Aluminium (AA6111-T4), Magnesium (AM60) and Mild Steel, which serves as baseline model. And the gauge thickness of the structure was increased from 0% to 40%, with 10% increments for each material. From the simulations, Lam considered that the third natural frequency corresponded to the dominant mode for every model and, taking this into account, the obtained results for the different combinations are as follow:

Table 3-4 - Dominant natural frequency and weight of each model

	3rd natural frequency (Hz)			Weight (N)		
% increase thickness	Mild Steel	Al	Mg	Mild Steel	Al	Mg
0	44,84	44,72	43,97	129,36	44,50	29,66
10	46,21	46,08	45,58	142,30	48,95	32,63
20	47,64	47,27	46,44	155,23	53,40	35,59
30	48,83	48,71	47,88	168,17	57,86	38,57
40	51,46	51,48	50,89	181,10	62,31	41,53

Table 3-4 shows us that the natural frequency is virtually the same for a CCB made from different materials with the same gauge thickness. However, the same does not apply if one varies the model thickness. As the thickness increases, the natural frequency also increases in a similar proportion for all materials, supporting the previous conclusion. Although predictable, it can also be observed that the weight increases with the increase of thickness, regardless of the material. As final conclusion, one might say that both Aluminium and Magnesium are well-qualified to substitute the mild steel once they present lower natural frequencies (for Mg the decrease is around 1 to 2%) and they are significantly lighter, having said that, it should be remembered that a mode analysis is just one part of the structural integrity analysis. The decision of choosing a different material has to consider additional parameters.

3.4 MATERIAL

When studying the ramifications of material selection for this particular component there should be some repetition within the presented arguments, since issues such as the product architecture or its functional parameters are necessarily linked or even dependent on the chosen material. In the figure below (Figure 3-31), is depicted the evolution of the CCB over the years and, along with the change in material, the parts consolidation is probably the most important aspect to take into account from this evolution.

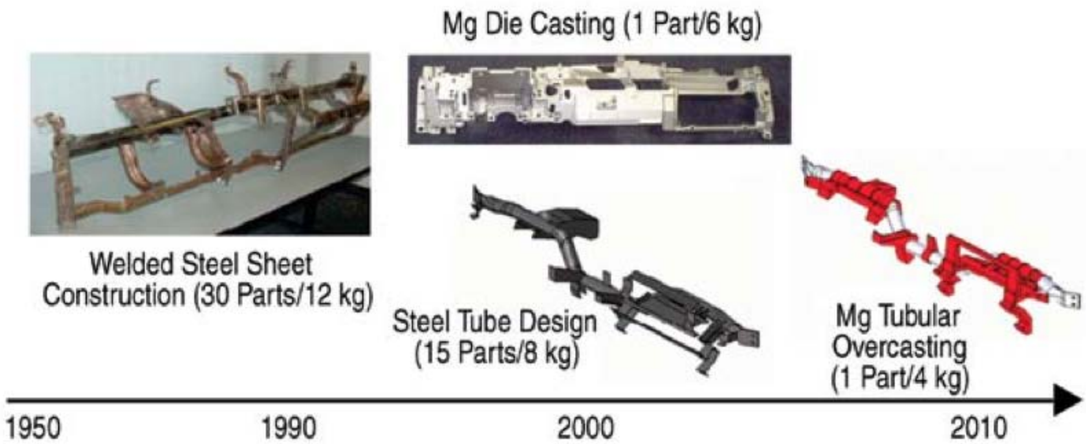


Figure 3-31- Evolution of the CCB material and manufacturing process throughout the last decades (Taub et al. 2007)

As can be seen in the picture, for years the traditional sheet steel design was the conventional solution as it provided the required mechanical resistance at a low cost. However, as mentioned before, it was mainly the need to produce lighter components that drove to the development of new solutions for alternative materials. So search for aluminium, magnesium, plastic and hybrid CCB's started to emerge.

On the next paragraphs, it will be given a few examples of these lightweight solutions. Mild steel CCBs can present very large structures creating weight and packaging problems. Aluminium CCBs have packaging problems similarly to steel although they have advantage of being lighter. Magnesium CCBs presents elevated costs and have manufacturing penalties. Plastics have lower mechanical properties compared to steel but they meet the weight and NVH requirements better (Jergens and Pitrof 1999).

3.4.1 STEEL

Steel is the mainstream material for this component, since it has excellent mechanical properties for the function to be performed. However, this material bears some significant disadvantages that are responsible for the willingness to find alternative materials.

Busuioc, for example, is of opinion (Busuioc, Mullen, and Gabrielli 2012) that among the disadvantages are the very high weight, somewhere between 14 kg and 22 kg depending on the size-type of the vehicle which goes against the industry goal of producing light weight components. Other major disadvantages of this type of CCB are related to the packaging issues, on one hand, the structure can often be too large and, thus taking up valuable space that might be needed to place adjacent components. And on the other hand, there is the multipart modular design that usually consists of a couple dozens of components that should be welded, which require a lot of time and money to assemble.

Regarding steel CCB's weight, as later it will become clear, it exists some discrepancies that do not add up. For instance, Busuioc refers to solutions that can go up to 22 kg but it does not specify what grade of steel is and/or from what year and that could make all the difference.

Despite the considerable evolution within steel grades, there is still room in the art of cross-car beam design for an alternative configuration, providing effective protection.

Figure 3-32 – A steel CCB from a BMW Serie 3 illustrating the complexity of some steel solutions with their multitude of support brackets welded to the main structural element (SODECIA 2012)

Figure 3-33 – A steel CCB from a Citroen C1 illustrating a very simple example made from two different tubular sections that are welded together (SODECIA 2012)

3.4.2 LIGHT METAL

When choosing a light metal, it is usually considered a solution made from Aluminium or Magnesium. In the bottom of this section are some illustrative pictures of such examples.

These materials are viable alternatives for the traditional steel cross car beams if weight savings is a crucial concern. Both aluminium and magnesium allow a more flexible configuration, which is a particularly interesting feature for a CCB because as previously stated this is a component that is intended to occupy the least space possible. However, there are also losses especially regarding mechanical properties, these light metals are more brittle and have a lower Young modulus comparing to steel. These materials can present a discouraging price, seeing that aluminium can reach twice the price of steel and magnesium quadruple, primarily due to the difficulty of obtaining the pure elements (Mani 2011)

Magnesium cross car beams have been produced by the majority of OEMs because of the reduced weight and its superior stiffness and strength. The price of the raw material can be an obstacle but recent data reveal an important decrease of this parameter. Magnesium die-castings are usually cast to a section thickness of 1 to 2,5 mm, whereas if they use low-pressure casting process the thickness will be higher. This is due to the lower fluidity and castability associated with low-pressure processes. Thin-wall die-castings are more attractive as they promote design efficiency. However, thicker sections contribute to higher mechanical performance, namely stiffness. (Lin, Lanka, and Ruden 2005)

Figure 3-34- Several photographs of different perspectives of a magnesium CCB from a Mercedes Class E of 2007 (SODECIA 2012)

The following figures illustrate with some detail a typical aluminium cross car beam. The aluminium solution is also used when weight reduction is a significant concern. However, the aluminium solution requires another manufacturing process, these CCBs generally consist of two stamped pieces which are welded together along the length. As stamped parts, the profile of the basic element will be naturally different from that obtained by extrusion as is the case of most steel profiles or by casting as is the case of magnesium. But there is another dissimilarity, the mounting of the support brackets is no longer secured by the usual welding method but instead was replaced by mechanical fasteners.

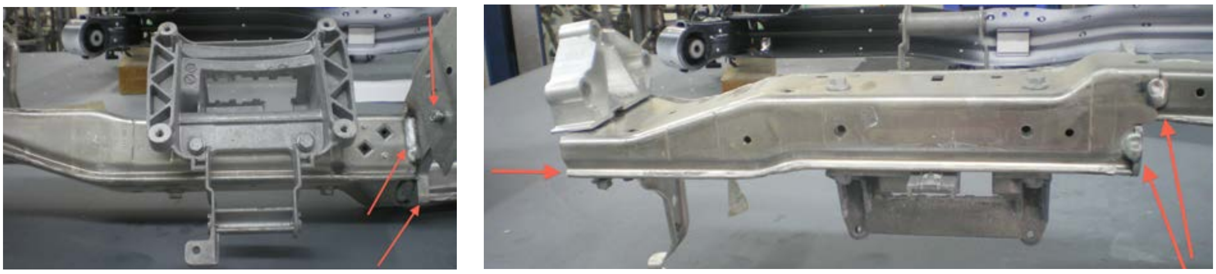


Figure 3-35- Several photographs of an aluminium CCB from a VolksWagen Passat of 2007 (SODECIA 2012)

3.4.3 Plastic

There are not many solutions for a cross car beam made entirely of plastic, mainly due to the mechanical inferiority of this material when compared to the steel, which continues to be the most common material for a CCB. To overcome the low resistance, most attempts to design a plastic CCB ends up being an overly thick and/or overly complex solution so, the equilibrium is usually found in adding a metal profile. More of these hybrid solutions will be addressed in the next section.

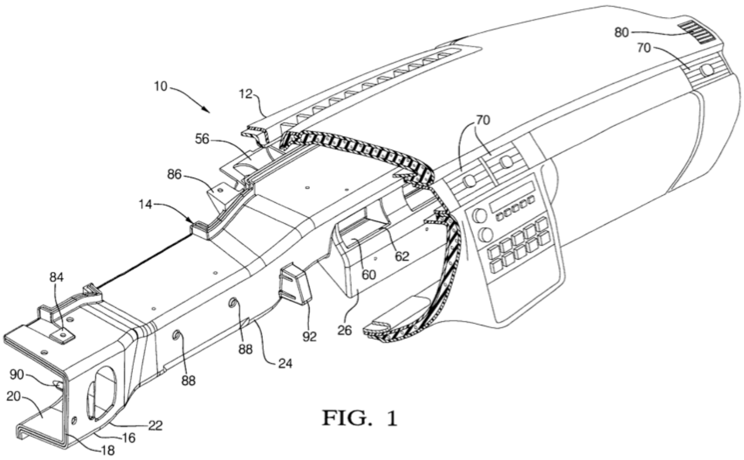


FIG. 1

Figure 3-36 – a pictorial view of a plastic three piece structural beam placed behind the instrument panel, which is partially cut for better understanding (Jergens and Pitrof 1999)

The figure above is from a Patent (Jergens and Pitrof 1999) that describes an invention where a cross car beam can be entirely made from a three pieces of injection moulded plastic and still has sufficient structural strength and stiffness to withstand static and dynamic loads. The achievement comes from nesting three pieces attached together along their four edges, and whose configuration ensures the required structural strength and rigidity. Said design works as follows:

- The outer member has a U-shaped cross-section and is that open area that will allow for the nesting of the intermediate member and afterwards the inner member as well (see Figure 3-37). This member is also where one can find mounting means for the instrument panel, the steering gear assembly and the airbag and HVAC support;

- The intermediate member has cross-section resembling a W-shape, the upper and lower walls lined up with the corresponding walls of the outer member, and in the area in-between there are two walls slightly angled towards one another that connect the short frontal walls, adjacent to the upper and lower sides, with the member rear section (see Figure 3-38);

- The inner member is practically flat and it closes any open areas of said other two members (see Figure 3-39);

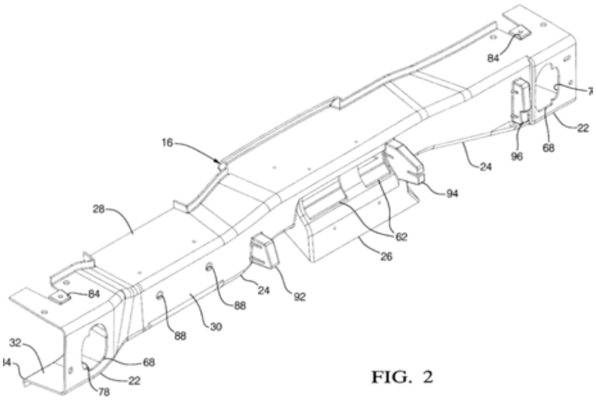


Figure 3-37 – outer member of the three-piece injection moulded plastic CCB (Jergens and Pitrof 1999)

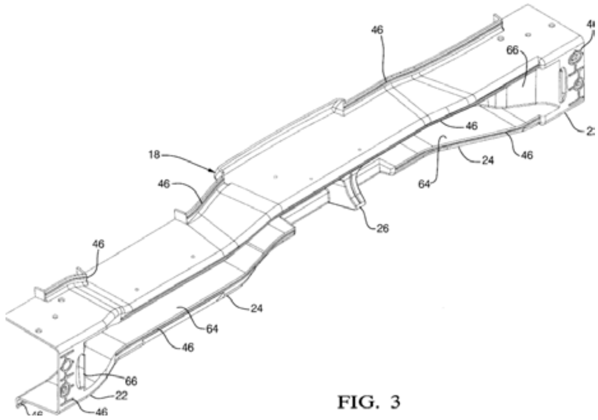


Figure 3-38 – intermediate member of the three-piece injection moulded plastic CCB (Jergens and Pitrof 1999)

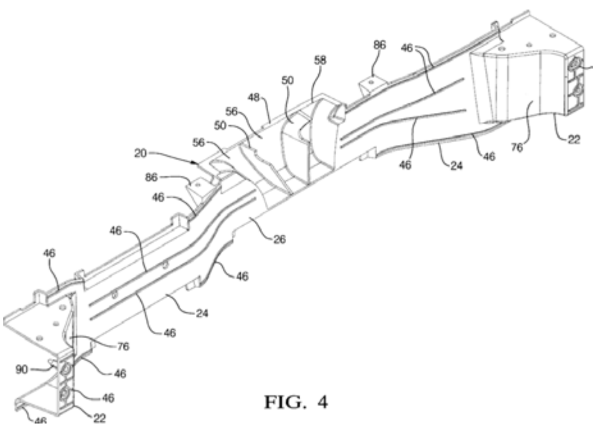


Figure 3-39 – inner member of the three-piece injection moulded plastic CCB (Jergens and Pitrof 1999)

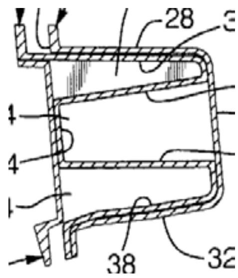


Figure 3-40 – cross-section of three-piece injection moulded plastic CCB (Jergens and Pitrof 1999)

This particular design not only provides structural support for the components attached to the CCB but also between the A-pillars and the body. On top of that, the way this solution is designed it enables the use of the internal openings as air ducts and thus the component integration becomes useful. With a three-piece design it is possible to improve the packaging space, the load distribution and dimensional stability. This solution was initially though to be manufactured by injection moulding because of the high dimensional accuracy it provides, and the member fixation would be by means of vibration welding, however none of these processes is imposed, one can use whatever method finds most appropriate.

Patent (Haba and Truman 2001) is very close in essence to the invention just described, it is also a three piece structural cross car beam assembly, which is produced by plastic injection moulding, preferably a PC/ABS material or the like.

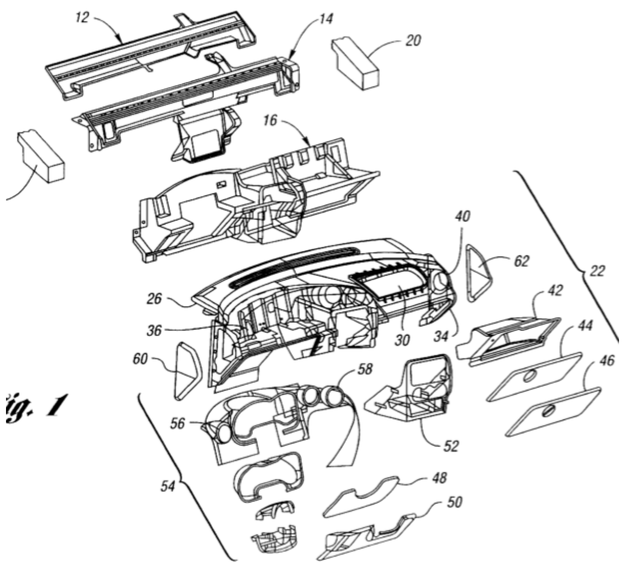


Figure 3-41 – an exploded view of the cockpit assembly with both the CCB assembly and the IP assembly (Haba and Truman 2001)

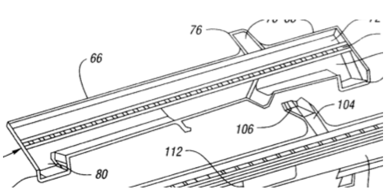


Figure 3-42 – the first panel of the CCB assembly (Haba and Truman 2001)

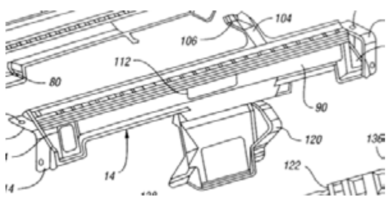


Figure 3-43 – the second panel of the CCB assembly (Haba and Truman 2001)

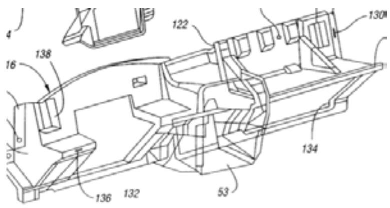


Figure 3-44 – the third panel of the CCB assembly (Haba and Truman 2001)

3.4.4 HYBRID

Owing to the fact that the CCB is after all a structural component then it is not very often to find solely plastic as the chosen material, instead hybrid solutions are being developed and implemented in a growing pace. If on one hand the steel, or other metal, provides the indispensable rigidity, on the other hand, the plastic drastically reduces the overall weight without sacrificing the requirement of plastic deformation. The figure below (see Figure 3-45) shows a great example of what a hybrid CCB would look like. Actually, this is more than a CCB, this illustrates a functional integration of a cross car beam with the instrument panel, which results in the reduction of component numbers, reduction of assembly steps and finally, savings in costs and weight. This particular solution consists of three pieces: a cross car beam made in a single steel tube, and a two parts IP, both glass-reinforced polypropylene (PP) composite. The upper IP part (see Figure 3-46) is injection moulded from PP-based Long-Fiber-Reinforcement Thermoplastic (LFRT) composite, and it will be vibration welded to the lower IP part. Insert moulding a steel beam with a compression moulded Glass-Mat-Thermoplastic (GMT) composite of polypropylene (PP) and chopped long-glass fiber forms this lower IP carrier (see Figure 3-47). And only together, these three pieces can meet the intended crash performance.

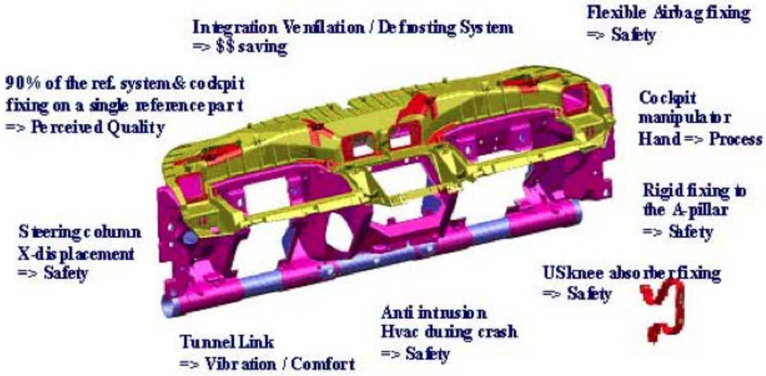


Figure 3-45 - a model of a hybrid cockpit structure (Jahn et al. 2004)

Figure 3-46 – the upper IP frame of the hybrid cockpit structure (Jahn et al. 2004)

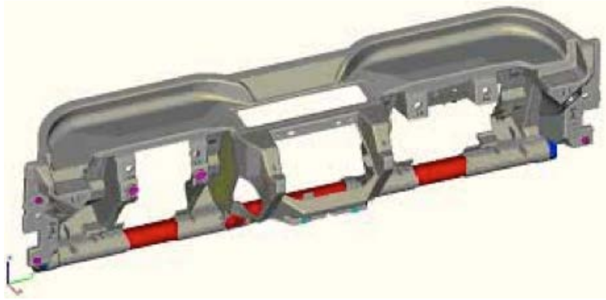


Figure 3-47 – the lower IP carrier of the hybrid cockpit structure (Jahn et al. 2004)

This kind of hybrid design has advantages in all critical aspects:

- Simplified assembly process;
- Improved NVH performance;
- Savings in weight;
- Excellent crashworthiness for both frontal and side collisions;
- Reduced manufacturing costs;
- Ability for high productivity and repeatability;
- Reduced tooling costs because it can be used in many different platforms;
- Reduced number of parts;
- Manufacturing flexibility;

4
METHODOLOGY

4.1 SODECIA

Sodecia was born in Portugal in 1980 as a privately owned company but, it wasn't until 1997 that it gained an international strength with the Sodecia Brazil in São Paulo. The first technological centre appeared in 2005, in Porto and in the meantime the group kept doing acquisitions of smaller companies and creating new plants both in Portugal and in Brazil. The group proceeded its expansion to new markets: Argentina (2006), Germany (2009), Canada and USA (2010), India and China (2011) establishing itself as a serious and respectful corporate in the sector. Nowadays, the group is spread over Europe, America and Asia, with a total of 32 different locations throughout 9 counties. (SODECIA 2011).

With the headquarters in Porto, Portugal, Sodecia is nowadays an industrial corporation that operates globally as a full supplier in the chassis, powertrain and body in white products. It counts with three technological centres that deliver full collaborative engineering service: Porto-Portugal, Hannover-Germany and Detroit-USA (SODECIA 2011).

4.1.1 BUSINESS STRATEGY

The association with the leading automotive OEM's in the world stimulates Sodecia to seek integrated product solutions that comply even the most demanding requirements of their customers (SODECIA 2011).

Sodecia strategy is to achieve success and exceed expectations by giving particular emphasis to innovation, creating personalised solutions and reducing time to market. The hard-work of the development team is the result of the will to create solutions that are fresh and different from what the competition offers so that their customers can be pleased and be succeeded (SODECIA 2012). The company guides itself through principles of value engineering, i.e., thinks and acts globally, follows the industry preoccupation regarding weight, recycling and safety matters and it is always alert for the latest technology developments and future trends in industrial processes (SODECIA 2011).

The work that the group has been developing reflects its determination to follow the established business strategy. The goal is to be known as one of the top suppliers of the major automotive OEM's and to reach a significant share of the market worldwide (SODECIA 2012).

4.2 PROJECT DESCRIPTION

4.2.1 GOALS

Considering the established knowledge of its engineer team, Sodecia aims to develop a new concept for the Cross Car Beam (CCB) that may enable the group to maintain its unique position over the competition, or even better, to gain some extra points in the market. The company intends to start the project of rethinking and redesigning the overall concept of this particular component by studying different options of materials and manufacture processes, in order to get a lighter and cheaper product without overlooking the product specifications.

It is important to remember that this particular paper does not contemplate the entire process of the product development process, that is, it does not intend to be as broad. Instead, its purpose is just to focus on the early steps of the product design and development process, by using Sodecia's project of developing a new integrated cross car beam as a case study.

4.2.2 CHALLENGES

This project brings together several different challenges. To start, CCB can comprise different roles, it can work mainly as a support component for other subsystems or it can also be an important structural component that improves the car's crash performance. Nonetheless, the fact that there is currently available a huge variety of possibilities regarding shape, materials and manufacturing processes also contributes to an even greater challenge.

When developing a component it is important to understand which part the component will play in the overall performance of the product. In this case the CCB is a part of the cockpit, which integrates the car. And, in order to know how to properly approach the problem at hands is crucial to do a thorough study like it is described in the Product Development Process chapter. Later in this paper, it will be possible to realise that this particular component, the Cross Car Beam, is a bit more complex when compared to others in regard to its development because there are too many dependent variables and too little independent ones.

The product specifications are usually stated in a document drafted by the very OEM that is going to launch the new model. As might be expected, this document can vary in format and content, if in one hand there are companies that present specially detailed requirements, others are vaguer, providing an appreciable level of freedom. Even so, the process is not that simple, despite the fact that each document corresponds directly to only one component of a particular model, this document can be difficult to acquire. But, further details on these procedures will be given in the next section.

Sodecia intends to be attuned to the concerns and expectations of customers by prizing the issues of both safety and reliability. As already mentioned in the previous section, the project have in mind designing a new Cross Car Beam that is lighter, cheaper, that fulfils all requirements and that takes in as many features as possible.

4.3 INFORMATION TOOLS

In order to better understand the company's practice regarding product development, it was conducted a series of interviews within Sodecia. It is worth to mention that the technological center is located in Portugal and, that the only currently existent plant dedicated to CCBs is based in Brazil, which means that meetings would have to resort mostly to electronic communications. The conversations held with the technological center in Porto were mainly face-to-face, however the email was also a very helpful tool. To communicate with the Brazilian departments the preferable way of contact was the Skype®.

One of the priorities was to gather and apprehend as most information as possible about the product in question: its function, its functionality, its configuration, and its fabrication process. Knowledge on the way the automotive industry operates is also an important matter to have into account as it has influence on the rules to fulfill and the trends to follow.

All the collected data derived from literature review, benchmarking, and interviews with some Sodecia employers from different departments, particularly with the Commercial, Production and Engineering ones.

The literature reviews consisted on:

- searching new product development practices and their analysis;
- looking for scientific articles about the current and future technologies for CCB materials and production;

The benchmarking analysis uses information from specialized outsourced companies that Sodecia complements with their own research. The database is filled based on:

- teardown programs: photographs, measurements, materials, weights, fastener types, suppliers; (A2mac1 1998-2012)
- center of dismantling end-of-life vehicles: parts and subsystems for later analysis;
- OEM's: 2D and 3D drawings, and product specification documentation of previous projects;
- competitors newsletters: mostly technology innovation;

It was tried that the interviews were made with people from different departments so that would be possible to have a broader notion of the problem. For this purpose, it was made contact with engineers representing the production department, the commercial department and the development department (technical centre): Mr. Antonio Mathias (Salvador, Br), Mr. Alexandre Pales (Belo Horizonte, Br) and Mr. Paulo Gomes (Porto, Pt), respectively.

These interviews and surveys held on Sodecia not only allowed to make sense of the relations between departments, and of their individual role in the process as, it also greatly contributed to the problem understanding. Since the company has been producing CCBs for a few years now, it gained a significant knowledge on the part and, this familiarisation enables a cleaner comprehension of the product in hands and its production challenges.

4.3.1 Tools for Analysis

A - Quality Function Deployment

Quality Function Deployment (QFD) has become a highly important managing tool that can be applied to just about any planning process, especially if it involves ranking different solutions. The QFD is one of those structured methods mentioned before that is quite handy when facing a product development challenge. By following the QFD procedure, the development team creates the means to better understand the customer needs and, as a consequence, to greatly improve the response to them, as the team will be more equipped to assess in what level does the solutions found will meet those needs. (Cohen 1995)

This method is all about the link between the product planning team and the "customer voice". This tool works as a common language that allows the mutual understanding between engineers and marketers without losing much information. There are additional advantages when facing a more complex problems like, structuring the problem by helping to organize the information and also, by facilitating the needs hierarchization according to their importance.

This method, however, should not be blindly used. Despite its great acceptance and its spread use, it is a tool that can deceive and lead to losses if not carefully implemented. It is important to know the limitations of the QFD methodology in advance so that erroneous early product decisions can be avoided. For instance, as the QFD is essentially a method for easily process information, if an error is made at one stage then the remaining stages will be compromised as well. Secondly, it is quite easy to understand that the complexity and size of the matrices used can influence their efficiency, the bigger and more complex the matrices get, the longer it takes to analyse them and the easiest it is to misread them. At last, for the QFD to be succeeded it is crucial to include in the equation not only the customer desires but also the organization constrains. The discredit of the latter can lead to unreachable targets or to increases of work with no benefits (Han et al. 2001).

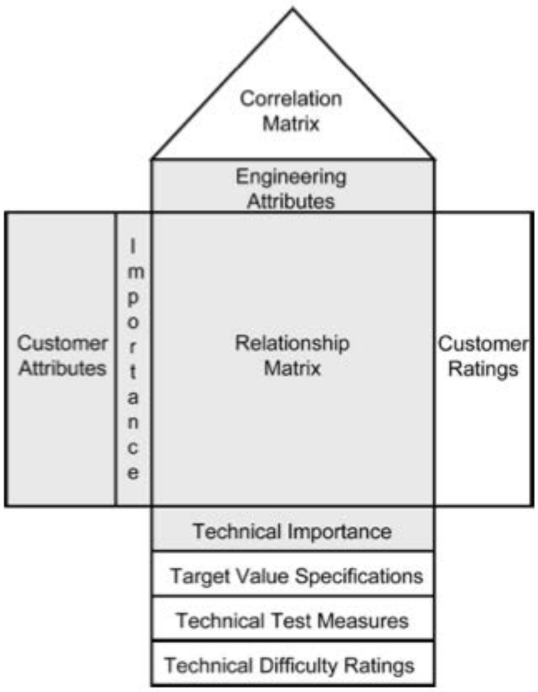


Figure 4-1 - HOQ matrix (Hoyle and Chen 2009)

The QFD method entails the creation of tables, in other words, entails the transformation of oral or written information into a code table (or several). Although it sounds complicated the method is used to simplify communication.

The House of Quality (HOQ) matrix assumes a very common form to do this analysis. This map provides a comprehensible overview of the relationships between customer needs and specification metrics, besides giving important information about the potential conflicts among the various metrics. For all that this matrix is a key for a good planning process. As can be seen in Figure 4-1, the HOQ includes several sections that should be filled in a pre-established way:

- **Customer attributes and their respective importance** - this will be explored in more detail in the next section (Kano's Model);
- **The specification metrics** - here as engineering attributes that should answer the question of how the needs will be fulfilled. These are measurable attributes that will allow to set target-values;
- **Planning matrix** - which may include competitive benchmarking and it can illustrate how well the team met the customer requirements in comparison to the competition;
- **Interrelationship matrix** - where the relationship between customer needs and metrics are established;
- **Correlation matrix –** the roof depicts the conflicts there might exists between some metrics. It is worth mentioning that this conflicts may be for the better, if the improvement of one metric necessarily improves another and, it may be for the worse, if the improvement of one metric necessarily worsens the other;
- **Technical properties –** this is the last section to be filled and it includes the importance of the specification requirements and the target-values for each one of them. This may also include technical benchmark, technical difficulties, estimated costs, etc.

The House of Quality is not supposed to be static seeing that it is a tool used in various steps of the development process and it should work as a mean to facilitate and strengthen communication among cross-functional teams.

B - KANO'S MODEL

In order to better understand the customer needs and expectations, it is necessary to develop a procedure that enables to perceive what will satisfy or even exceed their requirements. If a product causes dissatisfaction, the costumer will probably switch to another product or another brand at the next time. Having this in mind, Kano developed a useful model to organize product characteristics taking into account the duality between customer satisfaction and actual performance. The model consists of placing each product characteristic into one of the four existing groups: "expected", "satisfier", "attractive" and "indifferent" (Cohen 1995):

- An "expected" characteristic is a basic characteristic that usually customers don't ask for. Is the kind of feature that won't add customer's satisfaction when fulfilled but will cause dissatisfaction if not. These are easy to find in existing products by looking into the customer complaints.
- "Satisfiers" are those characteristics that customers explicitly ask for. Their level of compliance will affect proportionally the degree of customer's satisfaction. These attributes are frequently part of the benchmark analysis as they are present in all competitive products and are likely to be measured.

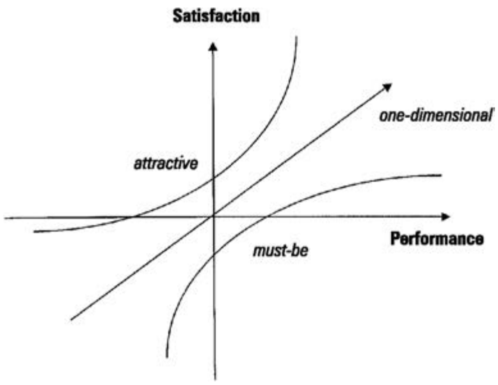


Figure 4-2- Kano's model

- “Attractive” characteristics are, in some extent, the opposite of the “expected” ones as they add customer’s satisfaction if met but they do not cause discontent if they are not. Nevertheless, the characteristics that fall into this group are not called for, as it happens with expected characteristics. Most of the times, the customer does not realize its importance until encounters it, which is why they can also be known as “hidden needs”.
- Finally, the “indifferent” characteristics are those that, as the name says, are the ones that do not cause neither satisfaction nor dissatisfaction if fulfilled. They are usually ignored later in the process.

Kano’s model illustrates the relationship there is between customer satisfaction and product performance and, on top of that it takes into account the dynamic aspect of attributes. In other words, this model contemplates the fact that what customer’s value today may not have the same weight in the near future. Attractive attributes can become one-dimensional attributes (satisfiers) and so on.

5
FINDINGS

5.1 MISSION STATEMENT

After going through “phase zero” in which one does the opportunity identification according to the company’s strategy and assesses the available technology and market trends, then the project of designing and develop a new product can be submitted for approval by the ones in charge. The mission statement is generally the first document to be produced regarding the direction to be followed by the product development team. It may not be as restricted as one would hope, but it will try to disclose all the conditions pre-established as detailed as possible so that the team knows best what to aim for and not waste valuable time. However, in this case it was decided to begin the study without bias by not making much restraints and welcoming all solutions. The result of such exercise is as follows:

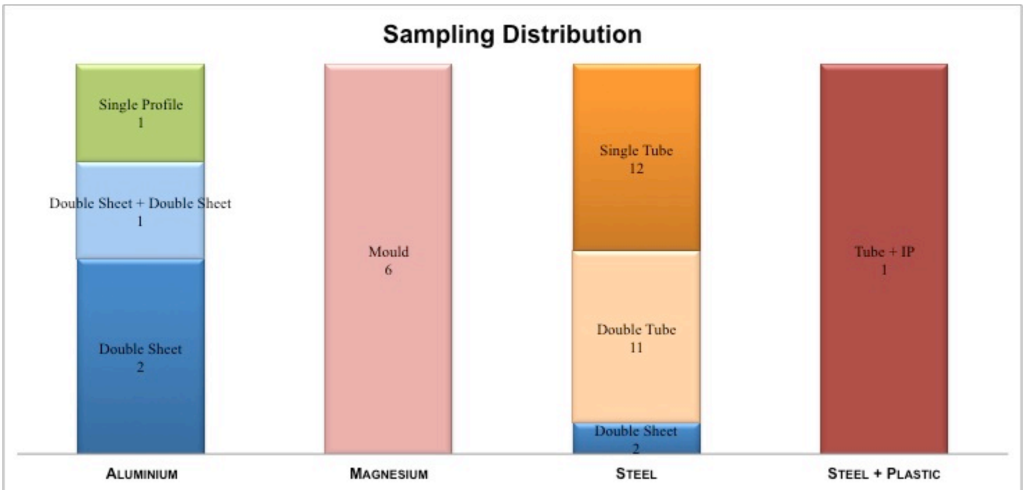
Product Description	• New concept of a cross car beam;
Benefit Proposition	• A simple CCB that can be easily adapted to different car models; • It should comprise as many functional modules as possible, i.e., will function both as a structural element and as a support component for some subsystems;
Key Business Goals	• Product ready to be launched around 2015; • Achieve 5% of the total world manufacture of CCBs; • Reduce production cost; • Environmental friendly: promoting an efficient production with less energy consumption and less wasted material;
Target Market	• Only cars that foresee large volumes of production: segments A, B and C;
Assumptions and Constrains	• Bringing novelty to the market; • Can be adapted to any vehicle of the segments mentioned above; • Budget: unknown; • Expected revenue: unknown; • Meet the country’s regulations for safety (?)
Stakeholders	• OEM (customer) commercial and technical teams; • Sodecia’s marketing team; • Sodecia’s design and engineering team from the technical center; • Sodecia’s production engineering team; • Sodecia’s manufacturing team; • Potential suppliers

5.2 BENCHMARK ANALYSIS

Benchmarking consists on a study of the best practices. The knowledge and understanding of other companies processes, methodologies, products or services in order to achieve better performance are a crucial part of new product development. Keeping an eye on the sector leading companies is important but looking outside the direct competitors and outside one's company can also contribute to break down fallacies and create new and innovative solutions. (Magrab 1997b)

The benchmarking data starts to be gathered in an early phase of the product development process and it can grow continuously during the entire process. The collected information enables the team to apprehend the competitor's choices regarding shape, materials, manufacturing process, etc. Although they are not sufficient to be representative, since a good part of the information is kept at arm's length for industry "outsiders" including academic members, the graphs below show the diversity of choices regarding different parameters.

As previously mentioned, the data used in our benchmark analysis was gathered mainly through two different sources, one international database for the automotive industry, A2mac1, and a product analysis performed by SODECIA of CCB's from different brands, within different segments. The distribution of the data records according to the materials used and product configuration are depicted in Graphic 5-1.

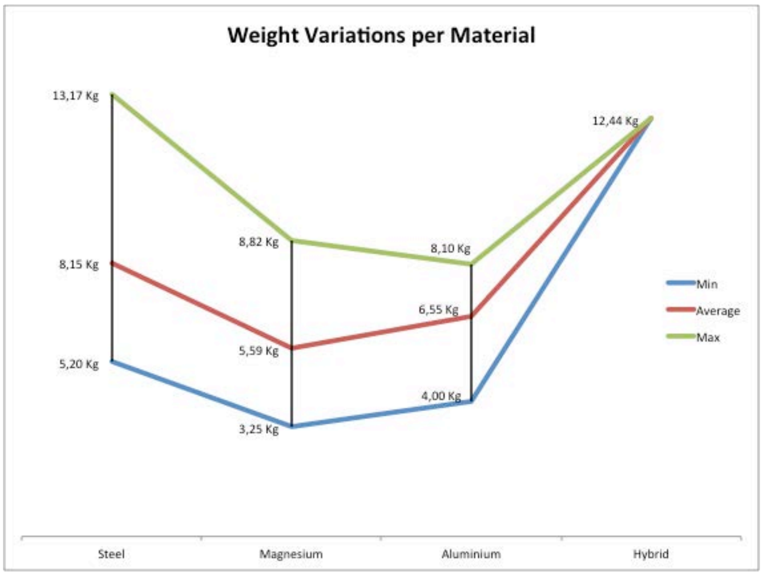


Graphic 5-1- Sampling distribution according to material and type of construction

The total number of components gathered for this analysis was 36. And, as can be seen in Graphic 5-1, the material that has more entries was steel, with a total of 25, and the one that has fewer entries was the hybrid (plastic + steel), with only one component. Furthermore, it can be observed that the remaining records are divided between Aluminium and Magnesium in a similar way, 4 entries for Aluminium and 6 for Magnesium. Because there is not much data and also because of this dispersion, any relevant analysis revealed to be extremely difficult to perform. Moreover, it was also observed that the information obtained is mostly qualitative instead of quantitative, which will also contribute for the graphical analysis fall short of the desired.

As already said there is not much quantitative information to analyse but because, the weight reduction is one of the major reasons for the continuous redesign of the CCB that will be where the focus of this analysis.

The design of the CCB has been improved over the years through a continuous adjustment of the product development process and through the introduction of new technologies and materials. One of the most crucial decisions in the product specification process is obviously which material to use to produce the component, since it has a direct influence in a number of its characteristics. As can be seen in Graphic 5-2 the weight of the component has a great variation depending upon which material used in its production.

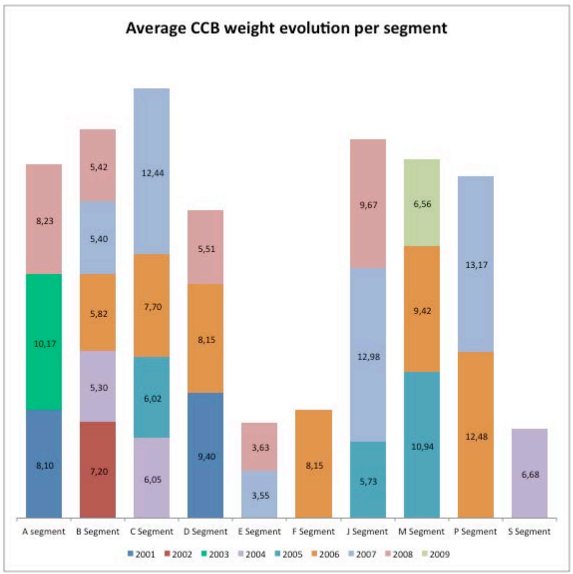


Graphic 5-2- Weight distribution per material

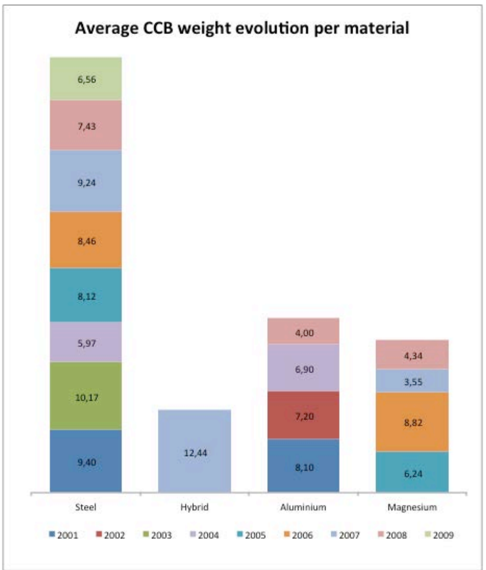
As would be expected, the two materials with the lowest average weight are Aluminium and Magnesium followed by Steel and then Hybrid. Nonetheless, the variance for component weight within the same material is impressively high, this can be explain due to the fact that this an analysis does not contemplate differences resulting from distinct segment and/or year, as it will be done next.

Regardless the hybrid CCB being represented by only one entry in the initial sample, the fact that it has the highest value for weight is probably due to the integral solution that is usually associated with them. That is, an integrated solution consisting of more than just a crossbeam. The problem with using materials like Magnesium is the high cost of the final product, thus, this material is mainly used in components design for niche segments, such as Specialist sports, Luxury and Executive. Nonetheless, mass production can help on reducing material costs allowing the use of the “luxury” materials in the mass production segments.

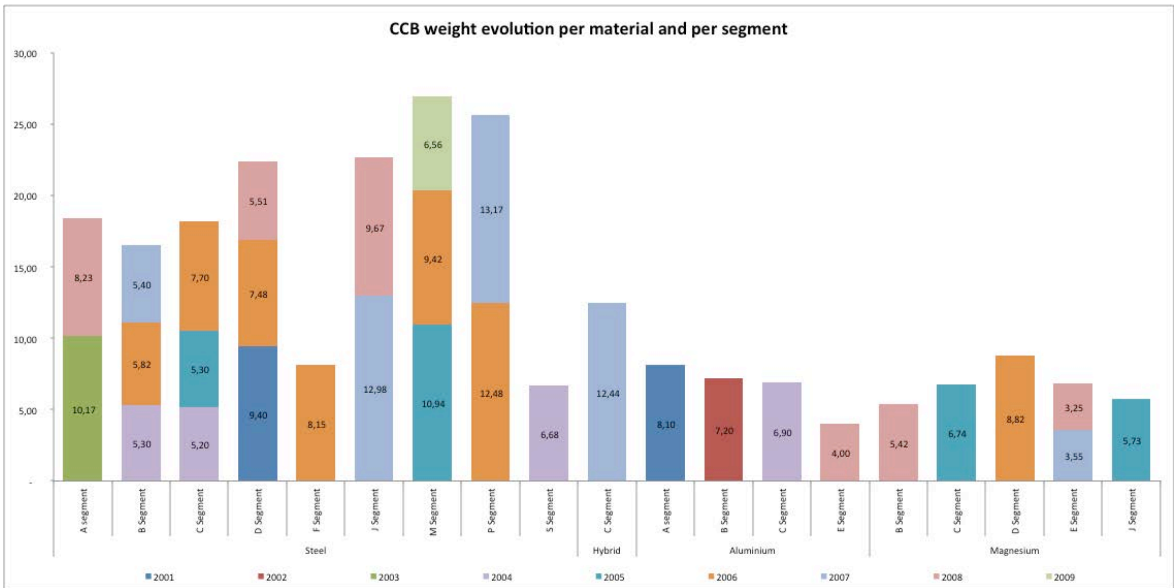
It was decided that the analysis regarding CCB’s weight evolution throughout the years should be performed separately by material and by segment. If we were to analyse all materials together, the information would not be of much value since it would be harder to identify the causes of some unexpected values/trends. Looking at Graphic 5-3 and Graphic 5-4 raises a lot of questions regarding the abrupt weight variations. Within the same brand, there are a few that might recurrently use the same material regardless the segment, whilst others may try to replace the material for a lighter or a cheaper one (which may mean the opposite). The result may seem an almost random distribution, and it is more difficult to perceive and conclude the presence of any trends. Graphic 5-5 is more detailed and thus it can lead to more accurate analysis. Nevertheless, as the sampling distribution clearly favours the Steel design over the alternatives materials (25 over 11), the analysis about the weight evolution with time will be focused on this material only. For the other materials it would be wrong to draw any conclusion other than the fact that the E segment represent the lightest designs and none of them are made of steel (see Graphic 5-5).



Graphic 5-3 -CCB weight evolution per segment



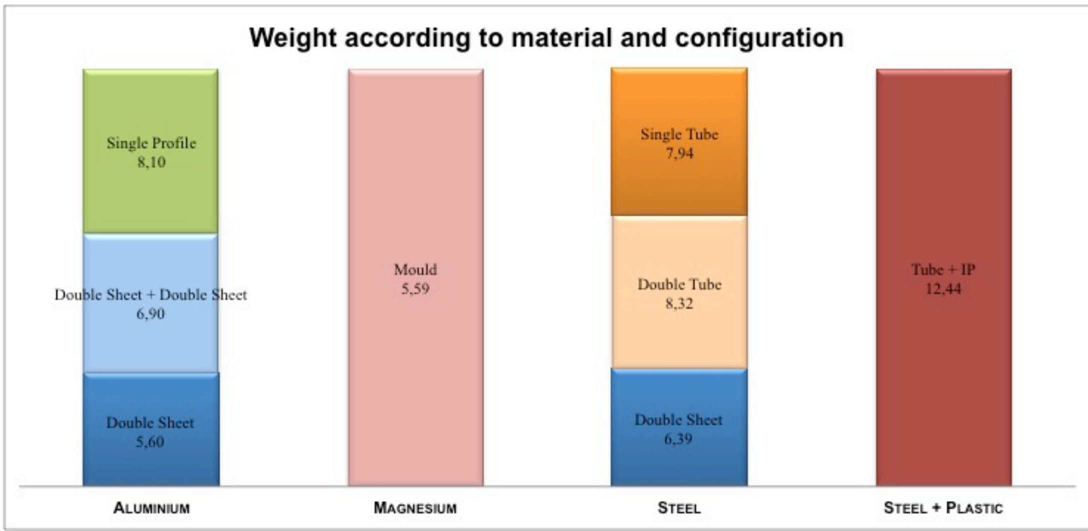
Graphic 5-4 -CCB weight evolution per material



Graphic 5-5 -CCB weight evolution per material and per segment

From the graphic above one can study the CCBs weight evolution throughout the years according to each segment and separated by material. As previously mentioned, this analysis based on the type of material will allow a better assessment of the reasons to such evolution. Nevertheless, it should be noted that different results across the segments could be explained by the difference of requirement priorities that OEMs give to each segment and, by the different production volumes that they entail. Also, different brands may be represented in each segment, which might mean that within a specific segment there can also be different priorities according to each OEM. Nevertheless, it can be seen that most segments present a tendency towards weight reduction of the CCB, namely in segments A, B, D, J, M and E. If looking at segment C (in both Graphic 5-3 and Graphic 5-5) the tendency is actually contrary to what would be expected, especially for a segment with one of the highest market shares. This could be more difficult to explain if in the initial sample there was more than one entry for the same brand and, for the specific case of steel it adds the fact that there was also only one entry for each year. One might assume that this particular segment enables strategy diversity by the OEMs. Thus, the results in this segment may be considered statistically irrelevant. The data from segments F and S have not enough samples to infer any conclusions. Finally, in segment P there are not notorious changes in component weight, there is a slight increase from 2006 to 2007 that can be explained due to the fact that in such segment (pickup trucks) the weight is not a major project concern.

The configuration of the component is another crucial factor in a CCB successful design. If the requirements are correctly evaluated and the CCB design is optimized then it can assure structural integrity without being oversized. This allows for less quantity of used material, thus reducing costs and weight. The variation of weight according to product configuration is depicted in Graphic 5-6.



Graphic 5-6- Influence of design configuration in weight

It would be expected the double tube to have a lower weight than the single tube due to over dimensioning of the component. However, as observed in the graphic above, the dispersion/low number of data records within the initial sample, in some cases, does not allow a statistically relevant analysis to be performed. Therefore, the only result we can confirm once more is that the weight is directly influenced by the chosen material and configuration, being Aluminium/Magnesium the two best over this perspective.

5.3 Attributes, Needs and Specifications

The analysis of industry tendencies, namely the evolution in the design process and in the development of a new product, in order to be relevant, has to be made using a number of different sources. In this chapter, it will be presented a review of patents and scientific articles, which was complemented with interviews made to the stakeholders involved in the design and production process of the CCB.

It is common knowledge that an automobile has thousands of components arranged in clusters, which in turn form subsystems, some larger than others, and ultimately those subsystems are connected to each other and the car, as we know it, starts to take shape. This complexity and dependency is one of the reasons for the development process within this industry being so complicated. Therefore, it is important to clarify what is meant by customer needs. Customer feedback is usually a good way to identify customer needs, however, in this case the comments received from the end-users are usually about an entire system or subsystem. Although nowadays, customers are more aware and concerned than always about certain aspects involving fabrication, design and/or performance of the vehicle, when it comes to a specific component, like in this case, it is natural not to know it even exists. Regarding the CCB, when searching for the client’s needs it is not the final consumer that one looks for, but the OEM instead. After all, it is the OEM who makes the order and, therefore, is them who define which are the existing needs through a Product Specification manual, which is usually specific to a particular brand/model of the vehicle. To help the determination of needs and metrics it was used information from two product specification manuals from two different OEMs, these were not purposely identified for confidentiality reasons.

5.3.1 Customer Needs

First of all, a CCB is a structural component that by linking both A-pillars should ensure the vehicle stiffness in the case of a side and frontal collision. At the same time, the CCB also has the support role, since all or nearly all elements that are supposed to be placed in the front area of the cockpit are supported directly or indirectly by this cross member. Finally, the CCB must meet the company’s goals and comply with applicable regulations and laws.

Next, it will be presented a detailed list of the customer needs gathered, and when deemed necessary it will be given a more exhaustive explanation of any of the points.

For Static Loading:

- Support its own weight;
- Support the weight of other subsystems that are attached as many as they might be;

Typically, a CCB is placed on a skid to be later installed on the vehicle. Adjacent components may be mounted before or after this installation depending on the chosen solution. This explains the relevance of this requirement during assembly, transport and service time.

For Dynamic Loading, as in Structural Integrity in case of collision:

- Ensure that the structure absorbs as much energy as it can;

A structure can only absorb energy if it deforms elastically or plastically, or if it collapses. However, there are specific zones that are more suitable for deformation than others and zones that should not collapse at all, as it would jeopardize the occupant’s safety.

- Ensure correct airbag deployment;

Without considering electronic matters, the proper functioning of the airbags is influenced by the behaviour of the components where they are installed. That is, if those components are subjected to rotation and/or displacement during impact, then the airbags will inflate in the wrong direction or in a position that was not intended. In this case, the occupants may end up being seriously injured instead of being protected.

- Protect the driver and passenger from intrusion;

The occupants cabin should not be invaded by foreign elements once they can seriously injure the passengers. The intrusion is generally a consequence of the collapse of some support bracket, which may project the corresponding element towards inside the cabin.

For the Driver's Comfort:

- Low vibration levels – NVH performance;
- Low buzz, squeak and rattle;

These requirements were addressed in chapter 3.3.2. Excessive vibration is undesirable for any structure because of the fatigue it causes, though in this case has more to do with the discomfort it causes to the driver. Thus, the vibration and noise felt by the driver through the steering wheel should be minimized.

For Environmental Concerns:

- Lightweight;

Make the component lighter as a mean to reduce CO_2 emissions and fuel consumptions.

- Easiness to disassemble;
- Recyclability;

The two requirements above referrer to the European directive to reduce the amount of waste remaining at the end of life.

- Reduced solid waste during manufacturing;
- Reduced energy consumption during manufacturing;

The two requirements above regard the life-cycle perspective. Environmental requirements seek to achieve ecologically sustainable product systems throughout materials production, manufacturing, use, and End-Of-Life management.

For Appearance issues:

- Improved packaging space;

This requirement is related to the ability to optimize the arrangement of the different components within the same package in order to support more components. The number of components will keep increasing but the volume they occupy should not.

- Flexible Design;

The design should be flexible enough to be used in different platforms if necessary, i.e., the same CCB should, for example, be suited for different car models and/or for both right-hand and left-hand drive vehicles.

For Costs Reduction:

- Low-cost materials
- Fast and low-cost manufacturing processes;
- Fast and low-cost bonding techniques;

- Fast and easy assembly processes;
- Short development times;

These requirements are intended to reduce component cost through the optimization of the design and production processes.

- Suitable for manufacture via conventional assembly process;

This last requirement has to do with the company's investment power in new manufacturing tooling and in training. If it is possible to maintain the equipment that already exists, the better.

5.3.2 Kano's Model

Classifying customer requirements according to Kano's model is a helpful way to understand what one needs to do in order to have a competitive and innovative product. While some requirements are described as being charmingly unexpected others can bring great displease. The goal is to make sure all "must-be" requirements are met, while trying to fulfil as many "satisfiers" as possible, so that the company can be at the forefront of the competition and, in the end, some of the attractive requirements should be added to the mix in order to achieve differentiation and become more appealing.

List of Needs	Attribute Category
Support its own weight;	Must-be (M)
Support the weight of other subsystems that are attached as many as they might be;	Must-be (M)
Ensure that the structure absorbs as much energy as it can;	Must-be (M)
Ensure correct airbag deployment;	Must-be (M)
Protect the driver and passenger from intrusion;	Must-be (M)
Low vibration levels – NVH performance;	Must-be (M)
Low buzz, squeak and rattle;	Satisfier (S)
Lightweight;	Satisfier (S)
Easiness to disassemble;	Attractive (A)
Recyclability;	Satisfier (S)
Reduced solid waste during manufacturing;	Attractive (A)
Reduced energy consumption during manufacturing;	Attractive (A)
Improved packaging space;	Satisfier (S)
Flexible Design;	Attractive (A)
Low-cost raw materials	Satisfier (S)
Fast and low-cost manufacturing processes;	Attractive (A)
Fast and low-cost bonding techniques;	Attractive (A)
Fast and easy assembly processes;	Attractive (A)
Short development times;	Must-be (M)
Suitable for manufacture via conventional assembly process;	Attractive (A)

5.3.3 Translation of Customer Needs into Specification Metrics

Now that the customer needs are known, the next step is to associate them with the most suited metrics. These specification metrics are also known as voice of engineer because they deal with measurable attributes. Along with the metrics it will be given a brief description of what they entail and a few reference values. It is important to mention that it was not possible to collect reference values for all specification metrics due, to some extent, to confidentiality reasons.

Static Loading

As said previously, static loading is about supporting its own weight and supporting the weight of other components and, the CCB should not deform plastically or sag due to static loading. The local strains due to self-weight during transportation and assembly have to be below the yield strain (Masur and Wetzel 2006). And, when the cockpit is assembled to the vehicle, there should be no permanent deformation.

The static stiffness is measured at the attachment point between the steering wheel and the steering column. Accidental forces such as the driver pulling the steering wheel will be considered additional load and may cause plastic deformation (Masur and Wetzel 2006). However, in case of such forces exist, deformation must be contained below 80% of the material elastic range, so that plasticization does not occur [Product Specification Manual]. When considering steering wheel structural stiffness for the static load requirements, the typical values are between 400 and 600 N/mm (Slik 2002).

Additionally, some OEMs require that the IP structure pass an oven test, where the full system is heated up to temperatures around 100 ºC at 24 hour sequences upon which no deformation is allowed (Slik 2002).

Specification Metric	Unit	Target
• Local strains	(%)	0,20
• Structural Steering System Stiffness	(N/mm)	400
• Maximum elastic deformation during transportation	(%)	80
• Maximum elastic deformation during assembly	(%)	80
• Maximum elastic deformation at High temperatures	(%)	80
• Maximum sag	(mm)	0

Dynamic Loading

In case of a collision, the cross car beam is crucial to ensure occupants safety as it serves to fasten the steering column and the airbags, among other items. By restricting their movements, the behaviour of these adjacent components is controlled and, only thus, it may contribute to achieve a satisfactory resistance of the cockpit.

The cross-member critical areas should be detected through qualitative analysis of the plasticization rate of the cross-member brackets. For instance, a plasticization rate of less than 2% is suggested particularly for the airbag connections with the cross car beam, but this target may be used for other cross-member components as well. However, for components like the windscreen cross-member tie rods the goal is to sustain more than 2% plasticization. These tie rods are supposed to be destructed in a crash in order to assure compression of the items in the front of the cockpit and prevent their intrusion into the driver and passenger cabin [Product Specification].

Regarding the optimum driver airbag deployment, it must be ensured a maximum displacement of the steering wheel for the three directions (ΔX= 30 mm; ΔY= 30 mm; ΔZ= 30 mm), and also a maximum value for the rotation of the steering column (θY=3º). With respect to the passenger airbag, it should be guaranteed that there is no permanent rupture between the cross-member and the airbag. The cross car beam should withstand up to three airbag deployments [Product Specification Manual].

A CCB should absorb impact energy in both side and frontal impact. There is a study (Lam, Behdinan, and Cleghorn 2003) where a side impact is analysed by measuring the axial crushing distance and the energy absorption capability in case of a collision from the right side (passenger) and left side (driver). And the target values were set by a mild steel CCB, because it is the traditional solution: 223,74 mm and 224,64 are the axial crushing distance for the left and the right side respectively and, 1597 J and 916,34 J are the CCB energy absorption capability in case of a left side collision and a right side collision, respectively.

Considering the femur loads for when the driver hits the knee bolster, OEMs usually target a lower value than the one suggested by the Federal Motor Vehicle Safety Standards and Regulations (FMVSS) in USA, which regulates that femur loads should be limited to 10 kN for the 50th percentile male and 6,81 kN for the 5th percentile female dummy (Slik 2002). For instance, in the study conducted by Lam (Lam, Behdinan, and Cleghorn 2003) the reference set by a mild steel CCB was 8,73 kN for the left knee and 7,74 kN for the right knee. But, within this matter there should also be referenced the maximum deformation withstood by the knee bolster upon the impact, which in the same study sets as 95,11 mm for the left knee and 11,69 for the right knee.

Specification Metric	Unit	Target
• Maximum movement of the steering column for all three directions	(mm)	30
• Maximum rotation of the steering wheel (OY)	(º)	3
• Axial deformation of the steering column	(%)	
• Toughness of the knee bolster	(J/m^3)	
• CCB energy absorption capacity	(J)	1597
• Axial Crushing Distance	(mm)	224,64
• Maximum force exerted on the left driver knee	(N)	6,81
• Maximum force exerted on the right driver knee	(N)	6,81
• Maximum displacement exerted by the left driver knee	(mm)	95,11
• Maximum displacement exerted by the right driver knee	(mm)	11,69
• Minimum/maximum components brackets plasticity	(%)	0,20

Driver's Comfort

In order to meet the comfort requirement, it is necessary to reduce the vibrations of all the components that might be in contact with the driver. It is all about avoiding resonance. And, that is accomplished by having a first natural frequency, whatever the direction of the mode, greater than the required value when idling. This value is set between 30 and 36 Hz [Product Specification Manual]; (Slik 2002).

Specification Metric	Unit	Target
• Minimum first natural frequency	(Hz)	36

Environmental Friendly and Appearance

In terms of Lightweighting, we will use the values from the benchmarking to set 3,5 kg as target value of 3,5 kg, which is just below the lightest steel and aluminium solution of the initial data.

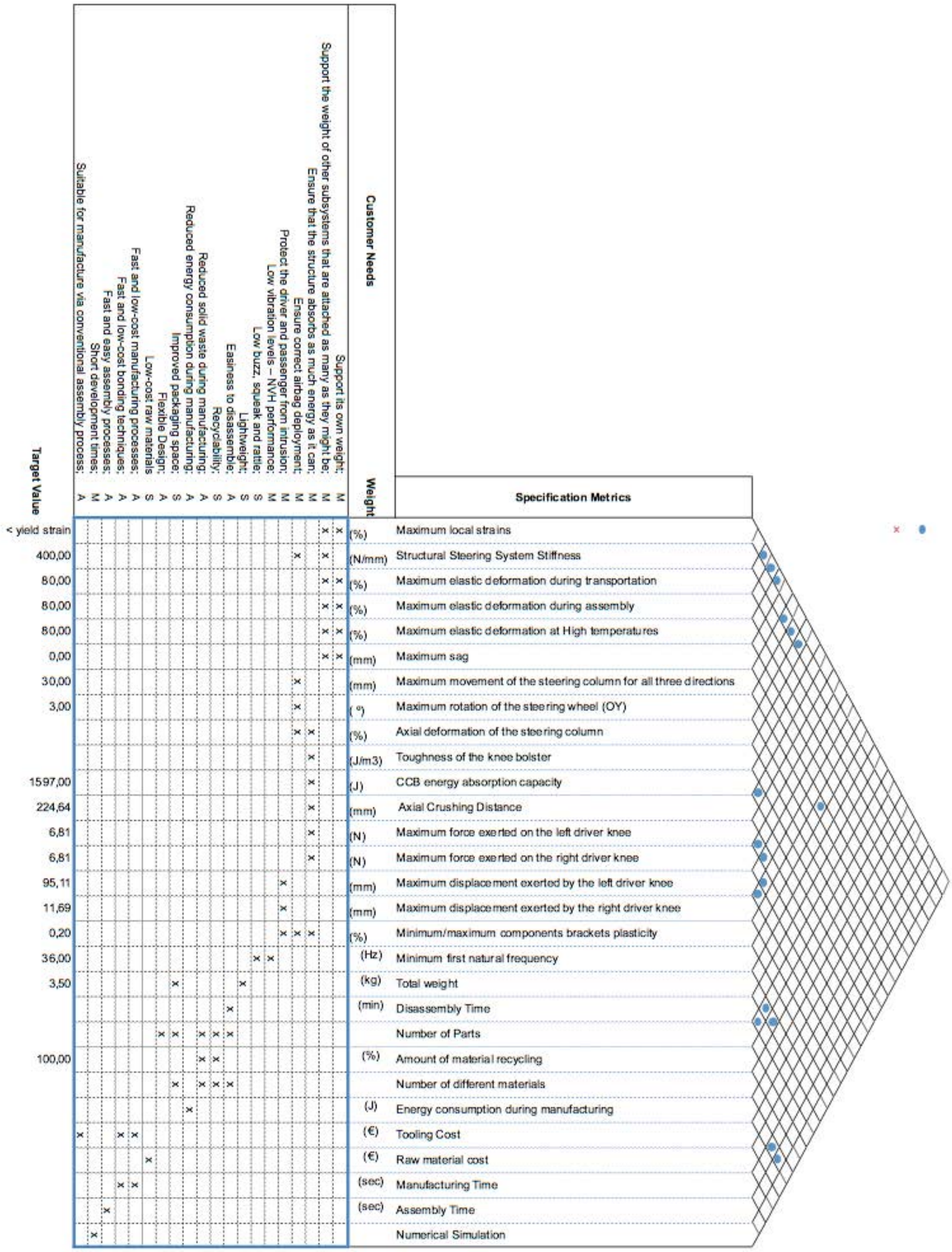
Specification Metric	Unit	Target
• Total weight	(kg)	3,50
• Disassembly Time	(min)	18,5
• Number of Parts		1
• Number of different materials		1
• Amount of material recycling	(kg/kg)	100

Cost Reduction

Specification Metric	Unit	Target
• Tooling cost	(€)	
• Raw material cost	(€)	
• Manufacturing Time	(min)	
• Assembly Time	(min)	
• Energy consumption during manufacturing	(J)	
• Numerical Simulation		

5.4 Quality Function Deployment Analysis

Having the customer needs exhaustively studied, that is, after classifying them and after being sure there are enough "must-be" and "attractive" requirements, then it is time to introduce them into the QFD analysis. The issue of having sufficient "must-be" and "attractive" requirements has to do with the fact that because these are often requirements not asked for, they can be forgotten and if so, the competitive advantage disappears. The QFD provides an expeditious mean to translate the needs into the appropriate technical specifications by using a matrix like a kind of conceptual map. The House of Quality Matrix is the most accepted and widely used form to capture a number of important interactions between the entered data and, it will prove quite decisive to the planning process. That is why this analysis is done in the early phase of the product development process.


Customer Needs
Weight
Support its own weight;
Support the weight of other subsystems that are attached as many as they might be;
Ensure that the structure absorbs as much energy as it can;
Ensure correct airbag deployment;
Protect the driver and passenger from intrusion;
Low vibration levels – NVH performance;
Low buzz, squeak and rattle;
Lightweight;
Easiness to disassemble;
Recyclability;
Reduced solid waste during manufacturing;
Reduced energy consumption during manufacturing;
Improved packaging space;
Flexible Design;
Low-cost raw materials
Fast and low-cost manufacturing processes;
Fast and low-cost bonding techniques;
Fast and easy assembly processes;
Short development times;
Suitable for manufacture via conventional assembly process;
Target Value
Specification Metrics
< yield strain (%) Maximum local strains
400,00 (N/mm) Structural Steering System Stiffness
80,00 (%) Maximum elastic deformation during transportation
80,00 (%) Maximum elastic deformation during assembly
80,00 (%) Maximum elastic deformation at High temperatures
0,00 (mm) Maximum sag
30,00 (mm) Maximum movement of the steering column for all three directions
3,00 (°) Maximum rotation of the steering wheel (OY)
(%) Axial deformation of the steering column
(J/m3) Toughness of the knee bolster
1597,00 (J) CCB energy absorption capacity
224,64 (mm) Axial Crushing Distance
6,81 (N) Maximum force exerted on the left driver knee
6,81 (N) Maximum force exerted on the right driver knee
95,11 (mm) Maximum displacement exerted by the left driver knee
11,69 (mm) Maximum displacement exerted by the right driver knee
0,20 (%) Minimum/maximum components brackets plasticity
36,00 (Hz) Minimum first natural frequency
3,50 (kg) Total weight
(min) Disassembly Time
Number of Parts
100,00 (%) Amount of material recycling
Number of different materials
(J) Energy consumption during manufacturing
(€) Tooling Cost
(€) Raw material cost
(sec) Manufacturing Time
(sec) Assembly Time
Numerical Simulation

5.5 DISCUSSION

Starting with the Mission Statement, it is quite immediate that the low number of restrictions will surely cause complicated challenges at the beginning of the process. However, it has also been said before that the product development process should start by being very broad and only then go narrowing down. If one falls into the temptation of excluding from the start different but feasible solutions, technological advances would never happen, or at least not so fast. But, it is also true that this comprehensiveness also makes the process more time-consuming since, it will necessarily contemplate solutions that fall outside the intended. The benchmark analysis, for instance, should contemplate all solutions in order to better asses market trends and to evaluate the existing innovative solutions, whether regarding materials, manufacturing processes, or design itself. The automotive industry is an example of innovation, as it invests millions in R&D projects every year. Notwithstanding, it is a business area that is very sensitive to confidentiality issues, as it is known for being very closed upon itself. And, it is not by widening the search boundaries that it will be easier to obtain information.

The benchmark analysis performed must be considered deficient in a sense that the larger the initial sample, the better one can depict reality. On the other hand, having more data than what one can handle can have the opposite effect. Thus, if the sampling is too large then a partition is advisable in order to give greater attention to a specific group, which should fall within the intended market, for example, in this case the partition could have been done by car segments. For the purpose of this work, however, this sample was considered sufficient. Through its analysis was possible to extract some important lessons. The first finding was inevitably the overwhelming presence of steel as the basic material for the CCB construction. This fact confirms the preference of this material for structural applications. In addition of being a significantly cheap material both in terms of raw material and in terms of manufacturing processes, steel is also known to be very reliable in terms of mechanical behaviour. The years of intensive use and study makes this material less risky to use when compared to more recent ones. The biggest drawback of conventional steel is undoubtedly its high specific weight, a property that goes against the tendency to reduce the overall vehicle weight. In order to overcome this problem, it has been developed new solutions whether it is new configurations that optimize design without sacrificing performance, in other words, designs that would eliminate the oversized areas. Or new materials whose specific gravity is not as high and whose mechanical properties are also satisfactory, such as high strength steels, light metals and composite materials. The study on the CCBs weight evolution over the years confirms the presence of this desire to reduce components weight by the methods mentioned before. Material replacement, design reconfiguration or technology developments. Technology evolution is somewhat slower and the automotive industry has a more passive role than otherwise. This kind of developments tends to be slow and its implementation occurs in a steady pace. Material selection depends utterly on the available range, being that the steel is still a strong competitor against the light non-ferrous metals and the composites. The newer and better steel grades maintain the high mechanical performances at a relatively low cost and with better weight ratios than the conventional mild steels used until a few years ago. This does not mean that steel will continue to be the favourite material for structural applications but it means that it has the potential to continue the fight against the current popular and appealing alternatives. Re-design is an ever-evolving matter that depends entirely on the industry ability to progress, the development teams use their deep knowledge of the products and technologies towards innovative solutions. As seen later, in the list of customer needs, the reduction of the overall weight is a pivotal concern but the demand for more compacted solutions is also a relevant need that will involve re-design and will also have consequences on the weight.

The conducted study on customer needs although quite transversal, is somewhat superficial. Access to product specifications books and requirements from both the OEM and competitors is not easy, on the contrary. Notwithstanding, a survey was made regarding mechanical requirements for static and dynamic loadings, comfort requirements, and also regarding manufacturing and environmental concerns. The main aspects to retain for the CCB design are the requirements for crashworthiness performance, which includes both the structural rigidity of the cabin so the passengers will not be crushed during a collision and the absorption of impact energy so that the energy resulted from de impact can be dissipated in a controlled way. Additionally, there are the passenger comfort regarding the cockpit vibrations, the environmental goals concerning product life-cycle and fuel consumptions, the reduced packaging demands and, the limited funds.

The weight reduction that is so popular nowadays, is a trend as much as it is a mandatory requirement driven by environmental motivation. The limited resource to fossil fuels and the prejudicial greenhouse emissions composes the primary reasons to want more efficient vehicles, but of course that this development is also beneficial for electric vehicles. And, as mentioned previously, weight reduction is the most efficient way to reduce fuel consumptions. However, this need will continue to gain importance so it is crucial that one starts to think more globally rather than locally, i.e., the weight reduction must be thought for an entire system or subsystem instead of thinking of a component at a time. This is where the integrated solutions have leverage, they provide a more compacted solution with a lower overall weight. In the last decades despite all efforts to reduce components weight the fact was that the total vehicle weight was increasing. This situation is due to the general demand for more equipment to be installed in the front area of the cockpit, like navigation or communication equipment. This is where it lays the significance of packaging requirements, although there is more demand for other equipment’s to be installed, the volume of those components should not be added to the ones that already exist. That would imply a smaller occupants cabin, which is undesirable for comfort and for crashworthiness requirements.

Cost savings is presented in this industry, as in many others, as one of the catalyst for the search of new and better solutions. The decrease in costs allows not only increase the company’s profits but also to create more affordable solutions. Costs are directly related to the investments in machinery and raw materials but also production times and even with the training of workers, although the latter is more difficult to assess. In this particular case, the starting point regarding costs is at a relatively low level already, so the goal is to improve performances and meet customer needs without much increase in cost. Technical specifications regarding costs are the most dificult ones to identify mostly because they are confidential and should not be disclosed to outsiders. These, together with the designs are hopefully the added value that the company needs to take out the competition and sign the contract with the OEM.

Despite the very precise instructions that one should follow when designing a new concept for a Cross Car Beam there are also various decisions to be made that will greatly infuence the final solution. This is why it is of utmost importance that one understands the repercussions of each decision. After the early phase of concept development is completed one should be able to make such decisions.

6 MAIN CONCLUSIONS

The aim of this work was to understand and implement the first steps of the product design and development process using an automotive component as a case study.

Automotive industry is a business sector that is known for making continuing improvements. It is an industry where its overwhelming competitiveness leads inevitably to innovation in order to survive. That is why this study began with an overview of the automotive industry that although superficial, was necessary for a better understanding of the problem.

In this review were discussed not only business issues but also, the critical concerns and trends that are particular to this sector. It was mentioned the safety specifications, the environmental goals, the complexity of calculating costs and some general considerations on the design. During this review it became obvious the complexity and comprehensiveness involved in this work. Having such a large number of components in every single vehicle is evident that the entire system from development to manufacture, then assembly and finally distribution have to be extremely complex. Partnerships between OEMs and suppliers are essential for a continuously evolving industry.

As would be expected, the following step was to analyze the evolution and current solutions for the component under study, the Cross Car Beam. A great variety of solutions were found regarding both architecture and materials. A reference was also made of some crucial functional parameters of this product including the assessment of safety and comfort levels. The architecture the CCBs is usually evaluated according to its degree of modularity. The different assembly solutions are also pertinent for the design process.

Regarding architecture, it was discussed the key advantages and disadvantages of different levels of modularity. The decision of producing a more or less modular component is greatly linked to the decision of choosing a particular material. Metals, for instance, are not as suited for complex designs as plastics are and, on the other hand, plastics have to comprise a more “robust” design in order to meet the desired mechanical requirements. The chosen assembly solution is important because additionally to the manufacturing time and cost factor it also allows varying the weight and performance of the product. Finally, the functional requirements are mentioned so that it becomes easier to understand what is behind some of the customer needs gathered later in the process.

To conclude the CCB analysis was provided a survey of some solutions made from different materials. The steel solution is the most traditional and, is still the most commonly used but, other solutions have been developed over the past decades, particularly, for problems whose weight reduction is a priority. These alternative materials can be light metals such as aluminum and magnesium, plastics, which do not have much popularity yet and, finally the hybrid solutions. There are some engineers that defend that these last ones are the most promising replacement for steel CCBs, its main disadvantages are its poor recyclability and price.

This project ends with the disclosure of the mission statement and the list of the specifications. This is the most important part of the work as it is where it is gathered and summarized all information from the various stakeholders involved. In this stage is also where it is defined what are the customer needs and how those needs can be translated into metric specifications. During this process it came to our attention some unavoidable trends such as the need to reduce weight and costs and to improve compact packaging.

The implementation of the development process has proved to be less immediate than anticipated, according to what has been said in the first chapters, the literature with respect to the different processes is vast but in practice, the approaches are made in view of the industry in which the product is inserted and the company that makes it. Automotive companies tend to have the knowledge distributed by the various work teams that are dispersed throughout the world, whether it is development teams in the technical centers or the production teams in the many plants the company owns. This peculiarity can hinder or delay the development process if it is not pre-established adequate procedures to match this reality. Despite that there were other challenges faced during the product development process, which were quite hard to overcome, mainly because it is a business area that is very close upon itself. Nonetheless, the structured methodology of product development process was very helpful in a sense that it allowed to systematize the several steps taken thus, reducing the risks involved while searching for innovative solutions.

Over the years great efforts were made to improve vehicle performance and manufacturing efficiency while making more affordable automobiles to the masses. At the same time, new laws kept appearing to fight the high numbers of accidents and deaths on the roads and, also to encourage manufacturers to become more environmental friendly. In order to continuously meet all current and future requirements, the industry is aware that continuous development regarding lightweight materials, manufacturing processes, bonding techniques, Computer-Aided Engineer predictive methods and others have to be pursued.

CONTRIBUTIONS

This work aims to contribute to the Sodecia's project to develop a new concept of a CCB, through a careful analysis of the various solutions found and an explanation that tried to be as simple as possible about the advantages and disadvantages of each solution presented. From the results presented here, the development team should have greater ease to conduct the project in the most appropriate direction for the company.

This work also contribute to make known to the academia of a practical example of how the product development methodologies can be applied, which so often lacks in the middle of all literature that exits, which is merely theoretical most of the times.

FUTURE WORK

There is always room for future work and this case is not an exception. Despite the obvious project continuation, since this work just focused on the early phase of product design and development. There is also more research that could have been done, issues such as the quantity and quality of the information gathered can differentiate a good market analysis, which is so important to the development process, especially the early phases. The “chinese walls” around some companies complicate this process. So, to try to address this barrier the suggestion is to create more collaborative partnerships with other component supplier or even OEMs in order to achieve a deeper understanding of the competitors CCBs. For example, it might be interesting to do a study devoted entirely to manufacturing processes having the costs, time and even manpower included.

Another aspect that could be interesting to pursue is the actual implementation of the product design development process in the automotive industry. This work did not allowed a more serious and thorough study on the major challenges that this industry faces during the implementation of the design methods. There are even methodologies that enable to do an evaluation of the processes used.

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