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CICLO XXI

DEFINITION OF R&D AND INNOVATION PROJECTS THROUGH THE ANALYSIS OF PRODUCT VALUE CHANGE IN A B2B ENVIRONMENT

Application to a Magnesium Die Casting automotive supplier

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PREFACE

This doctoral thesis is the result of three years full-time studies, carried at Department of Management and Engineering (DTG), University of Padova (Vicenza – Italy) and at Core Technology Europe department of Meridian Lightweight Technologies Inc. (Torino, Verres – Italy).

Professor Franco Bonollo was the principal supervisor of this work and Dr. Regis Alain supervised the work at Meridian Lightweight Technologies.

Some of the results were reported and published throughout the three years period.

- L. Zaffaina, R. Alain, F. Bonollo, Z. Fan, *New challenges and direction for high pressure diecast magnesium,* Proceeding HTDC Conference 2008, ISBN 88-85298-63-X

- L. Zaffaina, F. Bonollo, R. Alain, S*tatistical Process Analysis on Casting Defects and Performance for Large Thin-Walled Magnesium Parts*, Euromat 2007, European congress and Exhibition on Advanced Material and Processes

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- L. Zaffaina, F. Bonollo, R. Alain, *Il magnesio pressocolato nell'automobile: nuovi prodotti e nuove tecnologie. Direzioni di sviluppo e comprensione dei fabbisogni di innovazione*. XXIX Congress of Foundry, Iseo (BS) 24-25 Ottobre 2008. In: Proceedings

- L. Zaffaina, R. Alain, F. Bonollo, Z. Fan. (2008), *New challenges and directions for High Pressure Die Cast Magnesium.* In publication in "La Metallurgia Italiana"

In addition, the following M.S. thesis have been supervised:

- F. Piai, *Ottimizzazione del processo di pressocolata di componenti Automotive in lega di magnesio,* supervisors: F. Bonollo, R. Alain, L. Zaffaina. A.A. 2005-2006

- M. Cinel, *Tecniche per la protezione del magnesio e delle sue leghe dalla corrosione*, supervisors: F. Bonollo, L. Zaffaina. A.A. 2006-2007

- G. Stella, *Studio per lo sviluppo e l'ottimizzazione multiobiettivo di un concept di prodotto in lega di magnesio pressocolato per il mercato automotive mediante l'analisi a elementi finiti,* supervisors: F. Bonollo, D. Col, L. Zaffaina. A.A. 2007-2008

SOMMARIO

Il presente lavoro è stato sviluppato all'interno del reparto Ricerca e Sviluppo di Meridian Lightweight Technologies, un'azienda che produce componenti per l'industria automobilistica. Si tratta di un tentativo di sviluppare un approccio per identificare il tipo di attività di R&S che dovrebbe essere scelto al fine di supportare la crescita del mercato nel medio e breve periodo, tenendo in conto che le risorse di marketing e R&S sono limitate.

L'approccio sviluppato è stato applicato al reparto CTE (Core Technology Europe, R&S di Meridian) al fine di verificarne l'efficienza nell'individuazione di progetti di ricerca. Tuttavia, nell'arco di tempo del Dottorato, l'applicazione è stata limitata. Sarà comunque dimostrato nel corso di questo scritto come l'approccio realizzato sia stato efficiente, e come abbia consentito un aumento del livello di conoscenza del prodotto che ha portato a un miglioramento del metodo di definizione della R&S.

Meridian Lightweight Technologies è un fornitore dell'industria automobilistica che sviluppa e produce soluzioni in leghe di magnesio pressocolato. Il portafoglio di prodotti consiste prevalentemente di getti di grandi dimensioni che integrano svariate funzioni, quali traverse sottoplancia (IP), supporti per griglie frontali (FEC), strutture di sedili e alloggiamenti trasmissione.

Un'analisi del ruolo del magnesio nell'industria automobilistica e della posizione di Meridian in tale mercato è stata tracciata nel capitolo 2; è stata inoltre svolta una revisione della letteratura su Ricerca, Sviluppo e Innovazione e in particolare sulla definizione delle attività di R&S.

Il magnesio è l'ottavo elemento per abbondanza nella crosta terrestre che ne contiene approssimativamente il 2,5% in peso.

Circa un quinto della produzione mondiale di magnesio è utilizzato per la realizzazione di componenti in leghe di magnesio attraverso pressocolata, colata in gravità e processi di deformazione allo stato solido.

Il processo principale per la produzione di getti in magnesio è la pressocolata: nel 2007, sono state prodotte 160000 tonnellate di leghe di magnesio utilizzando circa il 20% della produzione mondiale del metallo; 140000 tonnellate (87%) sono state pressocolate; di queste circa 100000 sono state impiegate nell'industria automobilistica (62%).

Ad oggi le applicazioni delle leghe di magnesio nel mercato automobilistico variano da componenti piccoli e semplici a grandi getti molto complessi che integrano svariate funzioni. Alcune applicazioni sono mostrate in figura 1.

Il magnesio ha molte caratteristiche interessanti: è il metallo strutturale più leggero con una densità pari a due terzi di quella dell'alluminio e a un quarto di quella dell'acciaio, presenta una buona duttilità, eccellente colabilità e migliore smorzamento delle vibrazioni rispetto all'alluminio. D'altro canto ha caratteristiche indesiderabili quali l'alta reattività allo stato

liquido, limiti di fatica e resistenza alle alte temperature inferiori a quelli dell'alluminio e problemi di corrosione galvanica.

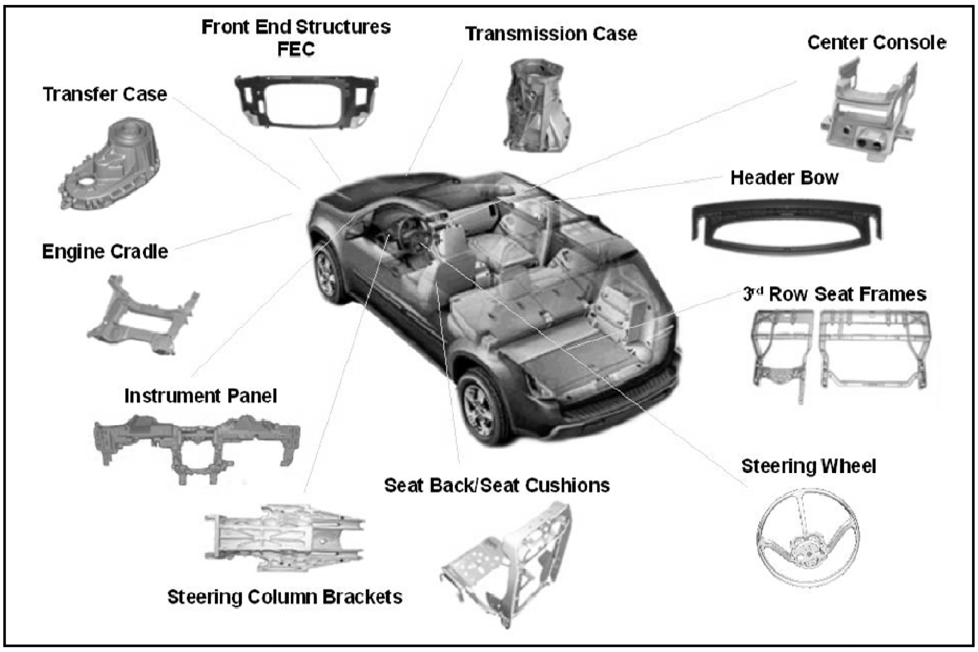

Fig. 1 Principali componenti in magnesio negli autoveicoli

Nel corso degli ultimi decenni, la richiesta di componenti in magnesio da parte dell'industria automobilistica ha registrato una crescita costante dovuta dal crescente bisogno di ridurre il peso dei veicoli. I fattori che hanno determinato tale necessità sono tesi alla riduzione dei consumi e delle emissioni inquinanti e al miglioramento delle caratteristiche dinamiche dei veicoli. Tuttavia, ad oggi, la crescita nel mercato del magnesio pressocolato si presenta difficoltosa.

Come per tutti i mercati, i produttori di automobili (OEM) spingono per una continua riduzione di costi e al contempo richiedono un aumento delle prestazioni; pur focalizzando la propria attività sulla riduzione dei costi e fornendo soluzioni che rispondono alle esigenze del mercato in termini di riduzione di peso, Meridian incontra difficoltà nella crescita del mercato del magnesio pressocolato.

Collocato nell'ambiente sopra descritto, il presente lavoro si pone lo scopo di analizzare l'attuale approccio di ricerca e sviluppo allo scopo comprendere come sia possibile migliorarlo al fine di supportare la crescita aziendale.

In generale, lo scopo dei reparti di R&S è di fornire innovazione al fine di migliorare le prestazioni del business e gli obiettivi sono forniti dalla strategia aziendale. In un ambiente B2C tali decisioni derivano prevalentemente da studi di mercato.

Nel caso di studio, un fornitore dell'industria automobilistica opera in un contesto B2B (ovvero ha come cliente un'altra impresa) ed è molto più difficile definire gli obiettivi. La difficoltà giace nel fatto che la possibilità di innovare in maniera efficiente implica la comprensione dei fabbisogni del cliente. Questa informazione è difficile da ottenere per diverse ragioni:

innanzitutto il cliente non ritiene utile comunicare il valore delle funzioni dei componenti soprattutto per mantenere bassi i costi; inoltre il grado di integrazione e la complessità del sistema sono tali che la descrizione delle funzioni e del loro valore per il cliente è estremamente difficile da ottenere.

La letteratura di sviluppo del prodotto concorda nel sottolineare l'importanza della considerazione dei fabbisogni del cliente nel momento in cui si sviluppa un nuovo prodotto e presenta diversi sistemi per comprendere tali fabbisogni. Tuttavia tali sistemi si applicano nella maggioranza dei casi a contesti B2C.

Quindi nel caso di studio, in un ambiente B2B con un numero limitato di risorse di marketing e di ricerca e sviluppo risulta difficile indirizzare le attività del dipartimentoR&S. Attualmente i progetti di ricerca e sviluppo sono avviati in base a informazioni che provengono in maniera non strutturata da clienti, conferenze, fornitori e personale interno. Questo lavoro è quindi un tentativo di capire come un reparto R&S potrebbe meglio definire le sue attività.

Se la letteratura è abbondante per quanto riguarda la selezione e la classificazione dei progetti di ricerca, è debole, per non dire inesistente, quando la domanda da porsi è *"Come identificare il tipo di progetti di R&S che dovrebbero essere sviluppati al fine di contribuire alla crescita aziendale?"*. E' stato identificato un metodo per l'ambiente B2B, ma questo metodo si applica in modo particolare alla manifattura di attrezzature per la produzione: tale sistema prevede la conoscenza dei vantaggi forniti dalle funzionalità del prodotto e un confronto con le soluzioni dei concorrenti; tale informazione non è accessibile nel caso di studio presente.

Nel terzo capitolo è stato esaminato l'attuale sistema di definizione delle attività di ricerca e sviluppo di Meridian ed è stata analizzata la genesi delle principali innovazioni introdotte nel passato. Meridian ha introdotto importanti innovazioni nel mercato nel corso degli ultimi vent'anni; in particolare ha sviluppato e realizzato per la prima volta alcuni componenti in magnesio che ad oggi sono utilizzati da molte case automobilistiche. Alcuni esempi sono la traversa sottoplancia, di cui Meridian attualmente produce 4 milioni di pezzi l'anno, il *Front End Carrier* e, più recentemente, il supporto motore.

Si è osservato come per le innovazioni che si sono rivelate con il tempo vincenti in termini di impatto sul mercato, i clienti, nello specifico le case automobilistiche, abbiano avuto un ruolo fondamentale nell'innescare le attività di sviluppo.

È stato schematizzato in figura 2 il flusso di informazioni che ha generato innovazioni di successo: richiedendo lo sviluppo di specifici componenti (freccia 2) o la soluzione di specifici problemi, il cliente innesca un flusso di attività teso a soddisfare specifici bisogni (1). Il cliente, infatti, conosce il sistema in cui il prodotto è applicato e si aspetta che la tecnologia che ha individuato consenta di soddisfare i propri bisogni a un costo accettabile. Il fornitore alimenta il ciclo di informazioni con il suo know-how (2) sulle proprietà del materiale e della tecnologia e può proporre sviluppi tesi a soddisfare le richieste del cliente, spingendo il cliente a fornire ulteriori dettagli su quali siano i suoi fabbisogni di innovazione.

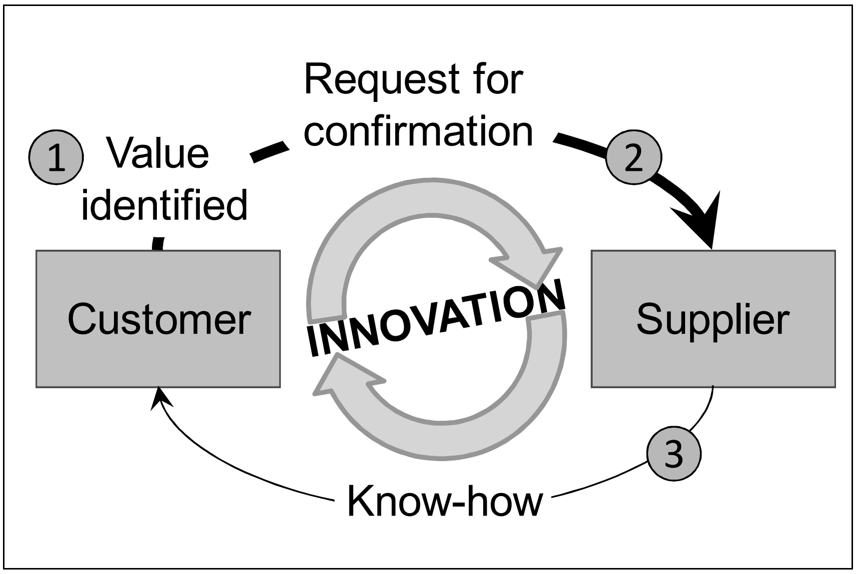

Fig. 2 Schema del flusso di informazione che innesca lo sviluppo di componenti innovativi.

Si è potuto costatare come le attività di sviluppo svolte secondo questo schema abbiano portato a prodotti che si sono estesi sul mercato anche ad altri clienti e che sono stati fondamentali nella crescita di Meridian.

Si è visto come sia di fondamentale importanza aumentare il grado di conoscenza sulle funzionalità del prodotto e come un approccio di definizione dei progetti di R&S debba considerare due direzioni principali: la riduzione dei costi e l'aumento del valore del prodotto a un costo che sia accettato dal mercato.

L'approccio, sviluppato nel corso del Dottorato e presentato nel capitolo 4, implica di innescare e sviluppare il flusso di informazioni sul valore del prodotto dal cliente al fornitore. In tale prospettiva è stato proposto un metodo che prevede di presentare, per ogni nuovo sviluppo, una proposta di prodotto con un prezzo base accompagnata da una serie di informazioni sulla possibilità di variarne le funzioni e sull'effetto sul prezzo del prodotto di tali variazioni.

Tale approccio ben si adegua a una tecnologia emergente per la quale sia il fornitore sia il cliente hanno interesse ad esplorare le potenzialità della tecnologia e i costi ad esse associati.

Per riuscire a stabilire tali variazioni di prezzo, tutte le funzioni sono state elencate e il loro costo stimato. Per ottenere tali informazioni si è adottato un metodo che prevede di rimuovere la funzione dal prodotto e di stimare il costo del prodotto così modificato. Sono state quindi confrontate e sviluppate, con gli esperti dei vari settori aziendali, idee al fine di trovare soluzioni tecniche che consentissero di aumentare o ridurre le specifiche funzioni. Le attività di R&S sono state identificate anche attraverso un'analisi che ha come fine l'individuazione delle potenzialità di riduzione dei costi; tale analisi è stata effettuata da un lato sul prodotto e sul processo, dall'altro sul costo delle singole funzioni.

Il metodo proposto è stato applicato a un prodotto (in particolare un Front End Carrier) per valutarne l'efficacia nell'identificare progetti di R&S. Come riportato nel capitolo 5, è stata generata una lista di attività che sono state confrontate e classificate nel capitolo 6 sulla base del loro valore atteso. È da evidenziare che per sfruttare tutto il potenziale del metodo, sia l'analisi sia la selezione dei progetti dovrebbero essere svolti coinvolgendo le varie funzioni aziendali.

L'applicazione del metodo ad un caso reale ha mostrato che molti degli incrementi di valore del prodotto possono essere raggiunti a livello di progettazione e che il bisogno di attività di R&S sia limitato a specifici temi. Sono state individuate diverse attività di R&S attraverso lo studio sulla riduzione dei costi e l'analisi funzionale ha permesso di individuarne altre tese allo stesso scopo. Le riduzioni di costo più interessanti sono state individuate per la parte meno matura della tecnologia (nello specifico la protezione dalla corrosione); tuttavia l'impatto di tali attività è limitato dato che è specifico di una famiglia di prodotti; si è visto come tali riduzioni di costo debbano essere implementate nella fase di sviluppo del prodotto. I potenziali risparmi applicabili alla parte matura della tecnologia hanno un impatto inferiore sul costo del singolo componente, ma sono trasversali a tutto il portafoglio prodotti.

L'approccio proposto ha portato a risultati interessanti per la specifica applicazione. Sarebbe interessante validarlo ulteriormente e saggiarne gli effettivi potenziali su altri prodotti. Potrebbe inoltre essere interessante applicarlo dal lato cliente per analizzare un sistema composto di diversi componenti ed eventualmente con diverse soluzioni tecnologiche per alcuni di essi. Assumendo di poter elencare le funzioni di ogni componente e di quantificarne i possibili livelli e i costi associati, tale approccio consentirebbe di trovare l'allocazione ottimale delle funzioni su uno o sull'altro componente minimizzando i costi. Eventualmente altri obiettivi potrebbero essere considerati, ad esempio il risparmio di peso o di ingombro secondo il sistema da analizzare.

Quattro progetti di R&S sono stati scelti in base alle considerazioni riportate nei capitoli 5 e 6, sono stati sviluppati e i concetti principali sono stati riportati negli allegati.

Allegato 1: Melt conditioned high pressure die casting (MC-HPDC)

La tecnologia MC-HPDC consiste nell'interporre tra il crogiolo e il sistema di iniezione di una cella di pressocolata un dispositivo che prende il nome di MCAST (si veda schema in figura 3). Tale apparato consiste di un cilindro contenente due viti controrotanti; il magnesio liquido passa attraverso questo dispositivo e viene sottoposto a un'intensa turbolenza e ad elevati sforzi di taglio.

Le condizioni di omogeneità che si creano all'interno del metallo fuso sono tali da favorire una nucleazione uniforme su tutto il bagno. Ciò si traduce nel getto in una struttura fine e uniforme, indipendente dalla zona del getto e dallo spessore della parete. Le caratteristiche meccaniche della lega migliorano di conseguenza.

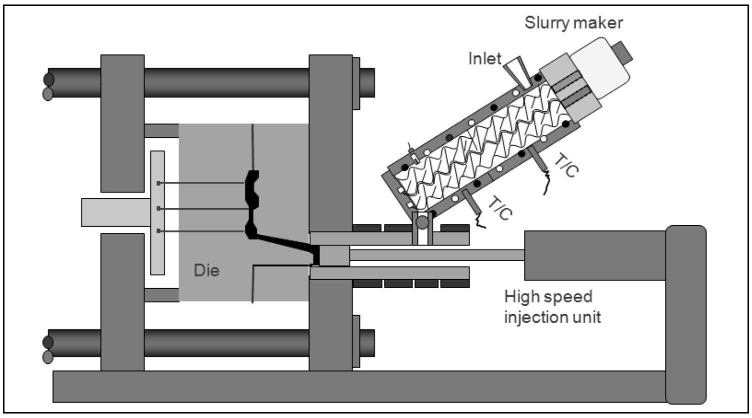

Fig. 3 Schema dell'apparato MC-HPDC

Un aspetto importante di questa tecnologia è il fatto che il dispositivo MCAST riduce ossidi e inclusioni presenti nel bagno in frammenti molto piccoli e di forma globulare che si disperdono in maniera uniforme nel getto. Questo consente di pensare a un utilizzo di tale tecnologia al fine di riutilizzare canali di colata e altro materiale di scarto senza il bisogno di raffinarlo. Ciò porterebbe a interessanti riduzioni di costo.

Test in laboratorio hanno confermato che l'utilizzo di materiale di scarto non ha un impatto significativo sulle caratteristiche meccaniche del getto.

Allegato 2: valutazione dell'infiammabilità per applicazioni aeronautiche

La riduzione di peso è fondamentale nelle applicazioni aeronautiche. Si può stimare che la riduzione di un chilogrammo su un aereo di linea comporti risparmi in carburante quantificabili in 1000$ / anno.

Il magnesio, in quanto materiale strutturale più leggero, presenta quindi potenzialità molto interessanti. Tuttavia l'utilizzo di tale materiale non è consentito per problemi associati all'infiammabilità: il divieto è stato posto negli anni Sessanta e non sono mai stati definiti degli obiettivi per le leghe di magnesio al fine di rivedere tale valutazione.

Meridian e Sicma Aeroseats hanno testato leghe di magnesio con gli standard applicati correntemente ai materiali utilizzati nelle cabine degli aeromobili civili con esiti interessanti. Tali risultati sono stati riportati alla FAA (Federal Aviation Administration) che ha accettato di intavolare una discussione sulla revisione del bando per l'utilizzo del magnesio. Altri attori sono entrati nella discussione e stanno lavorando per verificare che la sicurezza degli occupanti non sia messa in pericolo con l'introduzione del magnesio.

Nel presente lavoro sono stati confrontati gli esiti dei test di laboratorio e delle prove *full-scale*.

Un test di laboratorio è stato svolto per confrontare la temperatura di autoaccensione di varie leghe di magnesio e per valutare l'effetto degli elementi presenti in lega, in particolare Calcio e Ittrio.

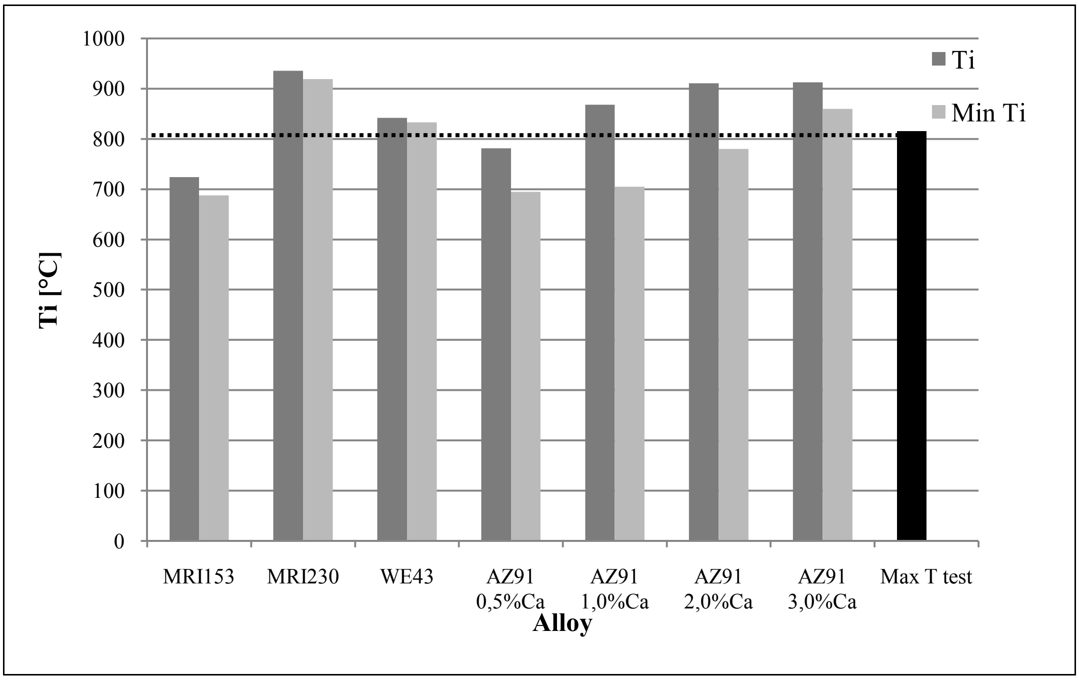

Fig. 4 Temperature di autoaccensione di varie leghe di magnesio. Sono riportate la media e la minima temperatura misurata nel corso dei test.

I risultati dei test svolti e riportati in figura 4 hanno dimostrato che la presenza di calcio in quantità superiori al 2% (in figura MRI 230) incrementa in maniera considerevole la temperatura di autoaccensione, consentendo di superare ampiamente le temperature massime misurate nei test full scale.

Oltre alla composizione della lega, è stato analizzato l'effetto di vernici intumescenti che consentono un ulteriore incremento delle prestazioni.

Allegato 3: ottimizzazione di concetto di prodotto.

L'analisi delle funzioni del prodotto svolta nel capitolo 5 ha portato ad evidenziare come sia interessante prendere in considerazione lo sviluppo di concetti di prodotto con un approccio funzionale utilizzando sistemi di ottimizzazione assistita da calcolatore. Nell'allegato si è sviluppato un concetto ottimizzando il peso e il costo, prendendo in considerazione la funzione "NVH" e facendo uso di strumenti di ottimizzazione topometrica e topologica.

Allegato 4: controllo statistico di processo.

L'influenza dei parametri di processo sulle caratteristiche meccaniche dei getti sulla formazione di difetti è stata analizzata nel corso di diverse campagne di test eseguite con tecniche di *Design of Experiment.* Sono stati individuati i parametri responsabili delle variazioni delle caratteristiche meccaniche dei componenti (in particolare dell'allungamento a rottura). È stato proposto un approccio semplificato da applicare alla produzione e ne è stata verificata la validità nel ridurre lo scarto.

SUMMARY

This work has been developed within the R&D department of a medium size automotive supplier. It is an attempt to develop an approach to better identify the type of R&D activities that have to be selected to grow short-midterm market, when marketing and R&D resources are limited. Once developed, the approach is applied to the Company to verify its efficiency in identifying interesting research project. However, in the timeframe of the Doctorate, the application had to be limited to some extent. Still, it will be demonstrated that the developed approach has been successful, higher level of information could be reached and the definition of R&D projects could be improved.

Meridian Lightweight Technologies is an automotive supplier, developing and manufacturing lightweight solutions in Magnesium alloys, using the technology of high pressure die casting. Meridian's portfolio mostly consists of large complex monolithic parts integrating many functions like Instrument Panels, Front End Carrier, seat frame structure, but also of transmission housings.

Chapter 2 contains a literature survey about R&D and innovation and the definition of R&D activities. The role of magnesium in the automotive market has been analysed together with the position of Meridian within this market.

Magnesium automotive parts are made by die casting and offer attractive weight saving. Though OEM are more and more seeking for weight saving, to lower fuel consumption and address vehicle handling issues, growth of magnesium die casting market is difficult.

In general, R&D departments target to innovate to help capturing new markets, and targets are usually defined by corporate strategy. In a B2C environment, these would be mostly driven by marketing studies.

In the present case, an automotive supplier is in a B2B environment and it is much more difficult to define targets. This difficulty lies in the fact that, when it comes to innovation, the possibility to innovate implies to fully understand customer’s needs. This information is knotty to capture for several reasons: to protect costs, the customer does not fully communicate on the product; also the complexity of the systems makes it difficult to fully describe the functions of the products and their value to the customer.

Product Development papers agree about the importance of understanding customers’ needs to develop new products. Several methods to identify customers’ needs are suggested in literature, but a large majority of the contents concerns B2C.

Hence, in such a B2B environment, with limited resources for marketing, surveys and R&D, it is difficult to structure CTE. Currently, R&D projects come from information “captured” from suppliers, conferences, customers and employee and not from a structured approach. This work is an attempt to understand how an R&D department could better define its activity.

If literature is abundant on how to rank and drive research projects, it is weak – not to say

inexistent – when it comes to the key question that is: *"How to identify the type of R&D projects that have to be done to grow market?"* One method for B2B has been identified, but it applies mostly on machines manufacturing and implies the knowledge of the advantages given by the product's functionality and a comparison with competitors' solutions: this information is not accessible in the present case.

Chapter 3 analyses the current approach for the definition of R&D activities and the genesis of past innovation at Meridian and shows the importance of knowing the product's values when trying to innovate.

The approach, developed in chapter 4, implies to develop the flux of information on values from the customer to the supplier. In the prospective to capture customer's values, a proposal is made. For each new development, the price could be presented not only for the level achieved for each function, but also with information on how it would change if the level of each of these functions was lowered or improved by a defined percentage.

Such an approach can suit challenging technologies as both the customer and supplier can find an interest in moving towards different products levels and cost.

To be able to establish price variations, all functions have to be listed and their cost evaluated. To run this cost evaluation, a method based on assessing the cost by removing the function has been developed. Ideas have to be brainstormed to find technical solutions to move to higher or lower function level. R&D activities have also been identified through cost reduction analysis. One analysis has been done on the product/process, and another one on the cost of the functions.

To assess the efficiency of the combination of these three analyses to identify R&D projects, the method has been applied to magnesium Front End Carrier in chapter 5. A list of projects has been generated and ranked on chapter 6 on the base of Expected NPV. Both the analysis and the final selection should be done at the corporate level.

The application of the method has shown that for value changes, most of them can be achieved through engineering work, and that the need for R&D is limited to a few topics. More R&D activities are required for cost reduction, and the analysis of function value has allowed further R&D activity identification. The highest cost reductions were found for the non matured part of the technology, however their impact is limited as they are specific to some products; these cost reductions have to be addressed in the development phases. Cost saving identified on the matured die cast technology are less impressive when reported to the part, but these apply to the whole portfolio.

The proposed approach needs to be extended to other products. It could be also of interest to apply it at the costumer, at a higher system level integrating different parts and eventually different competing technologies. Assuming that each supplier could list function levels and cost associated with function level changes, an approach with optimizers could be developed to assess the cost benefits if function levels were balanced from one side of the system to another.

Four projects have been selected and detailed in the annexes.

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ACRONYMS AND ABBREVIATIONS

4WD	Four wheel drive. Also indicates 4WD vehicles
Al	Chemical symbol for aluminium
AE	Advance Engineering
AM60	Mg HPDC alloy containing 6% aluminium, with <0.5% Mn, used for parts requiring high ductility (>10%)
AZ91	Mg HPDC alloy containing nominally 9% aluminium, 1% zinc
B2B	Business to business
B2C	Business to customer
BD	Business development
Ca	Chemical symbol for calcium
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CTE	Core Technology Europe department of Meridian Lightweight Technologies
DOE	Design of Experiments
EMI	Electromagnetic interference
ENPV	Expected Net Present Value
EVC	Economic Value to Customer
FEA	Finite Element Analysis
FEC	Front End Carrier
HPDC	High pressure die casting, where molten metal is injected at very high rate (>10 m/sec) into a steel die clamped within a press (the die casting machine)
IP	Instrument Panel
MC-HPDC	Melt Conditioned High Pressure Die Casting
Mg	Chemical symbol for magnesium
Mn	Chemical symbol for manganese
Nd	Chemical symbol for neodymium
NVH	Noise, Vibration, Harshness
NPV	Net Present Value

OEM	Original equipment manufacturer, also the term used for an automaker
PM	Person Month
ppm	Parts per million
RE	Rare Earths
R&D	Research and Development
Sr	Chemical symbol for Strontium
t	metric tons
Tier One	A full service supplier of components and sub-assemblies for delivery directly to OEM production lines
Y	Chemical symbol for yttrium
Zn	Chemical symbol for zinc
Zr	Chemical symbol for zirconium

PREAMBLE

This work has been developed within the R&D department of a medium size automotive supplier. It is an attempt to develop an approach to better identify the type of R&D activities that have to be selected to grow short-midterm market, when marketing and R&D resources are limited. Once developed, the approach is applied to the Company to verify its efficiency in identifying interesting research project. However, in the timeframe of the Doctorate, the application had to be limited to some extent. Still, it will be demonstrated that the developed approach has been successful, higher level of information could be reached and the definition of R&D projects could be improved.

1. INTRODUCTION

Meridian Lightweight Technologies is an automotive supplier, developing and manufacturing lightweight solutions in Magnesium alloys, using the technology of high pressure die casting. Meridian's portfolio mostly consists of large complex monolithic parts integrating many functions like Instrument Panels, Front End Carrier, seat frame structure, but also of transmission housings.

Over the last decades, the demand for magnesium components in the automotive industry kept growing; the strong need for weight saving on customer's side has been driven by two key factors: the need to reduce fuel consumption and emissions and the need to improve vehicle handling.

Like for any other market, OEMs put more and more pressure to reduce cost and ask for higher performances: though Meridian focuses a lot on cost reduction and though the need for weight saving is strong, the growth of the market of Magnesium die cast parts is difficult.

In the described environment, the present work aims to analyse the current R&D approach with the scope of understanding how it could be improved to support corporate growth.

Meridian's European R&D department is called CTE "Core Technology Europe" and covers activities ranging from R&D to validation; CTE also provides technical support to plants or Business Development "BD". CTE resources are limited and activity tends to be more and more validation.

In general, R&D departments target to innovate to help capturing new markets, and targets are usually defined by corporate strategy. In a B2C environment, these would be mostly driven by marketing studies.

In the present case, an automotive supplier is in a B2B environment and it is much more difficult to define targets. This difficulty lies in the fact that, when it comes to innovation, the possibility to innovate implies to fully understand customer's needs. This information is knotty to capture for several reasons: to protect costs, the customer does not fully communicate on the product; also the complexity of the systems makes it difficult to fully describe the functions of the products and their value to the customer.

Product Development papers agree about the importance of understanding customers' needs to develop new products. Several methods to identify customers' needs are suggested in literature, but a large majority of the contents concerns B2C.

Hence, in such a B2B environment, with limited resources for marketing, surveys and R&D, it is difficult to structure CTE. Currently, R&D projects come from information "captured" from suppliers, conferences, customers and employee and not from a structured approach. This work is an attempt to understand how an R&D department could better define its activity.

If literature is abundant on how to rank and drive research projects, it is weak – not to say inexistent – when it comes to the key question that is: *"How to identify the type of R&D projects that have to be done to grow market?"* One method for B2B has been identified, but it applies mostly on machines manufacturing and implies the knowledge of the advantages given by the product's functionality and a comparison with competitors' solutions: this information is not accessible in the present case.

In that perspective, in this work an attempt has been made to develop tools to help identifying R&D topics that should be done to grow business for a small-medium automotive supplier.

2. LITERATURE SURVEY

2.1 R&D, INNOVATION AND BUSINESS PERFORMANCE

When defining R&D, the Organization for Economic Co-Operation and Development reports in the Frascati Manual that *"Research and experimental development (R&D) comprise creative work undertaken on a systematic basis in order to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this stock of knowledge to devise new applications."* [1].

Research and Development is a term covering three basic activities: **basic research, applied research and experimental development.**

Basic research comprises experimental and theoretical work *undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application or use in view* [1]. It is crucial to highlight that there is no particular application in view: the result of basic research are generally published in scientific journals or circulated to colleagues and not sold. *In basic research, scientists have some freedom to set their own goals.*

Applied research is still an original investigation with the aim to acquire new knowledge; however in this case, activity is *directed primarily towards a specific practical aim or objective* [1]. Target of applied research is to find out possible applications for basic research outputs, to determine new methods to achieve predetermined objectives or to consider available knowledge to solve particular problems. It is often performed to explore possible applications of interesting outcome of basic research and the resulting knowledge may be patented or kept secret [1].

Experimental development is systematic work, based on existing knowledge made with practical experience and basic and applied research. The aim of experimental development is to produce *new materials, products or devices*, to install *new processes, systems and services*, or to improve *substantially those already produced or installed* [1]. This process aims to translate knowledge made through *research into operational programs.*

Basic research activities take place mostly in higher education sector and government sector; applied research involves big companies and, in a minor extent, also small-medium companies; but when it comes to experimental development followed by the industrialization of innovations, also smaller company can take advantage of big opportunities.

It follows that for automotive small and medium suppliers, generally R&D lies between Applied research and Experimental development. The objective of this function is then to bring the knowledge to reach new markets, to improve a current process or product, or to solve a specific problem.

There are many definitions for innovation: all include the fact that innovation brings something new that is valued by the market. The term innovation may refer to both radical and incremental changes to products, processes or services.

Drucker [2] defines innovation as *"a change that creates a **new dimension of performance**"*; in economics this **change must increase value**, customer value, or producer value. Innovations are intended to make someone better off, and the succession of many innovations grows the whole economy. Hence a fundamental purpose of innovation is to **improve business performance** [3] and it is quite extensively agreed that, in a business environment, an i**nnovation is not an innovation until someone** successfully implements and **makes money on an idea** [4-7].

Therefore, in can be affirmed that innovation is a way for R&D department to grow business, and that *the role of an R&D department is finally to bring innovation to the product.* All definitions of R&D, and mostly the ones referred to Applied Research and Experimental Development, are intimately linked to Innovation, Innovation being the output of the R&D exercise; still Innovation has to turn into a product or service.

2.2 DEFINITION OF R&D ACTIVITIES

As stated above, for small and medium automotive suppliers, R&D lies between Applied Research and Experimental Development. Enterprise, per definition, is directed toward profit, hence strong focus has also to be put on efficiency when dealing with Research and innovation. Therefore, even prior to structure an R&D activity, the biggest focus should be on the selection of the projects in order to have the best payback as the business logic requests. This ability to identify the best type of R&D activities actually depends on the knowledge of customers' needs and on the price acceptance of the customers.

It follows that *firms' economical success depends on their capabilities of identifying customers' needs and quickly create products to satisfy them at acceptable cost* [8]; As R&D is dedicated to build knowledge for future products, it is of key importance to drive activities with the aim to deliver innovation according to customers' needs and insure that products will meet market needs and expectation. Hence, as per product development [9], a critical facet of the R&D activities is marketing.

Understanding of customers' needs is key to success [8, 9, 11] and it is extensively treated in Product Development literature; however, a large majority of the contents concern B2C companies, and suggest several methods to identify customers' needs and understand the value to the customer of a product or a development [8,11].

When dealing with B2B market, customer needs are difficult to capture and literature is poor in ways on how to identify these needs.

Anderson and Naurus suggest a procedure to build customer value models [11], but this requires a big effort in terms of investigation, of resources to allocate, and a strict collaboration with regards to the sharing of information with customer. Though interesting, this approach can hardly be applied in the current situation due to the lack of resources and to the fact that customers will protect information to protect price. Also, in some cases, the system is so complex that it is difficult for the customer himself to detail all the functions and advantages he could be looking for: "*frequently, the customer doesn't know that it has the data or information the supplier is looking for*" [11].

One method for B2B has been identified: Forbis and Metha propose an interesting method to evaluate the Economic Value to the Customer (EVC) [10], comparing the proposed solution with competing ones. The aim of this model is *to figure out how much the customer will pay to switch from one product to the other*, but it also can help to *enable the supplier to segment the market more precisely, to design its products to meet the needs of the most profitable segments, and to charge those segments a premium for the extra value they receive*. The aim of this method fits with the purpose of this work, but it applies mostly on manufacturing tools and implies the knowledge of the advantages given by the product's functionalities and a comparison with competitors' solutions, so it is not applicable to the present case.

In the lack of methods, the definition of research topics is often based on unstructured decisions arising from different entities of the company: personal perceptions, suggestions from customers, ideas taken at conferences or from literature, information captured from marketing, BD, engineering. Still, all this generates a basket of potential activities for which the company will evaluate the interest and payback. Mostly, the lack lies in having a method identifying topics in a structured way.

In the described environment, focus is put to develop reliable solutions and little effort is devoted to capture customer's future needs and associated research. The main reason for that is the fact that the customer is not aimed to share information because he doesn't see the value in doing that and doesn't want to share strategic information.

This work is then aimed at understanding how to capture customer's needs in this B2B environment, and try to work out how R&D activities could be better identified to support corporate business growth. In other words:"how to identify R&D activities to grow market through innovation by understanding customer's needs, when tools to understand customer's needs lack?"

METHODOLOGICAL NOTE

All the research activities in this work took place in real-world situations, and are aimed to solve real problems. According to O'Brien [12], knowledge is derived from practice, and practice informed by knowledge, in an ongoing process, is a cornerstone of action research. Action researchers also reject the notion of researcher neutrality, understanding that the most active researcher is often one who has most at stake in resolving a problematic situation.

According with Action Research methodologies, all this work comes from a strong and continuous collaboration between an Academic and an Industrial partner, i.e. DTG of Università di Padova and Core Technology Europe department of Meridian Lightweight Technologies Inc.

2.3 MAGNESIUM IN AUTOMOTIVE MARKET

2.3.1 MAGNESIUM

Magnesium is the eight more abundant element on the land surface and represents approximately 2.5% of its composition. Because of its remarkable reactivity, it is not found in nature to the metallic state, but like compound.

The marine waters contain approximately 0.13% of magnesium hence a cubic meter of marine water contains 1.1 kg of magnesium [13]. Other common sources are dolomite ($(CaMg)CO_3$), magnesite ($MgCO_3$) and carnallite. There are moreover many silicates of magnesium, but very rarely they are sufficiently pure to guarantee processes for the obtaining of the metal.

Two processes to produce primary metal are currently in use, the thermal reduction of magnesium oxide (Pidgeon process and Magnetherm process) and the electrolysis of molten magnesium chloride [14]. The latter is the most used. World-wide production of magnesium has reached 726000 ton in 2006 and 774000 in 2007 [15] with a growth of 8%.

The main use of magnesium is as alloying addition to aluminium alloys: more than half of rough magnesium production is used this way, as shown in figure 2.1; small percentages of magnesium give to aluminium an increase in mechanical resistance and improve corrosion behaviour. The 5000 and 7000 series alloys of aluminium contain up to 5.5 percent and 3.5 percent magnesium, respectively.

Another important application field for magnesium is desulphurization of iron and steel. Desulphurization is a process to remove sulphur, which has serious effects on properties, from melt iron before it becomes steel. Magnesium has a high affinity with sulphur and makes a compound which separates from the melt. Magnesium is quite expensive if compared with other reagents but it has the best performance in term of desulphurization, pollution, heat loss, treatment time, and control of process.

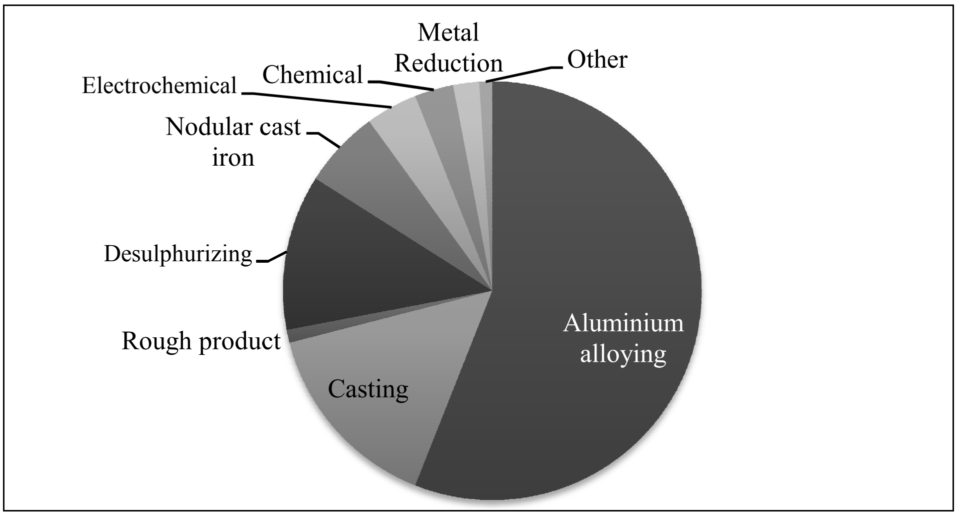


Fig. 2.1 Industrial utilization of magnesium (2004)

Magnesium is also important to produce nodular iron: small amounts of magnesium and rare earth are placed in melt; this make graphite nucleate with a sphere shape instead of flakes giving to iron resistance and ductility properties.

Magnesium anodes are used to prevent galvanic corrosion of steel in subterranean pipes, tanks and other situations.

Magnesium is also used as reducer in beryllium, uranium, zirconium and titanium production.

Around 15-20% of world production is used in magnesium-based alloys having structural uses in the forms of die castings, gravity castings and wrought products. Magnesium alloys have many desirable features: good ductility, excellent castability and better damping characteristics than aluminium. On the other side, there are also some negative features as high reactivity in the molten state, inferior fatigue and creep resistance compared to aluminium and issues in galvanic corrosion.

2.3.2 PHYSICAL – MECHANICAL PROPERTIES AND COMPARISON WITH OTHER MATERIALS

Magnesium is the lightest among structural alloys. With a density of 1,78g/cm^3 it is 30% lighter than aluminium and 75% lighter than steel. Physical and chemical properties are reported in table 2.1.

Tab. 2.1 Physical and chemical properties of Magnesium

ATOMIC NUMBER	12
ATOMIC MASS	24,31
COLOUR	SILVER GRAY
DENSITY	1,738 g/cm^3 at 20°C 1,58 g/cm^3 at 650°C
MELTING POINT	650°C
BOILING POINT	1103°C
CRYSTAL LATTICE	EXAGONAL CLOSE PACKED
COMBUSTION HEAT	25020 kJ/kg
MELTING HEAT	368 kJ/kg
SPECIFIC HEAT	1025 J/(kg·K) a 20°C
VAPOUR PRESSURE	20 Pa at 527 °C 360 Pa at 650 °C 1400 Pa at 727 °C
VALENCE	Mg^{2+}

Pure magnesium does not awaken interest for industrial applications; instead magnesium alloys are widely used especially in automotive and aeronautical industries. Automotive applications of magnesium are mainly produced by High pressure Die Casting (HPDC). Depending on the kind of application, magnesium castings could be in competition with steel, aluminium and plastic [16]. Table 2.2 shows the advantages of magnesium compared with stamped and welded steel, aluminium die casting and plastic mouldings.

Tab. 2.2 Qualitative comparison between magnesium and other materials.

Compared with stamped and welded steel: - Magnesium is 75% lighter - Casting technology allows component consolidation and integration: there is no necessity of welding and assembly, hence cost are lower - Tooling costs are significantly lower - Magnesium has higher heat conductivity - Complicated thin-walled *near-net-shape* monolithic parts can be produced - Magnesium allows superior dimensional stability/repeatability
Compared with aluminium die-castings: - Magnesium is 33% Lighter - Magnesium offers higher machinability - Longer Die Life - Larger thin-walled near-net-shape casting. - Thinner walls - Similar mechanical properties - Greater general corrosion resistance - Higher damping capacity (NVH) - Higher elongation without heat treatment - Greater energy absorbing capabilities
Compared with plastic: - Higher mechanical properties - Superior stiffness - Greater energy absorbing capabilities - Higher temperature applications - Higher damping capacity (NVH) - Higher electromagnetic shielding properties

On the other hand, magnesium alloys present some weaknesses: elastic modulus is low if compared to other structural metals, resistance to galvanic corrosion is the worst among all the competing solutions due to the fact that magnesium is anodic to most of the other engineering materials. In addition to that, common magnesium alloys have lower high temperature properties than aluminium alloys and steel.

2.3.3 DIECAST MAGNESIUM

Die casting is the most common process to produce magnesium components.

In that process parts are made by forcing molten metal under high pressure into permanent steel moulds called dies to produce complex shapes with a high degree of accuracy and repeatability.

The process is similar to HPDC of other alloys such aluminium and zinc, but some distinction must be made because of different material characteristics: molten magnesium ignites in contact with air, hence it is necessary to protect the melt with cover gases. Also thermodynamic properties of magnesium differ from aluminium ones: this has to be taken into account when designing the die and when setting process parameters. Magnesium can be cast with cold chamber and hot chamber machines.

Generally hot chamber shows lower transformation cost, but shot weight is limited at 3kilograms. Cold chamber allows casting components up to over 15 kilograms with complex shape and thin walls.

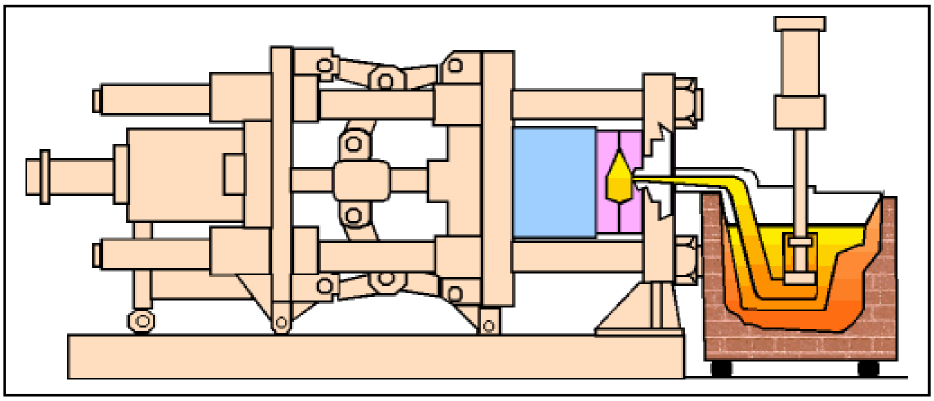


Fig 2.2 Scheme of a hot-chamber HPDC machine [17]

The injection system of a hot chamber machine is immersed in the molten metal; the crucible is attached to the machine by a metallic feed system called gooseneck. As the injection plunger rises, an aperture in the injection cylinder opens, allowing molten metal to fill the cylinder cavity. When the plunger is pushed downward, it seals the aperture and forces molten metal through the gooseneck and nozzle into the die cavity. After the metal solidification has completed in the die cavity, the plunger is withdrawn and the die opens allowing the casting is ejected (figure 2.2).

In cold chamber machines, the molten metal is poured into a cylindrical sleeve (the cold chamber), manually by a hand ladle or by an automatic ladle; when casting magnesium alloys, a siphon is use to minimise the contact between metal and air. A hydraulically operated plunger seals the cold chamber aperture and forces metal into the locked die at high pressures (figure 2.3).

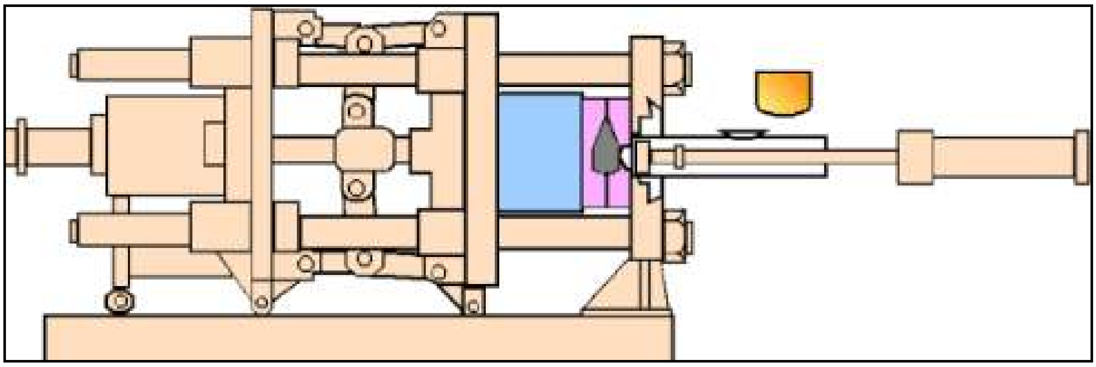


Fig 2.3 Scheme of a cold-chamber HPDC machine [17]

Die castings show very fine skin structure due to the fast solidification in contact with the die; part cast with ductile alloys are capable of high elongation and energy absorption without heat treatment. Similar properties can be obtained with special aluminium alloys which need to be cast using vacuum systems and to be heat treated: these higher process complexities lead to higher cost.

Large magnesium components with walls thickness below 2.5mm can be cast; such small thicknesses cannot be reached with aluminium die casting.

2.3.4 MAIN APPLICATIONS OF DIE-CAST MAGNESIUM

Figure 2.4 shows United States markets of magnesium casting in 2005. Worldwide proportion can be considered similar, with maybe a greater weight of computer and electronic products due to the Asian production.

A large majority of HPDC magnesium applications regards automotive industry. Engine and transmission components (housings) are extensively used from half of last century and structural applications have gained more and more credit over the last twenty years.

Die cast magnesium is used also in non-automotive housings, in particular with regards to power tools and electronic devices such as mobile phones, cameras and laptop computers. In this specific application field, the strength and lightness of magnesium are appreciated in comparison with plastic: the housings present also good electro-magnetic shielding, thermal conductivity and enhanced product quality perception.

Sport and leisure applications take advantage of the mechanical properties of magnesium alloys, of the possibility of making complex shapes with casting process and also of the appealing of a material which is often seen as “exotic”. Examples of sport applications are bicycle components, bow handles, ski and ski boots parts.

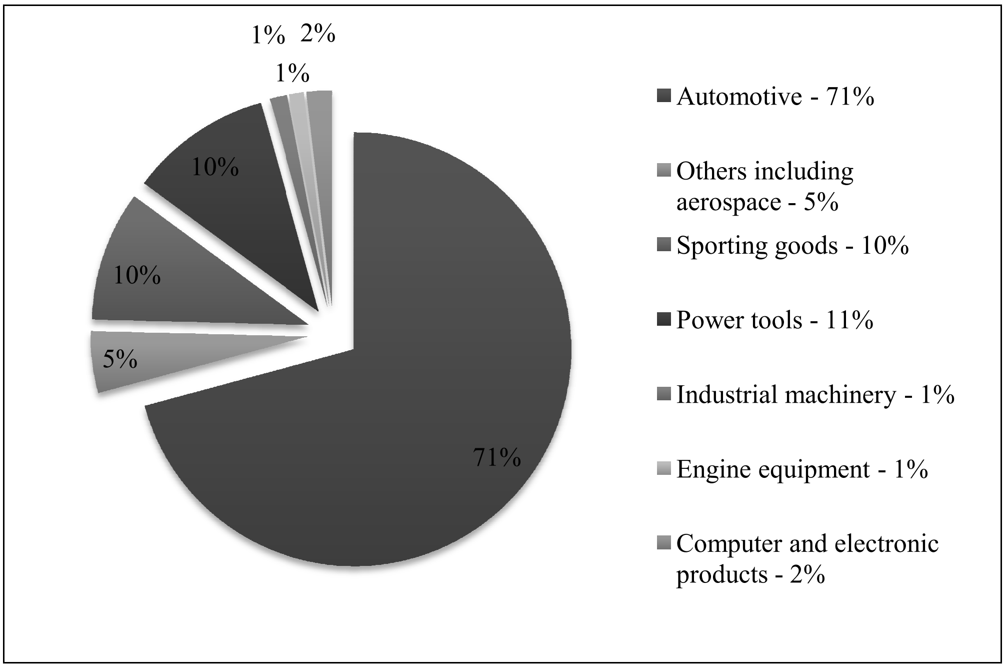


Fig.2.4 U.S. Magnesium Casting Markets Based on Tons Shipped (2005) [18]

In 2007, around 160000 tons of magnesium alloys has been produced (20% of Magnesium production); 140000 of them have been used in HPDC (87%); about 100000 have been cast in automotive components (62%) [19].

2.3.5 MAGNESIUM IN AUTOMOTIVE

Magnesium is not new in the automotive market: racing cars used magnesium parts in the 1920's and in 1920's and 1930's Elektronmetall Cannstadt produced more than 4 million die cast pistons [20]. Magnesium castings have been extensively used in commercial vehicles since 1936 when the Volkswagen Beetle was introduced; the car contained around 20 kg of magnesium in the engine block and transmission housing and during its peak production in 1971, consumption of magnesium reached 42000 tons per annum. More than 20 million of them have been built over the years consuming over 400000 tons of magnesium.

Today magnesium applications in the automotive market vary widely, from small to large parts and from simple valve covers to complex monolithic components integrating many functions. Some applications are shown in figure 2.5.

Two markets can be distinguished: one is in competition with aluminium castings and consists in powertrain applications such as manual transmission cases, 4WD transfer cases, cylinder head covers, intake manifolds, engine brackets. It represents about 55% (55000t) of the total market [19]. In this case magnesium can offer a significant saving in weight which ranges from 15 to 25% depending on the specific component. The main alloy for this kind of application is AZ91D; it shows excellent castability, good mechanical properties and excellent general corrosion resistance.

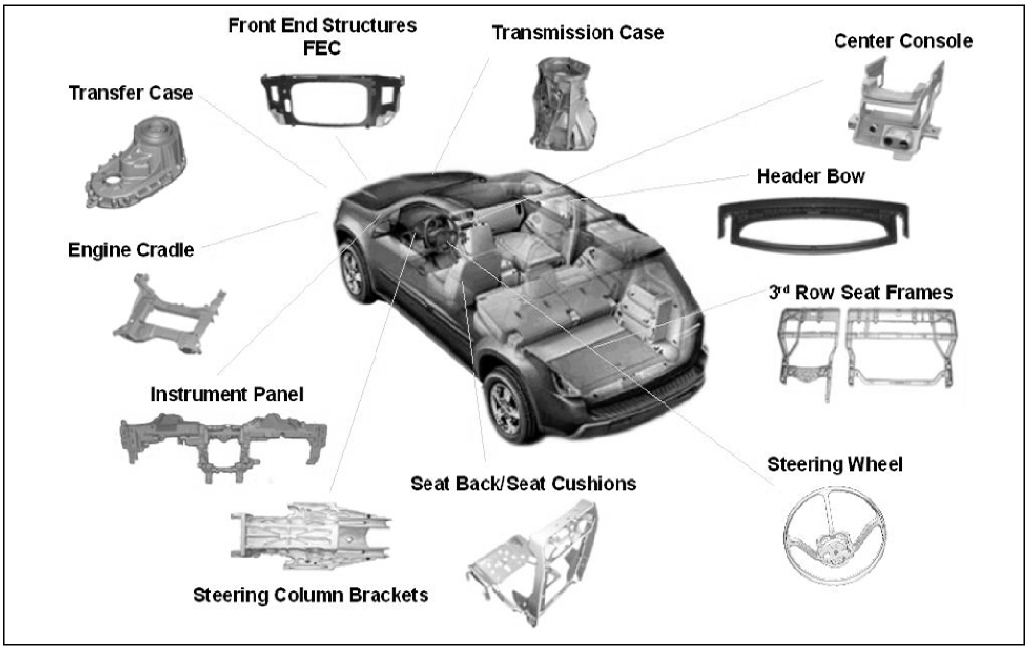


Fig. 2.5 Main automotive magnesium components

The so-called "Structural applications", i.e. parts contributing to the structure of the vehicle represent the second market (45% of the total): in this case magnesium is competing with stamped and welded steel assemblies, offering significant advantages in terms of weight saving (up to 50%), assembly precision and vibration absorption. The most common application is the cross car beam or instrumentation panel; other applications are front end carriers, seat frames or steering wheel frames. In these applications, fracture elongation is a key property and alloys of the AM series are generally used (see mechanical and physical properties of main magnesium die cast alloys in table 2.2.).

Tab. 2.2 Mechanical and Physical properties of HPDC magnesium alloys

Mechanical Properties	u.o.m.	AM50	AM60	AZ91
Ultimate Tensile Strength	MPa	210-230	220-240	230-250
Tensile Yield Strength (0.2% offset)	MPa	120-125	130-135	160-165
Compressive Yield Strength (0.1%)	MPa	120	130-135	165
Fracture elongation	%	6-10	6-9	3
Elastic modulus (tension)	GPa	45	45	45
Elastic modulus (shear)	GPa	17	17	17
Brinell Hardness	HB	60	62	67
Poisson Ratio		0.35	0.35	0.35
Fatigue resistance	MPa	70	70	70-97
Physical properties				
Density	g/cm^3	1.77	1.8	1.81
Liquidus temperature	°C	620	615	598
Incipient melting temperature	°C	420-435	420-435	420-435
Linear thermal exp. Coefficient	µm/m*K	26	26	26
Specific heat	kJ/kg*K	1.02	1.02	1.02
Specific heat of fusion	kJ/kg	370	370	370
Thermal conductivity	W/m*K	65	61	51
Electrical conductivity	MS/m	9.1	-	6.6

2.3.6 AUTOMOTIVE MAGNESIUM APPLICATIONS INDUSTRY

Automotive magnesium applications industry is briefly described below on the base of Porter model. A scheme of the model can be seen in figure 2.6

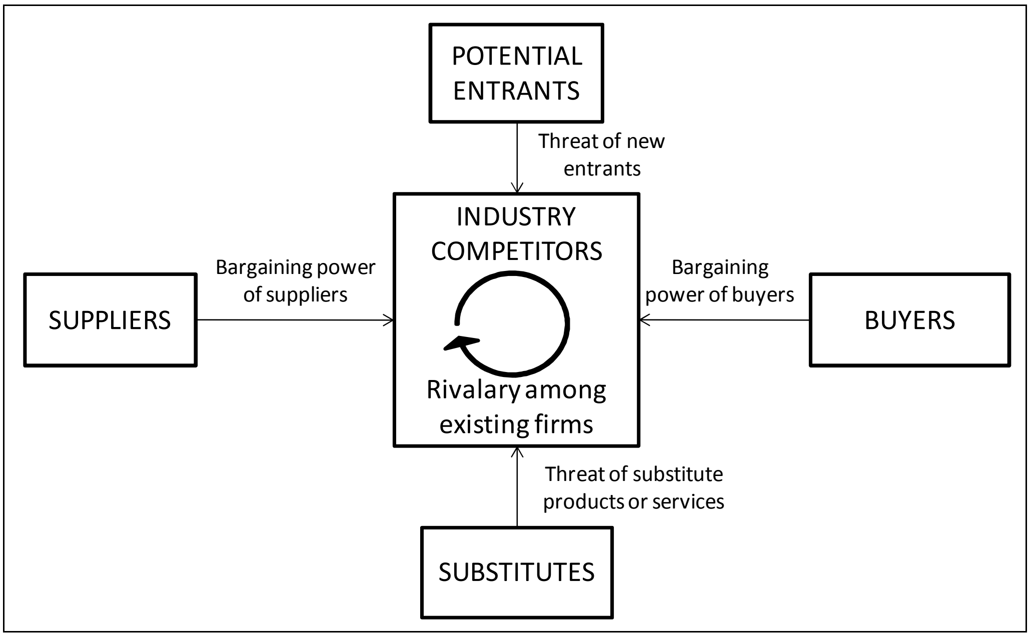


Fig. 2.6 Scheme of Porter model [21]

<u>Industry competitors</u>

Generally, the reference market for automotive supplier can be consider global; in the present case, when it comes to very large castings, transportation cost can be quite important, and analysis have to be done for the given market:, the European for this study.

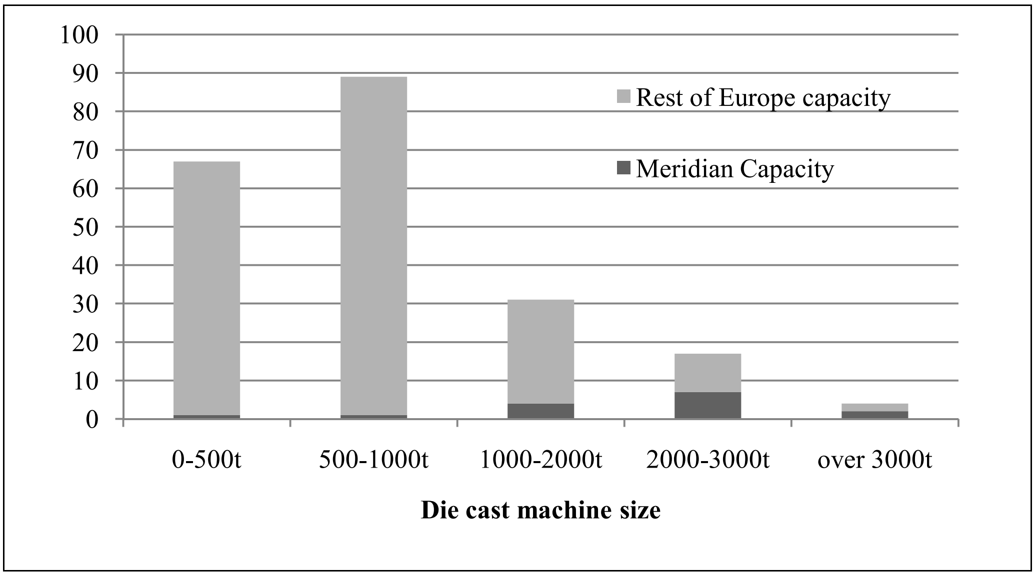


Fig 2.7 European capacity of cold chamber diecast machines [16, 19]

Figure 2.7 shows the European capacity for Cold Chamber die cast machines. It can be seen that the large majority of sizes is below 2000t. Meridian capacity is in dark gray in the chart: most installed machines have a clamp force above 1000t; more interesting information can be captured if the focus is put on the high-clamp force end of the chart as in figure 2.8.

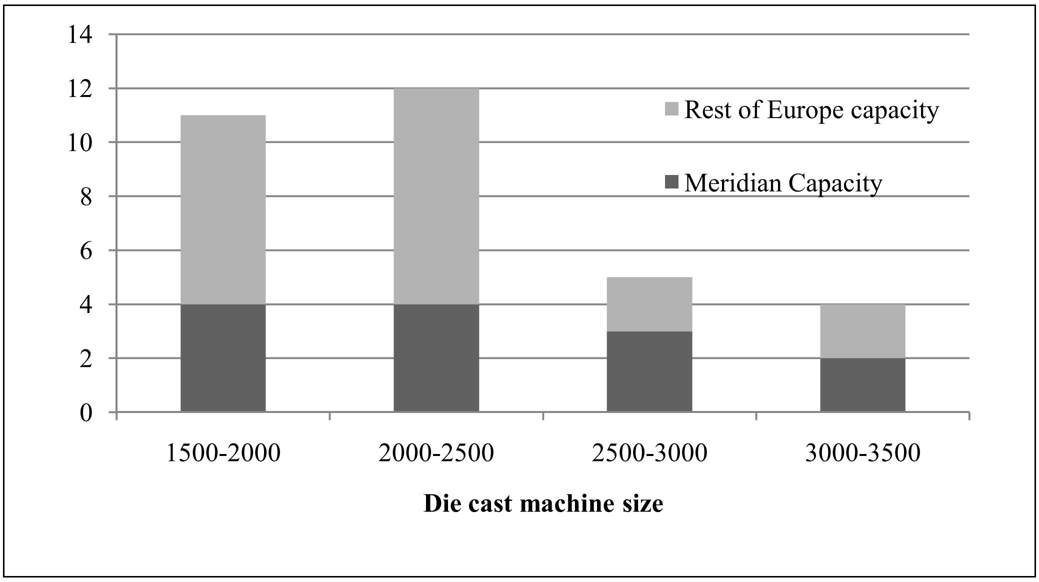


Fig 2.8 European capacity of cold chamber diecast machines [16, 19]

When it comes to high clamp capacity, above 2500t (capability for large thin walled castings), Meridian shows a dominant position. Meridian provides over 40% of the European capacity.

<u>Suppliers</u>

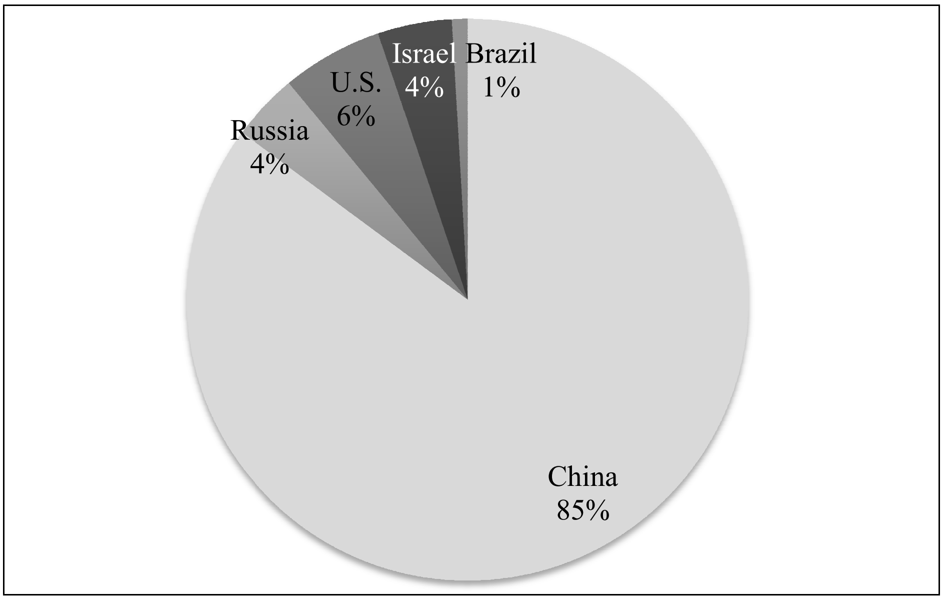


Fig 2.9 Primary magnesium producing countries in 2007 [22]

It will be shown in details how the most important cost item for a magnesium die-casting is the purchasing of the metal. Hence, looking at supplier means mostly looking at magnesium smelters. The number of primary magnesium producers is decreasing, hence there is a stronger bargaining power of remaining ones, which is likely to be one of the factors of the current high price instability (figure 2.10).

Figure 2.9 shows how Chinese magnesium suppliers now have a dominant position after that most European and North American smelters shut down over the last years.

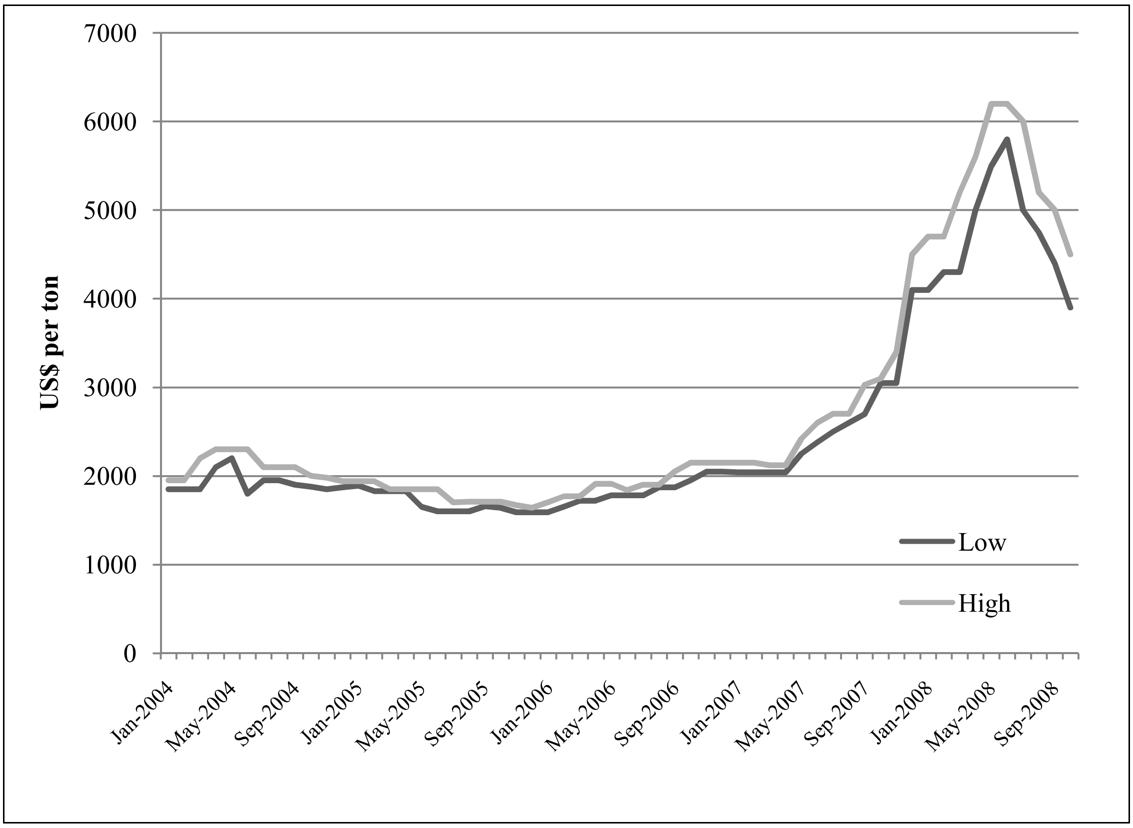


Fig. 2.10 World magnesium price (Low-High) in U.S. $ per ton vs. Time (January 2004 to October 2008) [23]

Buyers

Buyers are essentially OEMs and Tier One suppliers. The number of customers is stable and even if there is a perception of stronger needs for weight saving and if many publications report an increasing use of magnesium in the automotive market [19, 22, 24, 25]; the increase in demand of large thin-walled casting has slowed.

Substitutes

As explained in previous sections, magnesium castings compete with aluminium, steel and plastic solutions, depending on the application.

Aluminium is the substitute of magnesium for transmission housings: price is a key factor when dealing with housings. In addition to that, galvanic corrosion concerns have to be addressed.

Steel is competing with magnesium casting on structural parts such as IP and FEC; stamped and welded steel components require higher initial investments. Steel solutions have higher weight, lower precision in assembly and can have lower vibration absorption. On the other hand, part cost is lower and new high strength steel together with new forming technologies could potential narrow the gaps in terms of weight.

Compared with magnesium, plastic is more appropriate when there are no structural requirements or when cosmetic appearance is important. However coated magnesium aesthetic covers can give higher the perceived quality. Magnesium offers higher EMI shielding and strength and is applicable to higher temperatures. Future development in plastic could consist in a thread because of their low cost and potentially increased performance reached by reinforced polymers (ex. fibreglass reinforced polyamide) or with hybrid solutions (plastic-steel).

Potential entrants

Entering die-cast magnesium industry requires high initial investment in terms of equipments and very specific know-how is required in terms of casting process, numerical simulations, mechanical properties, engineering of magnesium components in general and corrosion protection. All this knowledge requires big efforts to acquire.

2.3.6 MERIDIAN MARKET

Meridian Lightweight Technologies is the world first automotive magnesium supplier [16] providing engineering and manufacturing of magnesium die cast components. It serves 100% Business customer (B2B), as Tier One supplying directly automakers (OEM), or as Tier Two supplying Tier One.

Production plants are located in North America, Europe and Asia. The European market is served by two plants located in Italy (Verres, AO) and United Kingdom (Sutton in Ashfield, Nottingham).

Global annual production of Meridian's facilities is given below for key products:

- Instrument Panels: 4 million per year
- 4WD Transfer Cases: 2 million sets per year (cases & covers)
- Front End Carriers: 800,000 per year
- Seat Frames: 400,000 per year
- Steering Column Brackets: 4 million per year

European production consists in large thin-walled structural castings for automotive applications; key products are IP, FEC, seat frames and centre consoles.

2.4 OEM VIEW ON THE USE OF MAGNESIUM

OEMs' efforts to reduce vehicle weight are driven by the will to reduce fuel consumption and emissions, and the need to improve vehicle handling. Reducing weight is more and more the key to reduce consumption as other technologies have already yield a lot of their potential (i.e. more efficient engines). Now about 60% of the potential fuel consumption reduction is mass-dependent [25].

When it comes to weight saving and the use of magnesium, the OEMs communicate on a premium price per kilogram saved. Attention has to be paid to this information as this premium price is generally what is observed on the market, i.e. it is an output after that the OEM have selected solutions to address weight issues. In the last phases of the vehicle development, if weight issues are met, the OEM will select for different functions among different solutions to address at the best weight and cost issues. Hence if the premium cost for magnesium is usually in the range of 2€ per kg saved it will vary depending on the customer, the function, the location of the function and the project. The premium price is generally an output and more seldom and input.

As an example, an OEM could select magnesium for a seat frame for a given vehicle and reject it for the next generation, though cost and performance remain the same. Still, it is known that the weight saving can be more attractive if it is achieved on a rotating part (inertial effect) or at the front/top of the vehicle to move the centre of gravity further back and down [26].

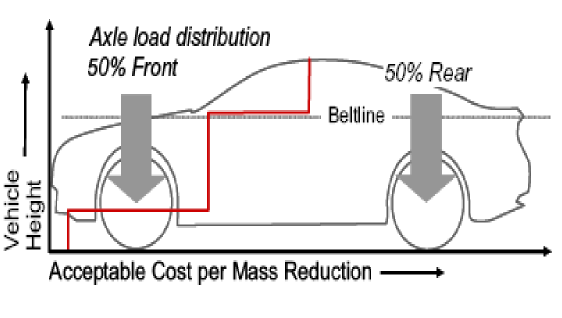


Fig. 2.11 Acceptable cost per mass reductions vs. vehicle height [19]

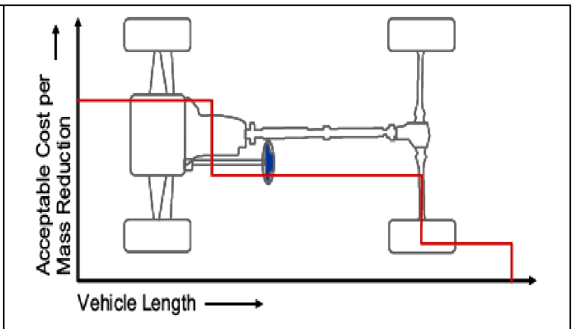


Fig. 2.12 Acceptable cost per mass reductions vs. vehicle length [19]

These movements improve handling; areas of interest are displayed in figures 2.11 and 2.12. If the key benefit of magnesium is expressed in terms of weight saving, others factors driving the business case remain vague as OEMs do not share information on all benefits they find with magnesium solutions.

2.5 CONCLUSIONS

The difficulty to identify efficient R&D projects lies to the fact that Meridian is working in a B2B environment. R&D can only be defined on the base of very good knowledge of customer's needs and price acceptance level. For small or medium automotive supplier with limited resources, no literature could be found on how to identify research projects in such an environment. The objective of this work is investigate on how R&D department could improve it is way to identify projects to support growth.

Magnesium automotive parts are made by die casting and offer attractive weight saving. Though OEM are more and more seeking for weight saving, to lower fuel consumption and address vehicle handling issues, growth of magnesium die casting market is difficult.

3. ANALYSIS OF CURRENT R&D DEFINITION APPROACH AT MERIDIAN EUROPE

3.1 VIEW ON THE "POSSIBILITIES TO BOOK BUSINESS"

A study on the past business at Meridian, showed three development routes for a customer to select and go in production with a Magnesium solution

The first one is ***"build to print"***: the contact comes from the costumer who is asking the die caster to quote for a defined product. This first solution represents less than 5% of Meridian quotes. The reason for such a small amount of *built to print* requests lies in the fact that Magnesium die casting is not a commodity business, and generally develop the parts to produce. Indeed, these quotations mostly apply to housings initially targeted to be cast in Aluminium. For this kind of request focus is made on cost.

The second possibility is to raise interest at the costumer **promoting the current portfolio**, in order to get a development that, later on, can turn into a production. This approach represents 90% of Meridian current business. Focus is mostly put on engineering to find concepts meeting customers' requirements and price. The current approach can be described as follow:

- Business Development and Advanced Engineering departments communicate about Magnesium die-cast capabilities and possibilities in order raise interest at the customer.
- If the customer shows interest, first concepts are developed for free and an initial proposal of a Magnesium solution is made in terms of weight, performance and price.
- If interest is raised, a development project starts and, step by step, the customer has to contribute to costs. A specific approach with gates called "*Meridian work plan"* is used to track the development. With an increasing contribution versus development time, customer commitment grows as well as the probability to get the business in production. It must be noted that tracking of both customer's interest and development costs is possible as the activity has a high probability of delivering the expected results; such a method is more difficult to apply to R&D projects.

The third possibility happens when customers have a good knowledge of Magnesium die cast technology and can come with a **proposal of development.** In this case, some products can turn to be a highly innovative concept to develop. It has been the case for first Cross Car Beam, FEC and Engine Cradle; these products are actually the major innovation that Meridian developed and later on spread over the market (using the approach described above). In other cases it could be an opportunistic approach for a product that would not be spread but it exists for just a specific case.

3.2 R&D AT MERIDIAN EUROPE

If at the earlier stages the activities have been focused on solving specific issues or concerns on the technology, nowadays Core Technology Europe is more and more involved in validating non matured solutions, helping to sort out plant issue, or supporting BD and AE people on technical aspects in front of the customer (see picture 3.1). The activity within applied research and experimental development is more and more limited. Research topics derive from decisions arising from different entities of the company.

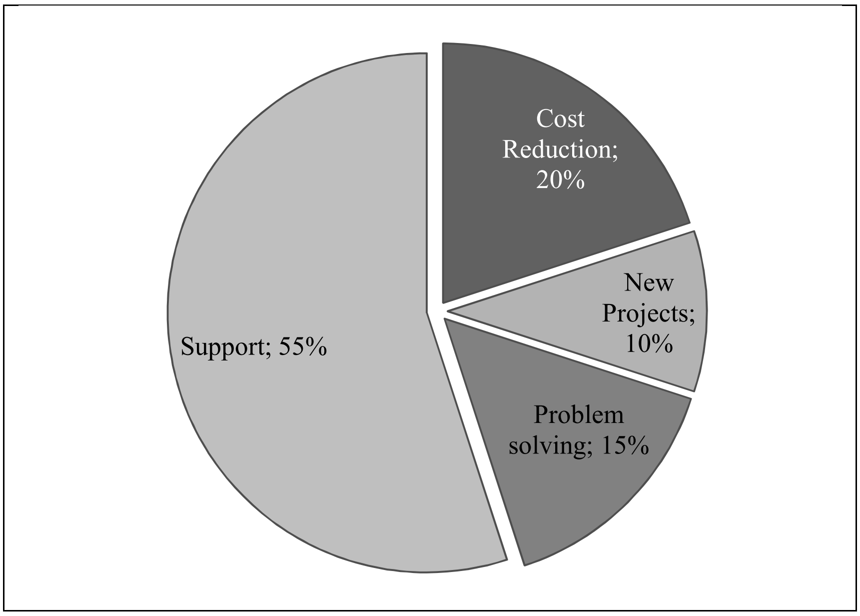


Fig. 3.1 Core Technology Europe's activities distribution

3.3 ANALYSIS OF INNOVATION AT MERIDIAN

An inquiry on both process and product innovations that occurred at Meridian, has shown four kinds of innovation genesis:

1. The fist kind of activity has been generated to **reduce production cost** and has been carried on the base of internal know-how and ideas.
2. A second group of innovations has been developed with the aim to **meet a new environmental requirement or a request from legislation**. An example of this could be the necessity of substitute greenhouse cover gas (SF_6) with more environment friendly solutions.
3. The third kind of items has been triggered by the need to **solve specific issue** on the product of to satisfy a request of the customer. The development of Robustness Approach [27] to address crash performance prediction is an example of this group as well as the development of solution for corrosion resistance improvement [28, 29].
4. The fourth way of innovating consists in the development of a brand new product for the market, driven by the request of a customer. The successful implementation of such

innovative products has a huge impact on future market.

It could also be seen how the type of innovation with the highest impact on the business were either activities on cost reduction or the introduction of radically new products.

Meridian has innovated by introducing on the market new components never made by magnesium die casting before:

- **Cross Car Beam**: is the basic backbone of the cockpit to which other components are attached; it provides rigidity to both the module and the car body.

- **Front End Carrier**: is the underlying structure of the front end module, it offers both functional and assembly integration possibilities [30, 31]. It is usually made of thermoplastic materials, composites, metal or metal/plastic hybrids.

- **Engine Cradle**: also called front cross member is a chassis application with high service load, and facing severe under-vehicle environment in terms of corrosion [32, 33].

When investigating the genesis of these product innovations, a common path can be seen. Figure 3.2 shows the flow of requests and information triggering the development of the innovative components: as a first step, a carmaker with a good knowledge of the high pressure diecast magnesium potential is asking for the development of a new type of application for magnesium. Following to the request, Meridian is validating the feasibility of the requested concept with the existent internal know-how and eventually developing or implementing specific solutions for some specific targets to achieve (e.g. high creep alloys for Engine Cradle or corrosion protection for FEC).

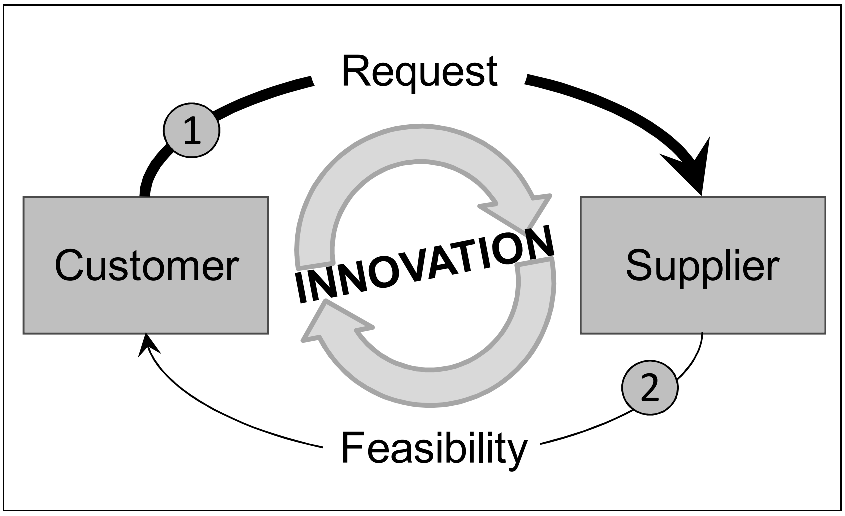


Fig. 3.2 Flow of requests and information triggering the development of the innovative components

After that the first development was successfully completed, Meridian worked to spread the concept to other customers by communicating on the achievement in terms of performance and cost. Figure 3.3 shows the flux of information for first innovation and the spreading of the achievement: arrows 1 and 3 represent the main flux of information.

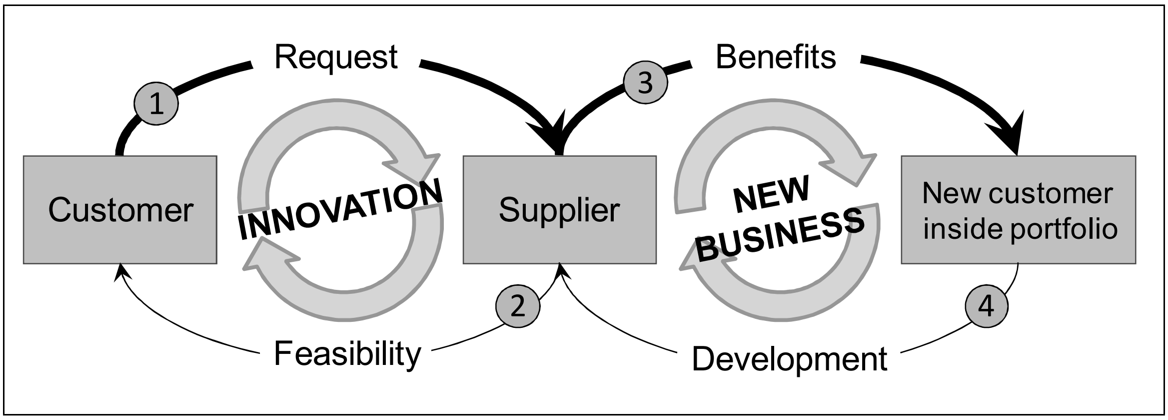


Fig. 3.3 Flux of information for first innovation and its spreading

For all key portfolio products the information loop has been triggered by the customer.

The generation of innovation, as well as the spread of business, will depend on Company's capability to raise interest on the benefits of the solution and their cost. It is of key importance to fully understand the benefits of a solution but also to understand how it could fit other customer's needs.

For this environment, R&D has then to be associated to the analysis of the technology / material / application benefits, so that eventual gaps can be closed to adapt to new markets. A survey of different Meridian people in contact with the customer showed that it is not obvious to capture all the customer's benefits of such an innovative products as a FEC or an EC. Obviously, the understanding of the product's benefits, as well as the cost acceptance of the market, grows with the development of a market, and even just with the experience gained through developments.

3.4 ANALSYSIS OF BUSINESS FAILURES (POST MORTEM ANALYSIS)

In order to understand Meridian Europe situation and to compare it to the innovation picture described above, a *post mortem analysis* has been run on all business lost, as well as on all successful business. This analysis was also targeted to better plot the picture of the advantages offered by the technology, as well as its limits. This analysis has been done by interviewing all European Business Development people.

Interviews have been completed later on specific topics with people from different departments of the organization:

- Business Development
- Advanced Engineering
- Marketing
- Core Technology

Name ____________ Date ____________
Position ____________ Time ____________
Location ____________ to ____________

Product ____________ Year/Month ____________
Segment ____________
Customer ____________

Reason for business loss:
☐ Cost
☐ Technical ☐ Vague
☐ Specific ____________

☐ Else ____________

When did we join the project? ____________
At wich stage did we fail? ____________
Did you feel to be colse to get the business? ____________

Level of integration ____________

Requirements:
NVH ____________
Crash ____________

Weight ____________
Wheight of the steel solution ____________
Selling price ____________
Competitors price ____________

Values for the customer ____________

Notes

Could you plot cost vs time/values for this item?

Fig. 3.4 Example of the template for the interviews.

An example of the template for the interviews is given in figure 3.4. More than one hundred business cases have been reviewed. Details of analysis are not reported in this work for confidentiality reasons, only the factors explaining business lost are presented in figure 3.4.

When analyzing the reasons for “business lost” (Figure 3.5), it can be seen that the most recurrent given factor is cost. It is mentioned as the first hurdle in more than 50% of the cases and often given as a secondary reason. Cost is perceived as the key blocker for business to book. This point is not surprising as business cases are obviously driven by price. The definition of R&D activities will have then to consider projects aiming at reducing cost.

It is also interesting to note that very often the reason for business lost was not possible to specify; by extent it could be considered that “price/cost” is given as the first factor as it is the most obvious reason for a business case to fail; further investigation shows that it is not so easy to state clearly on the actual reasons for “business lost”.

When asking the reason why the costumer was interested in the magnesium solution, i.e. when searching the value of this material/technology in comparison with others, it emerged that there is often incomplete understanding of all the benefits seen by the customer. For the remaining cases “price/cost” turns to be the factor for “business taken”. Most business taken can only be described as “good business case”, i.e.: “good price”, “interesting weight saving”, “solution meets requirements”.

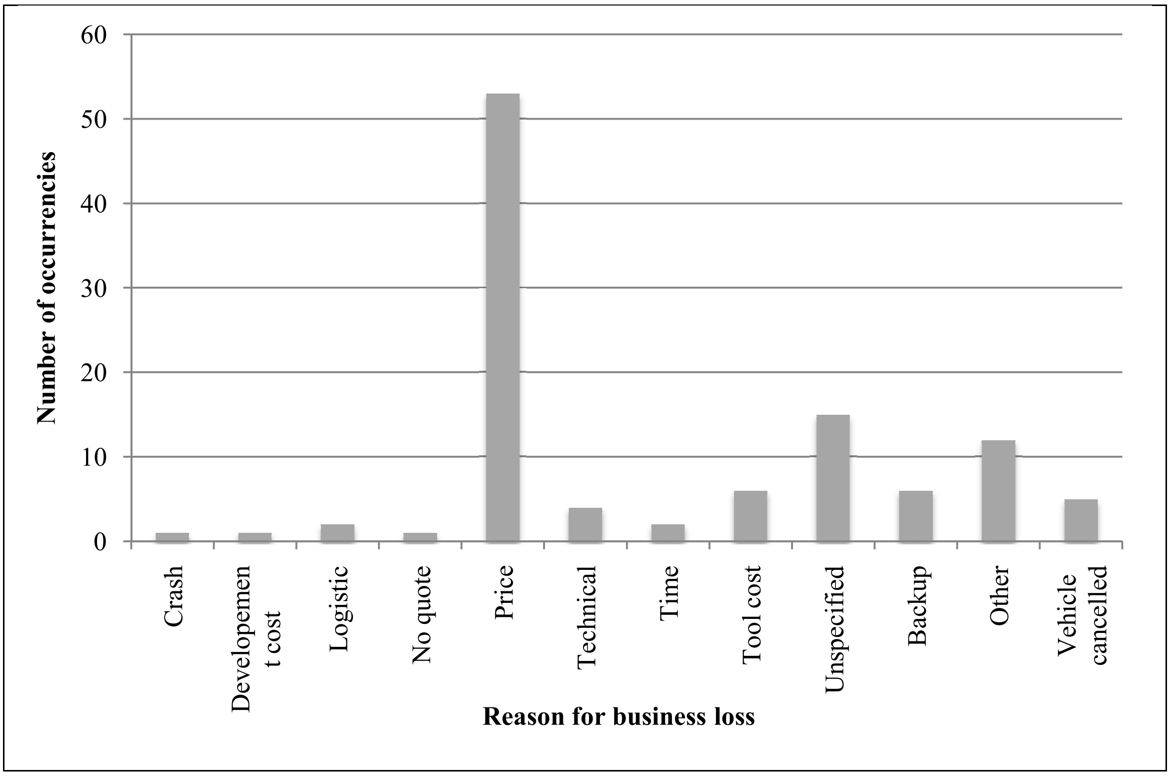


Fig. 3.5 Output of post mortem analysis, main reason for business loss.

Not knowing all the benefits of the proposed solution, it appears difficult by extent to convince the customer why Magnesium makes more sense than any other solution. In other words, there is a lack of knowledge of the product's values. That lack of understanding applies both for failed business and for successful business.

The Post Mortem Analysis simply confirms that the definition of R&D topics has to be based on the identification of values to the customer and market price acceptance.

3.5 UNDERSTANDING WHAT *VALUE* MEANS

Understanding the value of a component is of key interest for defining future directions for developments. It is then necessary to better understand the concept of value. There is abundance of works on value and value analysis in product development and R&D management literature.

According to J.C. Anderson and J. A. Naurus "*Value is the worth in monetary terms of the technical, economic, service and social benefits a customer company receives in exchange for the price it pays for a marketing offer*" [11].

According to Forbis and Metha [10] "*Economic value to the customer (EVC) is simply the purchase price that customers should be willing to pay for your product, given the price they are currently paying for the reference product and the added functionality and diminished costs provided by your product".*

When looking at a complex component, it is difficult to understand its values to the customer and Value Analysis techniques have to be used. According to L.D. Miles, the father of Value Analysis, when analysing a product, it is important to keep in mind that *the customer does not really want materials or services. He wants Use and/or Aesthetic functions to be accomplished.* [34] Products have then to be analyzed in terms of their functionality.

On Meridian's products two kinds of functions can be individuated: pre-requisites and attributes.

- **Pre-requisites** are the functions for which there is a target to reach and for which the customer does not see any value in an extra-performance.
- At the opposite, for **attributes**, the customer is willing to value a change in performance. Another aspect for an attribute can also be the fact that, with the solution under analysis, the customers is not facing anymore issues he had with other solutions.

As a note, with regards to pre-requisites, it may also be that the customer could review his requirements at the system level and allow a reduction in performance in exchange for a price reduction.

When running the analysis, the pre-requisite are easy to identify as they are given by the costumer and quantified with targets (customer requirements). Attributes are more difficult to capture: customer does not communicate on attributes and on their value mostly to protect cost, but also because he sometimes does not see the advantage to share this information.

An exercise has been carried on Meridian's current products and it has been interesting to find out that a large majority of the functions were internally perceived as attributes, while these were actually pre-requisites. The ability to distinguish pre-requisites from values is fundamental to spread a technology to other customers,

Using the concepts defined above, the genesis of innovation described at paragraph 3.3 can be seen in a more complete way as triggered by the identification of the values of a specific technology/product for a customer (see figure 3.6).

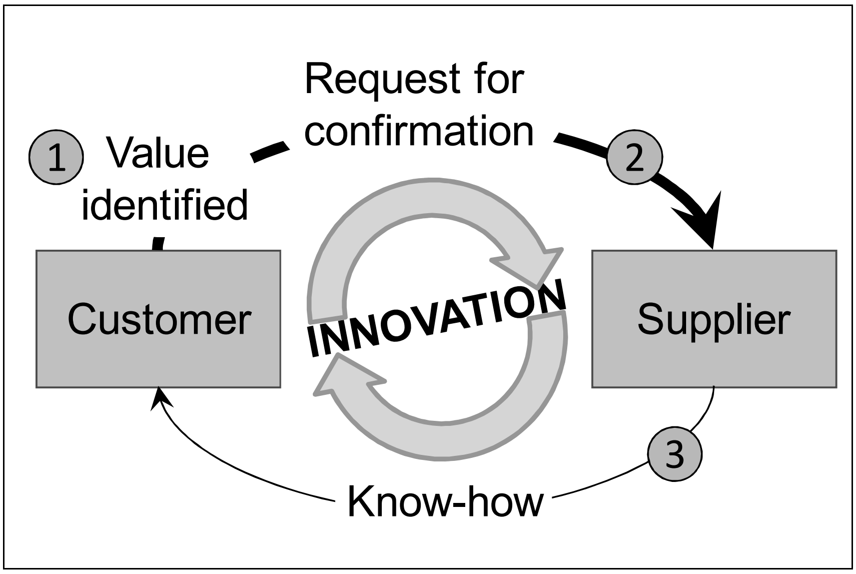


Fig. 3.6 Identification of values on the customer side and requests for information triggering the development of the innovative components

By asking some specific products to be developed (2) or specific issues to be solved, the customer is triggering an innovation loop to accomplish (1) specific functions (pre-requisite and attributes). The customer owns the knowledge of his system, and is expecting to confirm that the selected technology can deliver the values at an acceptable price. The supplier is feeding the loop with his know-how (3) and gives to the customer more information about the material/technology capabilities, pushing the costumer to further communicate on the achievement he is targeting. It is essential for the supplier to extract from this flux of information the targeted values.

It is important to remark that this mechanism can only be triggered if the customer has a sufficient knowledge of the technology.

At this stage it can be understood that it is probably more efficient to work on spreading the technology than to try to capture innovation coming from the customer; still to initiate new initial loops it is important to communicate on the global potential of the technology in order to improve customers' knowledge.

Communication on technology potential has to be continued, whether it is crash performance, possibilities to work with thin walls and complex shapes, corrosion resistance, flammability… When communicating globally, it is important to quantify with examples and quantified data on the range of possibilities (e.g. 25-35 Hz for NVH, up to 1000h salt-spray resistance) so that new customers can evaluate the potential with regards to their expectations. Though cost data cannot be given, it is also important to give evidence of market price acceptance, giving example of range of volumes and of customers using the technology (i.e. solutions at 500000 parts per year in production, but also at lower volumes, or "this solution exists at generalist OEMs"…).

This communication on performance and cost both applies on new innovation and also on the spread of technology. In that perspective it can be interesting to give evidence that there has been an evolution of the technology (new flame-resistance solutions, higher corrosion protection…). The objective here is to renew the vision some customer may have of the technology.

3.5 CONCLUSIONS

The post mortem analysis confirmed that setting up an efficient method to identify R&D activities implies to acquire a good knowledge of the market values and of the level of price acceptance for each value.

The approach to develop to identify R&D activity will have to consider cost reductions as the cost / price is perceived as a key problem by business development. In addition, supporting fast business growth implies to capture values and to focus first on spreading innovation to other customers.

The difficulty is to find a way to capture all this information considering the complexity of the market and the amount of points to identify. The points to develop should then be:

- How to identify pre-requisite
- How to identify attributes
- What are the attributes of competing technologies
- How to identify cost associated to functions
- Which Market it makes sense to focus on
- Which specific product
- …

As a summary, how to target other markets in terms of products, values, cost, and how R&D topics should be selected to allow this move to other markets.

4. PROPOSED APPROACH

As discussed previously, when focusing on short-midterm business growth, more efficiency should be found by working on spreading existing market. The key is to adapt the current portfolio products to other customers in terms of performance and price acceptance. The definition of R&D activity would then lie in adapting current products to other markets.

This implies three areas of knowledge: market (in terms customers and products), functions (pre-requisites and attributes) and value associated to the functions.

With regards to markets, as explained before, the approach of this work should mostly focus on the current portfolio of products and customers. On this market, the ideal situation would be to know all products, values and costs; yet this is a huge amount of information to capture.

The role of the R&D department would be to develop and provide solutions to be able to move to other market segments through the achievement of other targets at acceptable prices. It is not immediate to understand where to move to in terms of cost and functions; as a first step it would be useful to work to define the starting point on costs and values.

There are basically two steps to achieve: the first one is to map the environment, the second to understand what kind of direction should be taken in terms of R&D activities to enable the technology to reach other markets with competitive cost.

Mapping the environment means plotting the list of customers, the competing products, their functions, the magnitude of each function, its value to the customer and finally the sensitivity of the economic value to the customer to change in functions' magnitude. Such a picture of the market could help the supplier to discover which functions are the most valued per customer segments, and hence the potentially most profitable segments and the segments where a premium could be paid for the extra value.

In reality, situation is so complex that an analytic review of the situation cannot be done; a reverse approach could be a way to address the issue. Not having the market map, it is proposed to find out till which function levels the product could be brought to, to assess the associated costs, to propose the new levels to the costumer, and to find out if there is an interest in going towards the proposed direction or not.

It is not the scope of this work to do a perfect analysis of the system, but to be capable to identify which input could potentially change the system response.

4.1 ANALYSIS OF THE MARKET ASSUMING INFORMATION IS AVAILABLE

Forbis and Metha proposed a system to evaluate the EVC [10], but it requires a good knowledge of the product's functionality, its cost in terms of purchasing and start-up and the post-purchase cost compared with the reference product.

Knowing the reference product cost and its functionality is not an easy task: for a single component, the system may be so complex that the customer may hardly gather the information about component/system functions and their values: in fact the data may lie in different functional areas [11]. Consequently the EVC method is not applicable in this specific case.

Since the focus of this job is to develop the ideas, before entering this process, it has been decided to assume that the full picture of the market would be available to assess if an approach could be developed to propose ideas.

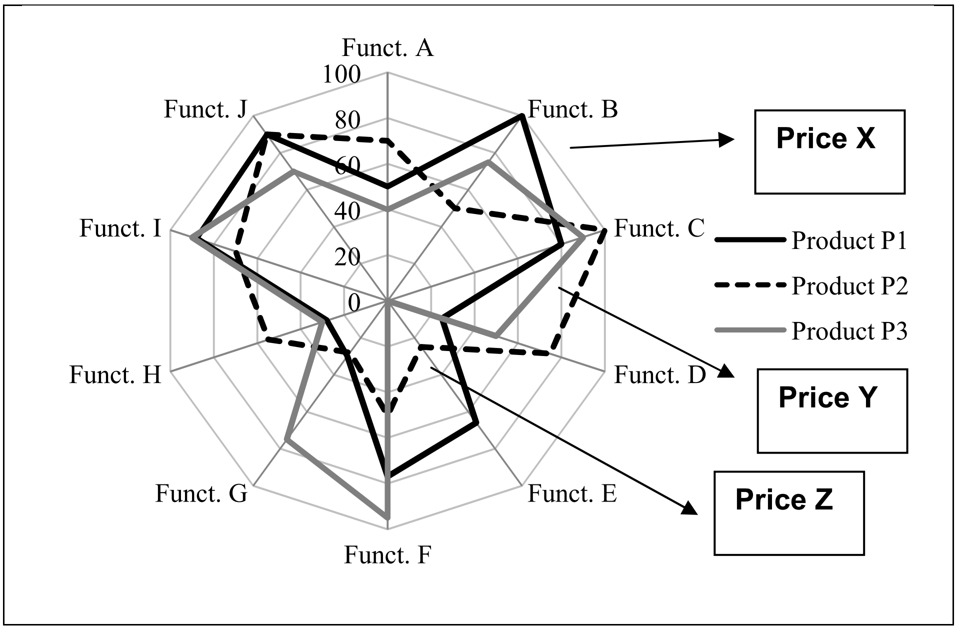


Fig. 4.1 Example of three products with different functions magnitude and different price

The focus is now put on a family of products, assuming that information is available for all the products of the market, including the price of every single product, and the list of all functions with their magnitude. An example taken from the analysis of three actual products is shown in the radar map at figure 4.1: it can be seen how three products at three different prices can have completely different functions maps.

At this stage it is not known which functions will be considered as a pre-requisites and which ones as values; this evaluation depends on customer and on the specific case. Since the analysis is focusing on functions, their cost and their value, the decision has been taken to plot the functions separately using the product price or cost on the x-axis and the function's magnitude on the y-axis (figure 4.2); this way of plotting allows to better visualize how cost and functions' level move over the market. Mapping all the product's functions, would imply plotting as many graphs as the number of functions identified.

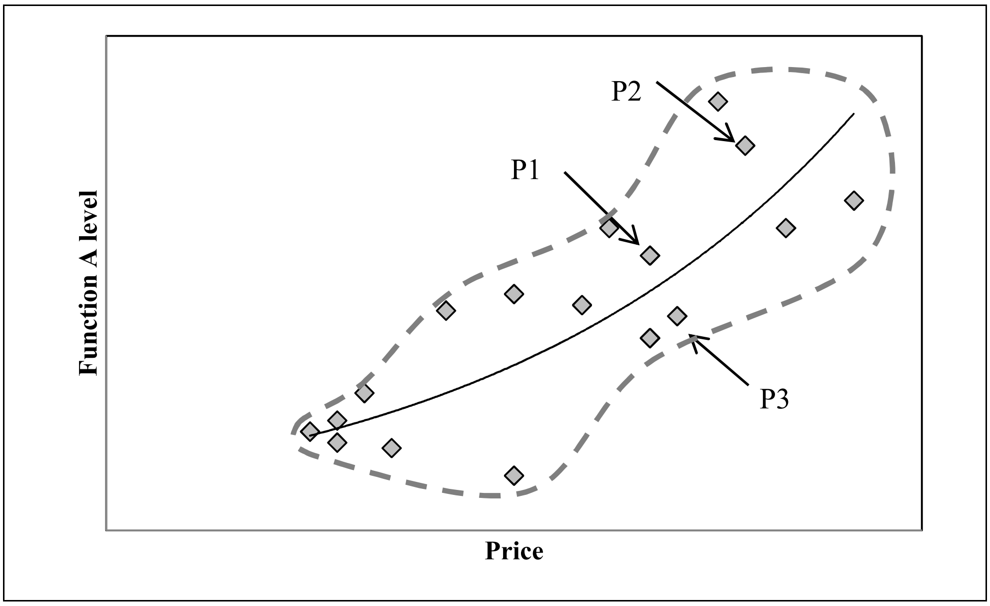


Fig. 4.2 Hypothetical map of a specific function of a product in the market

With this representation, it would be also immediate to visualize where the supplier's current technology ranges for a defined function. Black points on figure 4.3 represent magnesium solutions in the market.

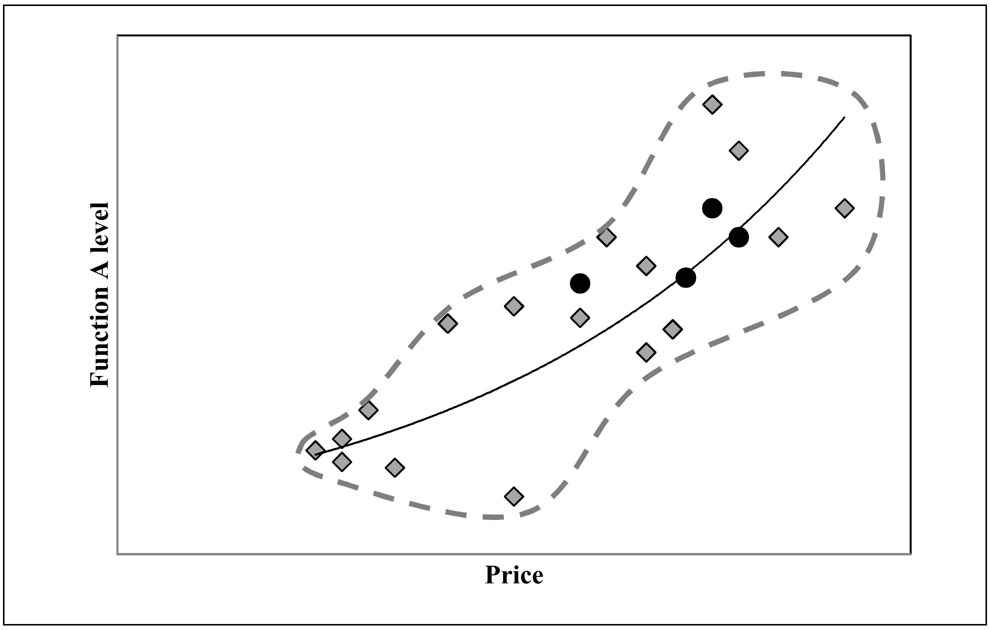


Fig. 4.3 Map of the market for a specific function highlighting the existing magnesium solutions

On such a graph if movement to new functions magnitude are under consideration, three directions are of interest:

1. Lower the cost for the same level of the function as indicated by yellow arrows in figure 4.4; in that case the first item revealed in the post mortem analysis is addressed.
2. Increase the function level. Targets for functions' magnitude and price levels cannot be set at this stage, but the evolution is likely to follow a slope higher than the average market trend at the considered magnitude (red arrows).
   That means giving a higher function level with the lowest impact on cost.
3. Eventually lower the function level, but conceding a high cost reduction, with a slope that is likely lower than the market trend (green arrows in figure)

As a note, points 2 and 3 cover the issue on values and associated cost identified in the post-mortem analysis.

It must be noted that this hypothetical visualization system does not catch interaction, i.e. how other function levels could be affected when one is moved. However, it could give the trends of the market and allows understanding magnitudes of functions.

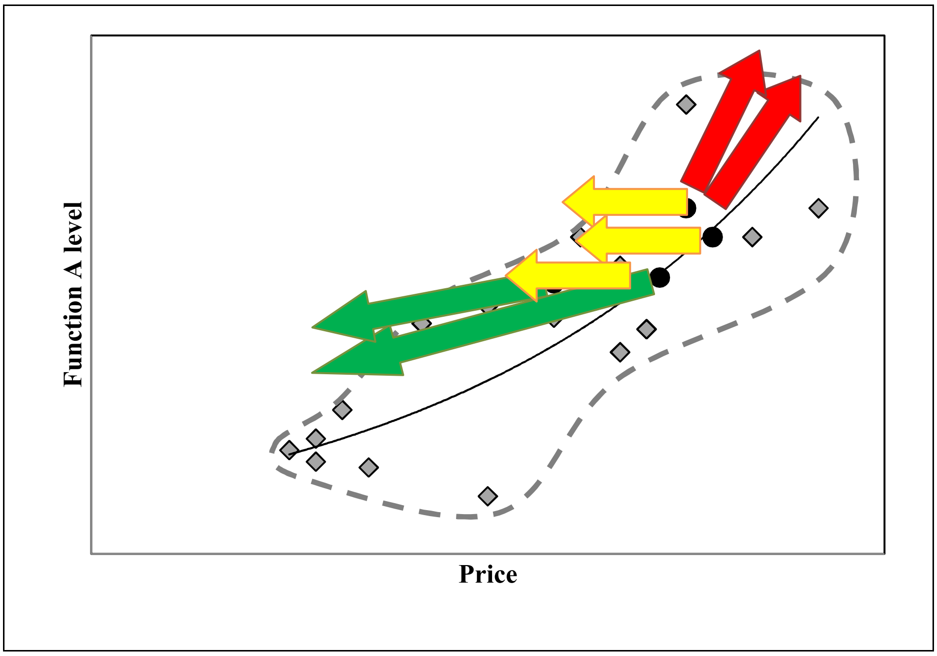


Fig. 4.4 Directions for development

To plot an absolute picture of the market, potential move in function magnitudes and associated cost is not realistic in terms of resources; moreover, prices are confidential. Hence, it could easier to work on the sensitivity of the market to a change in terms of functions magnitudes and costs for a given product.

As a note, a similar approach is actually achieved in the specific step of the initial concept development when Advanced Engineering is proposing different concepts to the customer (with a higher or lower integration).

R&D activities could then also focus on what variation of function level could be achieved and at which cost, by introducing, developing or extending to other products specific improvements.

Still considering the span of the work, activities have to be prioritized. To be achieved, that prioritization needs the feedback of the market interest for potential value change.

After having brainstormed many times about the sensitivity of the market to values variations, only one simple approach could be found. This approach proposes, for every new business, to present to the costumer the price, the list of functions, a proposal in higher or lower levels per function and the associated costs. An example of what could be presented is given in figure 4.5. In that case, the base product remains unchanged, but the price changes if one of the functions is changed.

Function	Lower	Nominal	Upper
A (crash)	-2kN, -0.5€	100€	+5kN, +2€
B (NVH)	-10Hz, -5€		+10Hz, +2€
C (torsional stiffness)	…		…
…	…		…

Fig. 4.5 Example of the proposal to present (figures just as example)

This proposal to the customer is interesting to introduce an innovative technology, both for the supplier and the customer; it would not be the case for a matured technology/product. In the latter case, the knowledge of the technology is strong on both sides and the supplier has no benefit to communicate too much on costs. Hence, this proposal is likely to fit mostly challenging technologies where many improvements can still be done.

At that stage, with regards to value / cost variations, for a given product, R&D activities could be set as performance targets to reach and for which a certain level of confidence is achieved with regards to the market acceptance. It must be pointed out that this means that R&D activities would now also need to focus on products for which Company manages to get developments and can offer this kind of sensitivity study. Besides, it must be remembered as identified before, that R&D must also focus on purely reducing cost.

4.2 INFORMATION TO CAPTURE

The decision has been taken to run two analyses in parallel, one purely on cost reduction and one on value change proposals; for the two activities, different sets of information need to be gathered.

For cost reduction activities, the base information available to develop an approach to identify R&D projects is:

- list of products (current and future production);
- volume and turnover of each product;

- product cost breakdown.

All this information is available at Meridian to a level of details that allows a complete analysis to define R&D activities; several evaluation methods of the literature can be used [35, 36]. More details will be given in chapter 6.

Regarding value analysis, the required information is not fully available and it is necessary to develop a method to capture the required data:

- list of functions of the products;
- assess how much function levels could be changed, and at what price, with the current know-how or with some possible development in view;
- understand the sensitivity of the market to the value change.

The first two items just require a detailed analysis of the products and the technology. The third topic implies an interaction with the customers and, in general, with the market, which involves the people of Company in contact with the customer. The customers may not be interested in sharing information up front, hence the way of presenting the benefits of potential value change needs to be immediate and clear; the example given in figure 4.5 could be used.

To evaluate the efficiency of the proposed method, the approach will be done on a single product; also this approach will have to be simple and light in order to be spread to all other products.

4.3 PROPOSAL OF AN APPROACH

4.3.1 SELECTION OF A PRODUCT FOR COST AND VALUE ANALYSIS / EXTENSION TO PORTFOLIO

For cost analysis, the parts to investigate have to be selected on the base of the current and future turnover shares.

For the value analysis, the previous analysis tends to show that, when searching for short term growth of the market, focus should be put on spreading the portfolio and working on current developments (i.e. where a price sensitivity to value variations can be proposed). Focus should also be put either on products which are important in the portfolio in terms of shares and/or on new types of products showing a fast growth.

Beside this type of activity, it is the responsibility of the Company to put seeds for the future and to decide how much R&D resources should also be allocated to generate other interests and trigger other primary innovation loops that may eventually come from other markets.

After these considerations, the decision has been made to develop and test the approach on a product of the portfolio showing the promising growth. In such cases knowledge of functions and the chance to capture information are reasonably high.

4.3.2 DEFINITION OF R&D ACTIVITIES DERIVED FROM COST ANALYSIS

The analysis of the product in terms of costs requires some considerations before looking at the mere data. It must be kept in mind that "*the customer does not really want materials or service: he wants Use and/or Aesthetic functions to be accomplished*" [33]. From this point of view, the product should not be analysed as sold to the customer, but at functionality level equal to the one of competing solutions. For example, the solution sold may imply that the customer changes his fixing solution to a more expensive one. It is important to analyze costs accordingly. On the other hand, this kind of analysis could also highlight a cost saving induced by the product to the system. The analysis should then be done at a "higher system level" trying to include all the different costs and change of functionality induced at the customer though the information might be difficult to capture.

After reviewing different cost analysis method proposed by the literature [35, 36, 37], a simple standard approach has been derived and is detailed below.

The first step consists in plotting the Pareto of cost for key portfolio products. The understanding of detailed cost items for a product is surely not simple and may change with the way of considering fixed and indirect cost. It is not aim of this work to discuss of the ways to calculate cost and, for the purpose of this study, the analysis is done with the Company cost models.

The following step consists in creating a "basket of R&D projects" to address each of bar of the Pareto on cost. The list should take into account current R&D projects, projects under definition, information from literature, conferences and suggestions and requests from people of the Company or from suppliers and customers.

Each bar of Pareto of cost can then be reviewed with the identified projects and potential cost saving can be assessed; the initial savings are approximate values, but are sufficient to start the investigation.

If for a given bar, there are no proposed projects, a hypothetic range of cost saving has to be assessed. This applies mostly to higher bars where small saving could have high impact, further literature review and brainstorming new ideas could be requested afterwards if it is assessed that the potential saving could be achieved at low risk .

Projects should then be ranked and key R&D projects selected according to specific criteria. Literature proposes several methods to select key projects [35, 37]; these methods present lots of similarity and since it is not the aim of this work to state on their effectiveness, it has been decided to consider the Net Present Value weighted with risk [36], the investment payback and the available resources .

All company skills should be involved to when dealing with this of analysis.

4.3.3 DEFINITION OF R&D ACTIVITIES DERIVED FROM VALUE ANALYSIS

4.3.3.1 IDENTIFICATION OF FUNCTIONS

Once the product has been defined, the first step is to **identify functions**; in a small structure the most efficient method is again to gather all people that have been working on that kind of product, including Product Development Engineers, Business Development, Production, all the people who have worked in contact with the customer from the initial concept to the final product definition and also took part to approval, design reviews, testing and industrialization. More efficiency should be gained to capture the information given by the customer. Deep analysis has to be done at this stage; in the present case the function of every bracket, rib, fixing holes, all the details of the component's architecture has to be reviewed.

4.3.3.2 IMPACT OF FUNCTIONS ON PRODUCT COST: DIFFERENTIAL APPROACH

Given the complexity of every product in terms of interaction of the functions, it is difficult to access the cost of each function as an absolute value. However, function costs could be evaluated by using a differential approach, i.e. by assessing how much the cost of the product could be lowered if the function was not to achieve anymore (i.e. evaluate the cost saving if the specific function is removed).

Pareto charts will be used to identify the key functions driving product cost, but also the functions that do not impact cost.

The activity then consists in scrolling the list made in the previous paragraph and to figure out the changes in the product and the new part cost when the specific function is removed.

4.3.3.3 SENSITIVITY OF COST TO FUNCTIONS' LEVEL VARIATION

The final step is to target other functions' magnitude and to investigate if market will accept the change. This analysis is to be done for the key cost driving functions. It must be assessed in this phase if there is a technical solution to **move to a different value** and what would be the impact on cost. It is precisely at this stage that the definition of R&D activities on product can take place.

It is likely that R&D activities are more bound to an improvement of the performance, while a move to a lower value is more bound to an acceptance by the customer.

The developed approach will be applied to a real case study, following the steps described above.

All decisions on which product to analyze and on the activities to work on are strongly linked to the specific Meridian's environment.

This approach is intended also to improve the knowledge of a challenging technology on both supplier and customer side; it would have to be adapted for different environments.

5. APPLICATION TO MERIDIAN AND CTE

Chapters 5 and 6 contain an analysis of the cost of a product. For confidentiality reasons the figures are not reported in this work. The cost voices reported here are given in a fictitious cost unit and will be indicated with the symbol £.

5.1 SELECTION OF A PRODUCT

For both cost and value analysis, the decision has been made to select the FEC because the market share of this product is showing the highest potential growth. FEC have been in production for five years; six models are in production, and about 13 new products are under development as it can be seen in figure 5.1 [24]. Current annual volume is about 800000 parts per year and an increase is expected. An example of FEC is given in figure 5.3.

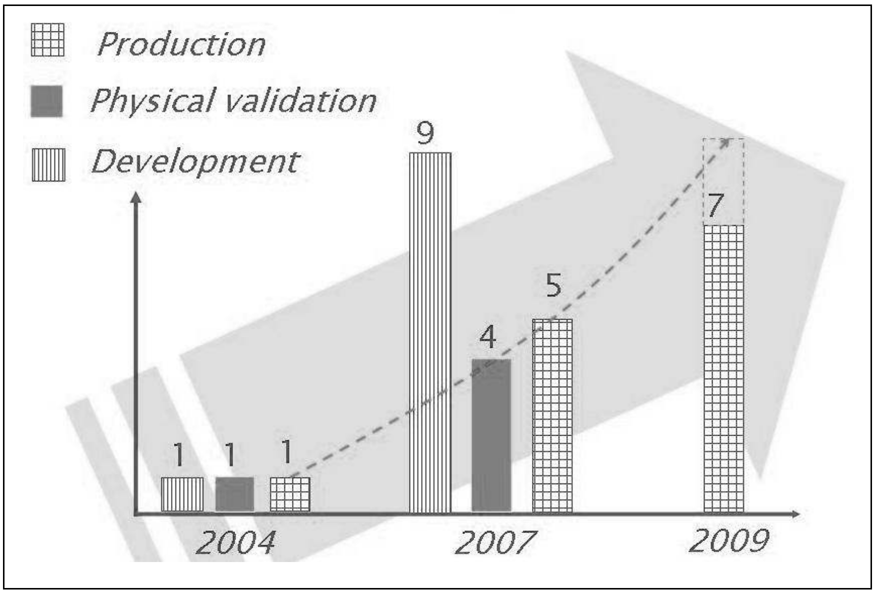


Fig. 5.1 FECs developments and production trend

FEC differs from current portfolio products in the sense that it is a cosmetic – hence coated – part, while all other products are bare; however FEC includes the full die casting process, just like any other product.

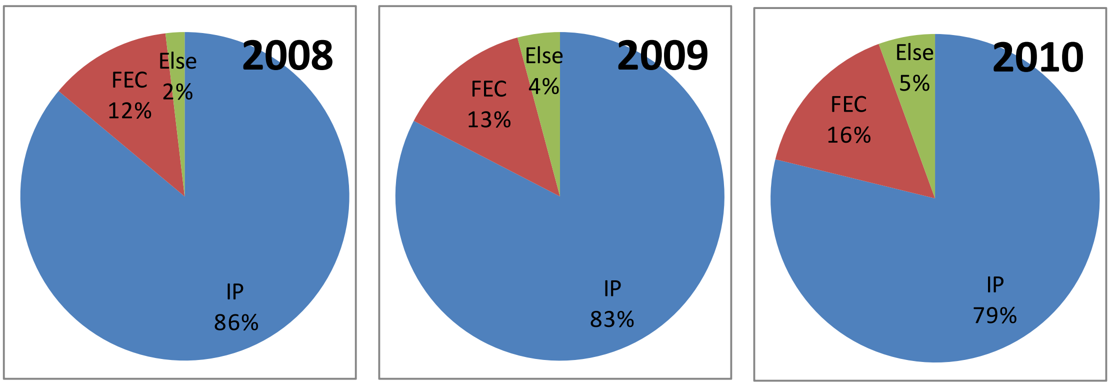


Fig. 5.2 Potential market share of FECs on Meridian European portfolio

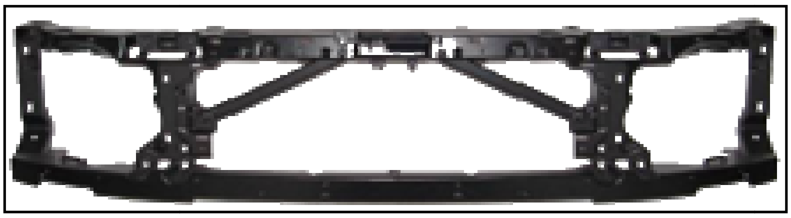


Fig. 5.3 Example of a production FEC, front view

5.2 ANALYSIS ON COST

5.2.1 ANALYSIS OF THE COST BREAKDOWN

The present analysis has been carried out on the basis of Meridian's cost model. As discussed in chapter 2, the price of raw material has faced strong variations over the last two years. To simplify the analysis, the raw material price has been considered at the levels of 2007.

Figure 5.4 reports the Pareto of costs for the selected component, split per cost item and considered at the competing system level. Overheads and tooling are considered to be a cost per kilogram of processed material; in this analysis, tooling cost has been included into the "capital" cost.

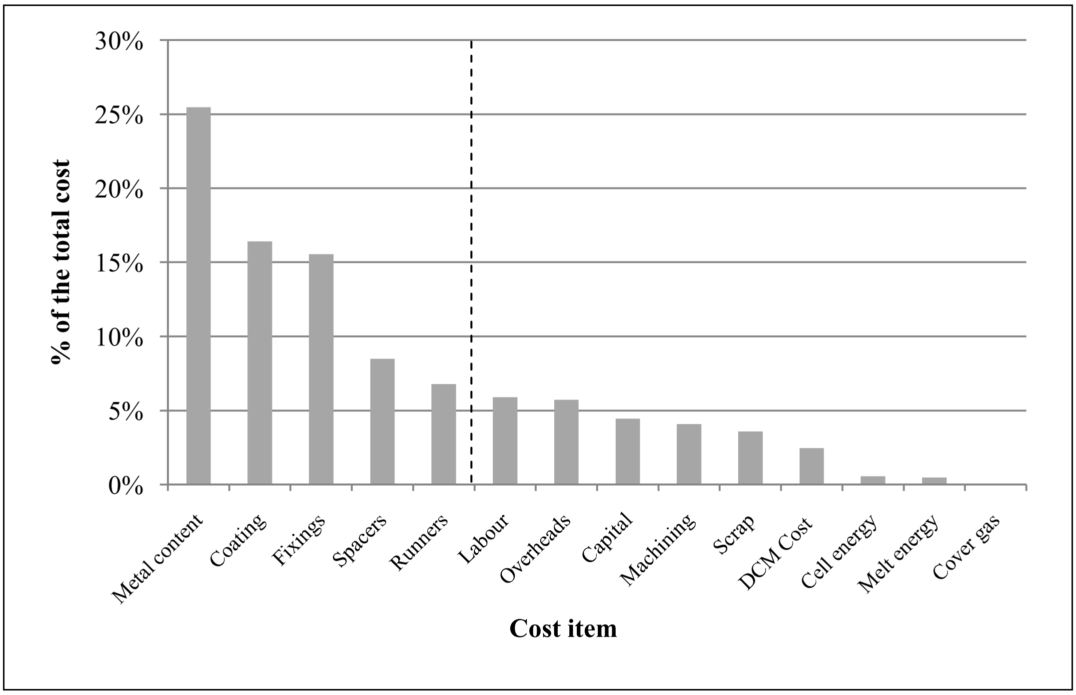


Fig. 5.4 Pareto of costs for the FEC

The Pareto shows on the left side that five items cover 70% of the cost:

"Metal content" in the part counts for 49£ (25% of the system cost). This cost is first driven by raw material market price and by the actual material content. It depends on shape, mechanical and geometrical requirements, level of integration and castability.

"Coating" cost is the cost for magnesium to meet cosmetic requirements similar to steel ("or plastic"); it counts for 31£, (16% of the total cost). The reasons why the coating is so expensive are:

- the peculiarity of the process to coat magnesium and the low volumes: for this reason only two suppliers in Europe are currently capable of achieving automotive requirements;

- to some extent, the cost may be also influenced by some of over-engineering for corrosion. Little experience exist on the actual performance of the paint systems in long term field conditions, hence some OEMs require even up to 1000 hours salt spray; the accelerated test is not proven to be representative of reality;

- as a final consideration, some OEMs give too much importance to the paint system as a protection for galvanic corrosion and push for higher thicknesses or double coating. In reality galvanic cells are to prevent by matching materials electro compatibility by using spacers to separate magnesium from more noble material. If the protection induced with a proper spacer counts for 1 then a coating probable counts for 0.01.

"Fixings cost": this cost is mostly driven by the screw coating required to improve magnesium galvanic performance. The objective is to prevent rust to drain on magnesium which could cause local cells especially if Magnesium coating is damaged. As a note a scratch on the coating would localize the damage, while it would be spread and less significant on a bare part. This cost counts for 30£ (16% of the total; 7£ for screws, 23£ for coating), knowing that the same solution for steel would cost just 3€ in total.

"Spacers" are parts specific for magnesium / steel assembly: a different material is introduced to break galvanic configuration. Aluminium is the material used to separate magnesium from steel (brackets and screws). The total cost of spacers is 16£.

"Runners" is the cost for recycling the feeding system and overflows required to insure a proper filling of the parts; it counts for 13£ (7% of the total cost). The shape, and hence the mass of the runner system, strongly depends on the shape of the part and in particular size and thickness. This cost is independent from raw material cost.

At this stage it is interesting to note, on this first part of the Pareto, that the extra cost compared to a competing steel solution is mostly driven by items linked to corrosion protection: all together, those count for about 70£.

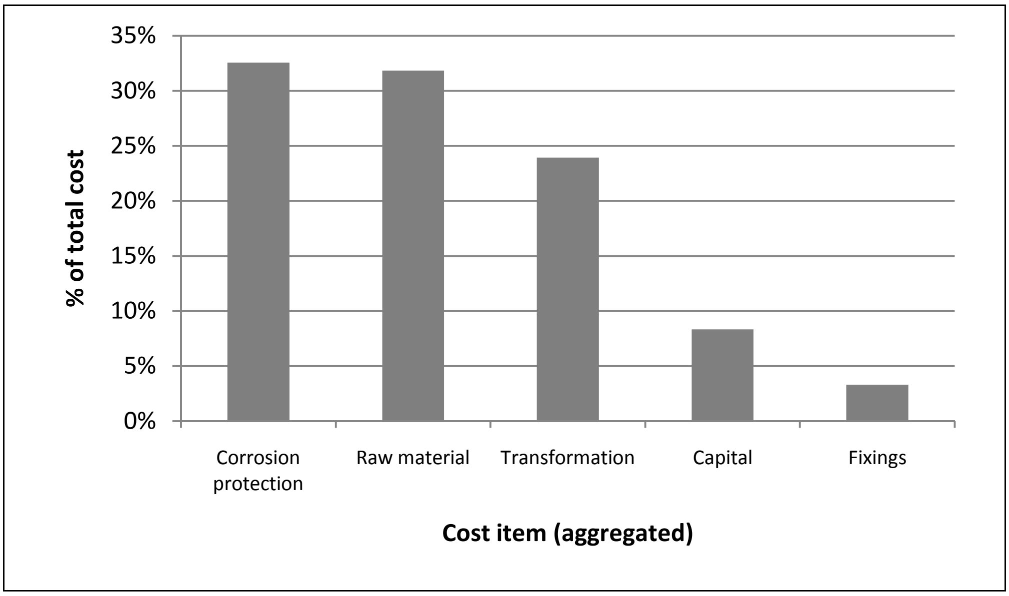


Fig. 5.5 Pareto of costs, aggregated

On figure 5.5, the cost items related to corrosion protection have been gathered on a single bar, since they are driven by a single issue that actually does not exist on the rest of Meridian's portfolio. It can be seen that the overall corrosion protection represents more than 30% of the piece price. The rest of the Pareto is actually a typical cost distribution for a non-painted casting, i.e. for the rest of the portfolio.

In figure 5.5, costs could be summarized as follows: a first bar showing big cost, hence probably interesting potential savings on a non matured technology, applying to 12% of the portfolio, and on the right side cost related to a matured technology and hence probably with a lower potential, but on 100% of the portfolio. The Pareto for these matured products is further detailed in figure 5.6; the Pareto for the extra cost induced on FEC is given in figure 5.7.

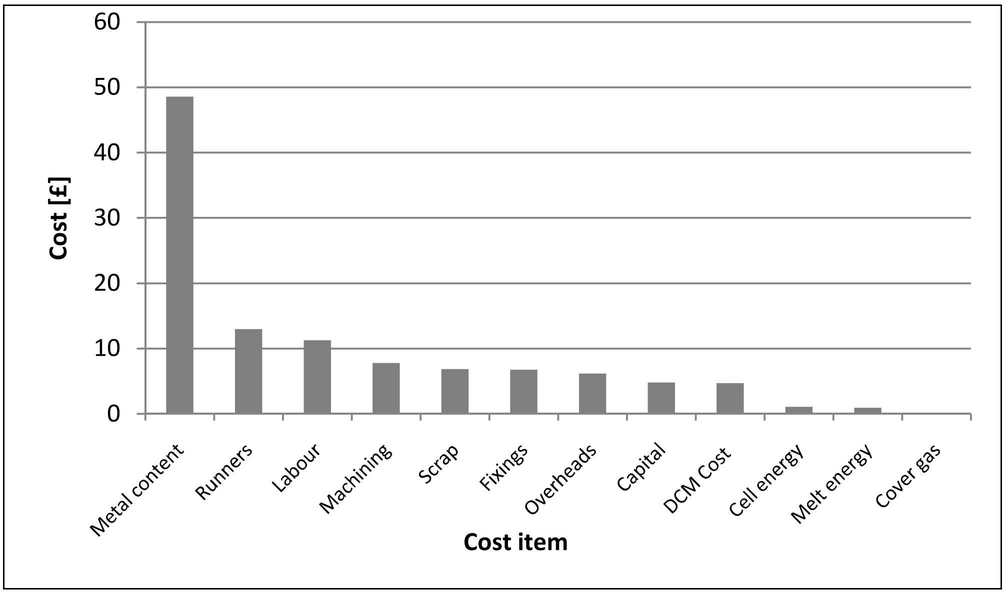


Fig. 5.6 Pareto of costs for matured portfolio

For the right hand of the first Pareto (fig. 5.4), which counts for 51£ (30 %), the costs are then transversal to all portfolio and come as follow.

"Labour" is related to the workmanship to run the die cast machine and the rest of the production. An important part of this item is deburring after trimming to remove remaining flash and to improve component's finishing (20% of the cost). Labour cost is bound to cycle time and to the amount of post-trimming operations.

"Overheads" will not be detailed in the frame of this work as they are not related to R&D.

"Capital" cost is related to die cast machines, trims and plant. Also the tooling has been included in this item and will not be detailed further in the frame of this work. As a note, tooling cost is very important factor for customers to choose a magnesium solution. The costumer will balance total tooling cost (1 set for steel versus 1 tool every 250000 parts for Magnesium), and the money to put upfront for the first tool to start production (initial investment for Magnesium being lower).

"Machining" counts for 8£. Actually, this cost strongly depends on the components and can vary from 0 to more than 10£, hence it does not come as a real transversal cost driver.

"Scrap" counts for 7£ and it is common to every products, especially when it comes to large thin walled parts where it can be as high as 12%. Moreover, a scrap part implies to recycle the gate.

All next bars count for less than 5% and will not be analyzed in this work.

5.2.2 IDENTIFICATION OF ACTIVITIES

From an initial Pareto with fourteen bars, seven key cost drivers have emerged. To identify potential R&D activities to reduce cost, these items have to be ranked in terms of potential savings. This has been done by:

- Reviewing the basket of current R&D activities, either they are in progress, under development or just at the evaluation stage.
- Brainstorming other solutions if no promising activity had been identified for some specific bar of the chart.
- Assessing potential savings or assuming a reasonable saving if no solution was not found yet; further analysis will indicate if it is deserved to spend more efforts in finding and developing solutions to specific issues.
- Evaluating the impact of the activities on the cost of the product and their possible extension to other products in the portfolio.

Notes: As a reminder, though the full analysis could not be done within the time frame of this work, some hypothesis of R&D activity and potential solutions are given below for each of the key cost items.

1) “Metal content” cost is first driven by purchasing price: on this, the only R&D possibility could be to feed cells with scrap material from other cells. The problem here lies in the presence of oxides which are proven to have a deleterious effect on the mechanical performances, mostly on elongation. A new technology is in the “basket of activities” and could potentially provide a solution to this issue, allowing the use of scrap material. MC-HPDC is a potentially interesting technology to break-up oxides into small particles removing all the effects on mechanical properties; on the other hand, a reduction of corrosion resistance could be expected as chemical composition can change [23, 38]. MC-HPDC basically consists in a device to interpose between the furnace and the injection system; this device contains two counter-rotating screws through which the molten metal is constrained to flow. Further detail will be given in annex 1.

On the other hand, material content is also related to shape, filling and mechanical requirements of the parts; on this item it’s difficult to assess interesting savings considering the engineering efforts and experience over 20 last years. It would deserve to brainstorm engineering and production / flow simulation to understand if substantial improvements could be achieved.

2) “Coating”: This cost covers three major process steps: acid etch (removal of iron particles that would decrease general corrosion performance), pre-treatment (for adhesion of the final layer) and actual coating (e-coat plus powder coat or powder coat only). The final coating is either epoxy based powder or e-coat (10% extra cost) plus epoxy based powder. Today the epoxy based powder has been found to be the most robust with regards to cosmetic corrosion. The alternative on the market is polyester, which is UV resistant but shows slightly poorer general corrosion performance; its price is in line with Epoxy. Different pre-treatments and kind of coatings have been tested back to back with the current solution; none could reach the performance of the current solution. Hence reducing this cost probably goes through purchasing and the development of coaters’ competition on the market. Technically the first action might be to help the market gaining more experience on actual field conditions and adapt corrosion tests to better replicate reality, and eventually lower requirement through accelerated tests.

3) “Fixings”: the cost of fixings is driven by the coating and is actually calculated on the mass of the screws. The reason of this coating is both cosmetic, as the screws must look nice after exposure to aggressive environment, and galvanic as the rust formed on the screw may drain on magnesium. Initially most screws were M6 (diameter 6mm), and the mass to coat was meaningless; in new developments more and more screws tend to be M10 (10mm) and M12 (12mm). The mass/surface ratio is the getting much bigger and the cost increases. On last projects this cost went up to 20% of the total cost of the part. The lack of feedback from field conditions push carmakers to ask the best-in-class in the market, hence some OEM extended the time exposures. For example, in salt spray tests exposures went up to 1000 hours, instead of the 720 hours commonly requested for steel. It is worth testing other solutions back to back with current one. As per coating, the increasing of knowledge of actual field condition and the development of a test better replicating reality could help to reduce cost.

4) “Spacers”: the aim of spacers is to minimize galvanic corrosion splitting the cells into two lower galvanic cells. The solution is provided by stamped aluminium washers and specific

spacers that separate the two materials by about 10mm. Current solution is 2mm-thick 6000 series aluminium washers and flat plates or 5000 series if spacers need to be stamped. The selected alloy must have a low content in Ni, Fe, and Cu. A tool for spacers is in the range of 20k€ and a spacer is about 0.2 - 0.3€. Other materials with similar galvanic potential could be investigated; still, FECs work up to 120°C and attention will have to be paid to relaxation phenomena. Replacing aluminium with plastic could be interesting as both material and tooling costs would be lower, however the use of plastic has been hold due to the fears related to relaxation and strength. Still, designing without clamping directly on plastic could be interesting; an idea could be to clamp metallic parts in direct contact using plastic as a surrounding spacer and sealer (see figure 5.7).

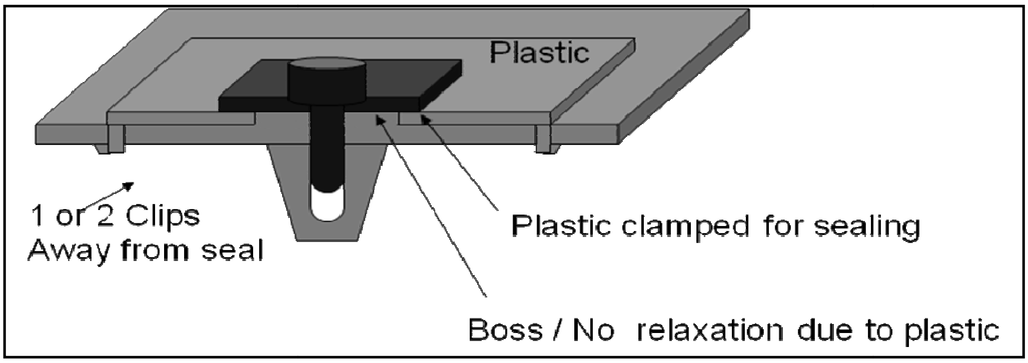


Fig. 5.7 Example of design for plastic spacers

Another alternative could be the use of cardboard, (material similar to engine gaskets, so it would not creep); in this case the fear is the ageing of the cardboard with time as, at the opposite of an engine, it may stick out from the clamped area and get damaged with time. Cost of tooling would be very low compared with current solutions, but today, because of the low volumes, cardboard material costs are quite high. This solution could still be of interest on low-volume applications or if a cheap cardboard material can be found. As a note, the substitution of aluminium with both plastic and cardboard could further improve the weight saving potential of magnesium solutions. This is even truer for powertrain area where Magnesium parts are smaller and where the use of aluminium spacers can in some cases lower the weight saving from 25% to 15%.

5) "Runners": this cost is the price paid for recycling the runners. Meridian currently purchases this service; internal recycling facilities are available but volumes are too low to make it cost efficient. Resources could be spent to lower the volume to recycle through gate optimization. Considerations here are similar to the ones done with regards to metal content. More than twenty years of experience and activities on this topic led to big improvements and the current situation is probably not too far from the optimum. Further improvement may still be achievable through advanced flow simulation and process improvements, but major cost reductions do not seem obvious. Still, as the item applies to all products, brainstorming with production, engineering and flow simulation people is of interest.

6) "Labour" is related to cycle time and post casting operations. At this stage there are no activities in view, hence this topic would also be interesting to brainstorm.

7) "Scrap": large thin walled magnesium die castings are challenging products to cast; furthermore the quality of castings is strongly related to the crash performance of the component. Many efforts have been done and some activities are currently under development to optimise the production process. Initial studies tend to show that statistical process control with the use of small DOEs is a promising system to reduce scrap [39]. It would be interesting to further investigate the approach. This activity will be further detailed in annex 4.

These potential projects will be reviewed together with the ones identified by the value analysis. The final list will be established after having assessed all the projects in terms of potential savings, potential performance, available resources, potential impact on the portfolio and risk.

After all these analysis on costs, it interesting to note the following: a steel e-coated solution would have a coating about 14£ cheaper, a coating on screw also 15£ cheaper and would have no spacers, for other 16£ saved. All together this is 45£ extra cost to meet similar corrosion performance. Compared to steel, magnesium parts are usually valued 1,5€ per kg saved, which in the present case would be 7,5€ more for a 5 kilograms saving. The solution would then be about *7,5€ + 45£* more expensive than steel, which would represent an *x* € per kg saved. *Is that the premium price for weight saving or does the costumer sees other values in the product?*

5.3 IDENTIFICATION OF VALUES, CHANGE OF VALUES AND ASSOCIATED COSTS

5.3.1 IDENTIFICATION OF FUNCTIONS

In the frame of this work, the functions of the product have been identified by interviewing Meridian people from Advanced Engineering, Business Development and Core Technology. Every part of the component has been analysed in order to understand the function of every hole, rib, particular geometric feature. The exercise has been run on two different FECs of two different customers in order to avoid missing functions. It would be probably preferable to have an offsite meeting gathering all people that have worked on the topic to go faster, have a higher efficiency and minimize loss of information.

The functions have been first described as an action verb and a precise name (example: support headlight) [40]. The functions have then been quantified as far as possible and classified as pre-requisite or attribute. Table 5.1 reports the name of the functions, their classification as attribute or pre-requisite and their description for one of the two analysed FECs.

When looking at the table, the following appears: it is clear that, when working on functions, the full description of the system may not be achievable. Still most of the system functions could be described and only one of them could not be qualified.

Tab. 5.1 List of functions and their description

	Function name	A/R	Function description
1	Connection A (Y direction)	R	connect attachments (Y)
2	Connection B (Z direction)	R	connect attachments (Z)
3	Strength 1	R	Resists impact: Primary latch
4	Strength 2	R	Resist impact: Secondary latch
5	Strength 3	R	Resist Bumper abuse
6	Static Load 1	R	Achieve Torsional stiffness
7	Static Load 2	R	Achieve Attachment x stiffness
8	Static Load 3	R	Achieve Attachment y stiffness
9	Static Load 1	R	Achieve Attachment z stiffness
10	NVH	R	NVH - Normal mode
11	Fatigue	R	Pass test: 4g bump loading cruise control sensor
12	Crash 1	R	Resist low speed impact (insurance repair)
13	Crash 2	R	Resist High speed impact (structural integrity)
14	Crash 3	R	Prevent Fender Separation (Loading y-direction)
15	Durability	R	Pass Road load input test
16	Corrosion: cosmetic	R	Resist 6 years simulation test
17	Corrosion: galvanic	R	Resist 12 years simulation test
18	**Integration OVERALL**	A	
19	Integration1	A	Prevent horns assembly rotation
20	Integration2	A	Hold horns assembly
21	Integration3	A	Hold Adaptive Cruise Control
22	Integration4	A	Hold Adaptive Cruise Control bracket
23	Integration5	A	Hold Alternative Pollution sensor
24	Integration6	A	Hold Ambient temperature sensor
25	Integration7	A	Bonnet buffer reaction

26	Integration8	A	Locate Bonnet seal attachments
27	Integration9	A	Position Bumper trim
28	Integration10	A	Fix Bumper trim
29	Integration11	A	Bumper trim support moulding assistor
30	Integration12	A	Attach Bumper trim support moulding attachment
31	Integration13	A	Locate Bumper trim support: moulding locator
32	Integration14	A	Locate Bumper trim: Y locator
33	Integration15	A	Attach Condenser
34	Integration16	A	Attach Coolant expansion tank
35	Integration17	A	Attach Coolant hose
36	Integration18	A	Fix Duct - lower
37	Integration19	A	Fix Duct - upper
38	Integration20	A	Attach Grille receptable
39	Integration21	A	Locate Grille - Y
40	Integration22	A	Locate Grille - Z
41	Integration23	A	Locate Headlamp 2-way
42	Integration24	A	Locate Headlamp 4-way
43	Integration25	A	Mount Headlamp protector
44	Integration26	A	Headlamp twist and fix
45	Integration27	A	Attach Intercooler
46	Integration28	A	Fix Latch cable clip
47	Integration29	A	Fix Latch wear plate
48	Integration30	A	Fix Lower frame rail
49	Integration31	A	Fix Lower grill
50	Integration32	A	Attach Lower valance
51	Integration33	A	Mount Main lower body
52	Integration34	A	Mount Main upper shotgun

53	Integration35	A	Attach Pollution sensor
54	Integration36	A	Mount Primary latch
55	Integration37	A	Fix Radiator Bushing
56	Integration38	A	Attach Radiator pack ducting
57	Integration39	A	Locate Shotgun
58	Integration40	A	Increase stiffness - Structural cross braces
59	Integration41	A	Attach Wiring harness
60	Fit And Finish	A	
61	Air flow	A	Allow air to flow - aperture

For the case of this FEC, the analysis on functions can be summarised as follow:

61 functions have been identified

60 of them could be qualified properly;

58 (95%) of them could be quantified;

16 with a measure, ex. 10kN (3 to 17 and 61);

42 as achieved target, ex. Position headlight (18 to 59);

2 could not be quantified properly (1 and 2);

1 could not be qualified properly (60).

Due to the complexity of the part, the possible interactions between different functions and the role of the component in the system (i.e. the interaction with the other components of the front of the vehicle) it can be guessed that all functions could not be fully captured. However, the aim of this work is to build the most complete view of the system to be capable to make improvements.

In table 5.1, integrations have been detailed one by one (grey in the table); they have then been gathered as “overall-integration” to simplify the discussion.

At a first glance, over these 61 functions, only two of them can be perceived as an attribute for the customer: “integration” and “fit and finish”. The rest can be consider as pre-requisites; still it will be discussed further how integrations could also be considered, as with die-casting some functions of integrations can be added to the system with a non-significant impact on the cost.

“Fit and finish” gathers the ease to mount the part due to the fact that it is a monolith and that tolerances are much tighter than any assembled solution. This feature, together with the possibility to have continuous surfaces, leads to a higher finishing level with an improvement of the perceived quality.

“Air Flow” is the free surface in the centre of the FEC to allow air to flow to cool the radiator. The possibility to work on the surrounding section and maintain mechanical performance without affecting the open central surface is another plus of the material/process combination. This item can be seen as an attribute up to a certain level and strongly depends on the power of the engine and consequently on the amount of heat to remove.

The functions could be achieved with a considerable weight reduction in comparison with the competing steel solutions. Weight reduction is of key importance, especially in such an advanced area in the vehicle (see paragraph 2.4). It should then be seen as a function as it is an attribute. The function could be described as follow: reduce front weight by 5kilograms.

In addition to weight, stiffness is another important feature achievable through the material-process capabilities with a low impact on the weight (geometry freedom superior to steel, Magnesium stronger than plastic). From the interviews, it emerged how an increase in the FEC’s stiffness even above the pre-requisites could potentially enhance the system stiffness allowing a weight and cost reduction in the front of the vehicle. This consideration is valid for global torsional stiffness, but also for specific local stiffness (ex. lower leg). Hence local and global “stiffness” can be seen as attributes.

In a similar manner, some customers have explained that this technology can easily solve local fatigue issues without affecting the mass, while with steel the weight impact would be higher (higher weight impact on the rest of the structure).

It must be highlighted that weight saving and stiffness improvement on the front end of the vehicle can induce weight saving over the rest of the frontal structure because of a lower hanging mass and some stiffness obtained by geometry in the front end.

To summarise, the key attributes are:

- Weight saving
- Fit and finish
- Air flow
- Stiffness :
    - In comparison with steel, stiffness is achieved with geometry allowed by material/process with a significant weight reduction.
    - When compared with plastic, the achievable stiffness is much higher due to the metal properties.

It is interesting to note that the only function that could not be qualified properly is an attribute (fit and finish); this is in line with the discussion on the flow of information between the customer and the supplier about values: pre requisites can be easily grabbed because they are measurable figures. When it comes to attributes, it can be much more difficult to assess the functions and their value to the customer. At the opposite of pre-requisites, attributes quantification differ between competing solutions.

5.3.2 IMPACT OF FUNCTIONS ON PRODUCT COST: DIFFERENTIAL APPROACH

Given the complexity of every product in terms of interaction of the functions, it is difficult to access to the cost of each function as an absolute value. As explained in chapter 4, a differential approach is used here, with the aim of assessing how much the cost of the product could be lowered if the function was not to achieve anymore. Each function has been removed from the system and the cost of the final product is evaluated in order to understand the impact of the specific function. The method does not take into account the interaction between functions and the evaluation of costs is an approximation. However, the macro-information level that can be captured allows running a higher level of analysis on how to move to other markets.

When a function is removed from the system, in most cases, the impact is a reduction of mass (12 of the 18 functions). Hence the removal of a function could easily be translated into a mass of magnesium to remove and into a cost saving.

For a few other functions (3 functions), cost saving is related to the removal of specific step of the process; for the remaining 3 functions the cost saving could only be assessed. The results of the potential cost saving are sorted out in the Pareto in figure 5.8.

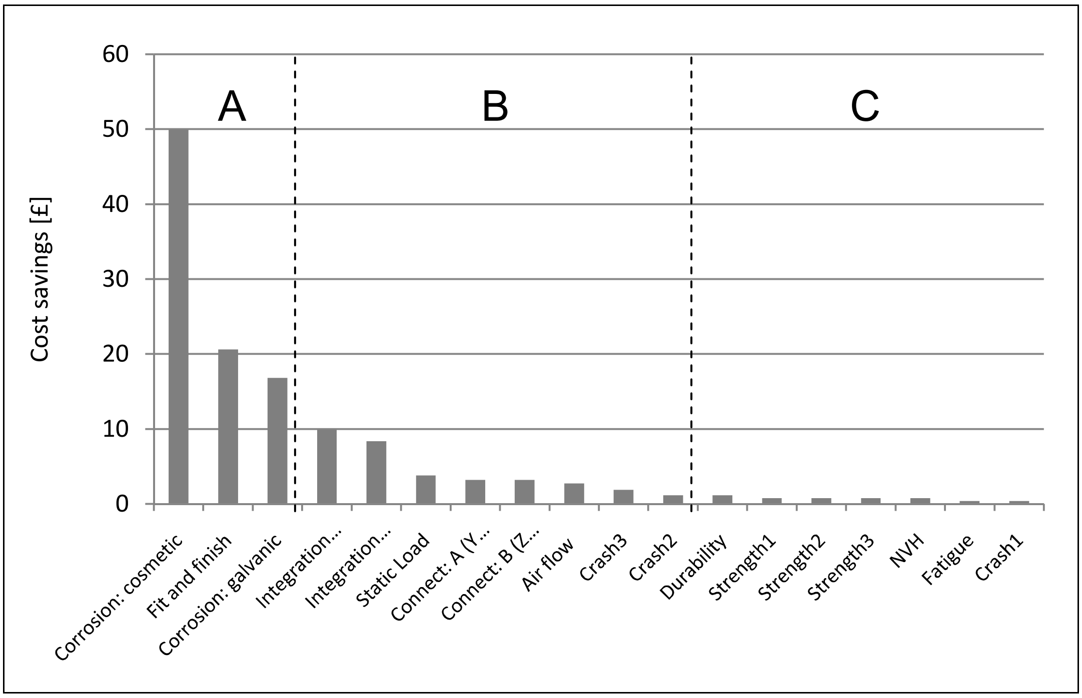


Fig. 5.8 Pareto of the cost saving induced by removing a function

To simplify the visualization, integration has been considered in groups of 10 integrations; a distinction has been done for as cast and machined holes in order to capture possible different cost related to some differences in the process

As per the topics identified on cost, it is on the new functions of the part that the highest cost drivers have been found.

At this stage the ranking and selection of R&D activities and potential research programs will not be evaluated for the single bars. The selection will be made in chapter 6, including the activities initially identified with the cost reduction analysis. The focus is now put only on the key information that can be drawn from the Pareto on values. This Pareto has been split in 3 regions to simplify the description (A, B, C in figure 5.8).

Three functions drive 70% of the cost saving that could be achieved if they were not required.

If the scope is to reduce cost of functions, then the focus has to be put initially on the three first functions (area A), The cost analysis (paragraph 5.2.2), has already covered two of these items, **"fit and finish"** is the only major new cost driver identified. As a reminder, this function could not be quantified; the cost is driven by the material required to better match interfaces with mating components.

The centre of the Pareto (area B) represents 23% of the potential savings. Out of these five functions, 64% is **integration**. It must be reminded that integrations are considered here in group of 10 to simplify the visualization; actually, the average cost of an integration is 1£. This underlines the cost efficiency of technology to integrate functions, to the system at the opposite of welded steel (especially when it comes to add a fixing, a locator or a poka-yoke as it is just a local little management of the material). The rest of the bars corresponds to **pre-requisites**. With regards to the area "B" of the Pareto, no cost reduction activity has been identified. Assuming 20% cost reduction is achievable, it would give in total 6£ for all the functions in the area "B" (for example it would mean a potential of 0,2£ per integration). Due to the low potential of this area of the Pareto and to the fact that the potential improvements are likely to be specific of a specific function of a specific product, it has been concluded that it is not worth brainstorming R&D activities on this.

On the right hand side of the Pareto, many functions have almost no impact on cost: these functions are crash, NVH, durability, fatigue. Those functions are requirements, and though they may be difficult and time consuming to achieve, issues are actually addressed by a local management of the distribution of the material. The reason why it is only a local management is that the function is either covered in achieving another function or driven by a technological limit (i.e. the geometrical constrains necessary to feed the die, such as the minimum wall thickness).

The overall right hand side of the Pareto, including areas "B" and "C", does not represent a big share of the cost ("B" 30£, "C" 11£); it is surprising that key requirements have not more impact on cost. All together, the ten structural pre-requisites only represent 6% of the possible savings if they were not to achieve.

Reviewing the engineering of the part, the genesis of the final geometry goes through first an assessment of how all major integrations could be achieved, how the part could meet the different joining locations in the body in white and of the capability to fill the die. This process is now supported by using optimizers on CAE tools for mechanical targets (NVH, stiffness…), then *filling simulation* verifies the feasibility. Hypothesis driving the shape and the size are then made right from the beginning of the design. To be on the safe side, the designers usually design using the maximum packaging space available. It could then be assumed that the initial geometry assumptions and constrains lead to an over-engineering of the structure when trying to make the initial shape, focussing at integrating the key functions and insuring castability.

Hence for some products, it might be interesting to try to design for functions using the minimum packaging space, but also optimizing projected surface area as it drives the machine size and hence transformation cost. Eventually, in some cases, this approach could even lead to a step down in machine size or to a move to a dual-cavity tool. No data are available to quantify this benefit; however assuming 5% weight reduction will represent a potential above 3£ per part that could potentially be applied to many products. More details of this evaluation will be given in chapter 6, and a description of the functional optimization approach is reported in annex 3.

An interesting output of this activity is the fact that an R&D topic has been individuated for the matured part of the technology and could not emerge from cost analysis. Another output of this analysis is the information on the functions that drive cost and the ones having a minor effect. In some cases, functions are perceived as expensive as they are difficult to achieve, while, though they require big engineering efforts, they actually have a low impact on the final product cost (many load cases, NVH).

5.3.3 SENSITIVITY OF COST TO FUNCTIONS' LEVEL VARIATION

In this section, the objective is to assess the effect of a variation in the function magnitude on cost, when the level of the function is changed in a significant way. For this exercise the assumption of a +/- 20% variation in magnitude is taken. Other figures could also be considered and probably deserve to be adopted for some specific functions when 20% is not a realistic. It must be also said that some variations are not easy to quantify and that the experience of people working on the specific topic is fundamental.

An example of the table used for the evaluation of possible variations in functions magnitude is given in figure 5.9. The proposal to improve the function by 20% is given in column "solution"; the following column is giving the type of activity considered for the improvement. The "confidence" column indicates the confidence in estimating cost and magnitude variation; for some of the functions, those two parameters had to be assessed on the base of experience and on the available information. Still, at this stage, an evaluation is sufficient for the final selection of the projects.

The work on magnitude variations showed that, for most functions and to a certain extent, the 20% value change can be addressed through engineering. The need for R&D activities would only be triggered when the limit of the technology is reached. Hence, where the function is achievable by engineering, the cost is easy to assess. When a technology change is required the assessment of the cost might be more difficult.

The sensitivity study has been done on the same list of functions presented in the previous paragraph analysing all the cost items found in paragraph 5.2 and adjusting costs.

IMPROVE VALUE BY 20%

Figure 5.10 shows a section of the table used for the evaluations when functions' magnitude is improved by 20%. 19 functions or groups of functions have been analyzed on the base of the list made in the previous paragraph. Two functions have not been quantified and hence are not considered in this analysis.

Function	Comments	Solution	Type of improvement / activity	Confidence
Connect: A (Y direction)	1500mm	no		unknown
Connect: B (Z direction)	450mm	no		unknown
Strenght 1	Primary latch	thicken path load	engineering change	OK
Strength 2	Secondary latch	thicken path load	engineering change	OK
Strength 3	Bumper abuse	thicken path load	engineering change	OK
Static Load	Torsional stiffness	ribbing	engineering change	OK
NVH	NVH Normal mode	ribbing	engineering change	OK
Fatigue	4g bump loading crise control sensor	thicken area	engineering change	OK
Crash 1	Low speed insurance repair	thicken area	engineering change	OK
Crash 2	High speed structural integrity	design or higher ductility	eng. ch./material properties	assessment
Crash 3	Fender Separation Loading (y load)	design or higher ductility	eng. ch./material properties	assessment
Durability	Road load input	thicken area	engineering change	OK
Corrosion: cosmetic		thicker coating, higher adesion	process/e-coat, materials	assessment
Corrosion: cosmetic screws		different coating, higher adesion	process, materials	assessment
Corrosion: galvanic		design / improve insulation	engineering change	OK
Air flow		design	engineering change	assessment
Fit and finish		design and stiffen	engineering change	not assessable
Integration as cast		design	engineering change	OK
Integration machined		design	engineering change	OK

Fig. 5.9 Section of the table used for functions variation evaluation. (+20%)

"Fit and finish" could not be qualified and an improvement cannot be properly assessed in terms of feasibility, magnitude and cost. Yet, it can be said that this function could be improved through design, in particular by enhancing stiffness and increase the contact surfaces between the FEC and the various trims.

In the column "Solution", a possible way to reach the increased target is given; the following column ("Type of improvement / activity") indicates the type of activity that has been selected. Activities are of 3 kinds:

- engineering change: it mostly regards design changes, such as modification in a local thickness, adding of one/some ribs, modify the path load, modify geometry for further integration or improved air flow;
- material properties: it includes the improvement of mechanical, physical or chemical properties of materials (alloys, coatings);

- process: it includes changing in the casting process as well as improvement in the coating process, including new coating for screws.

At a first glance, it can be seen how 70% (13 groups of functions over 17) of the improvement can be achieved by engineering change; this addresses the following functions:

- Strength
- Static load
- NVH
- Fatigue
- Crash
- Durability
- Air flow
- Fit and finish
- Integration

Cost of improvement have been calculated or, when it was not possible, assessed. The result of the analysis is shown in the Pareto chart in figure 5.10.

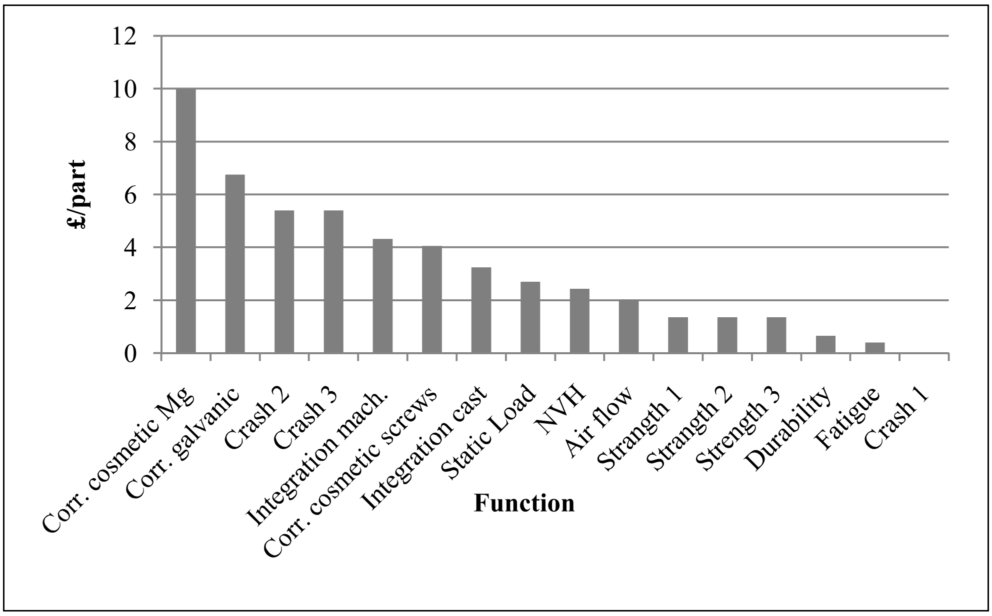


Fig. 5.10 Pareto of cost per function improvement.

Apart for the displacement–driven crashes where the introduction of an higher ductility material could increase cost quite significantly, the costs related to engineering change are less than 3£.

When presenting the product to the customer, it could worth mentioning that, for the functions listed above, the system could be stretched with non significant cost impact.

Two functions quickly get to the limit of the technology. These are the two displacement-driven crash load cases (crash 2 and crash 3), for which the limit of the achieved ductility would be exceed. Two solutions could be proposed. One is an engineering solution which consist in a **hinge mechanism**; an example is given in figure 5.11; this would still need be validated in terms of performance (load at which possible displacement is released, maximum load and corrosion resistance).The other solution would imply to improve the intrinsic ductility through material/process. The only solution identified is **MC-HPDC**; the potential ductility improvement of the process (from 6% DC to 12% MC-HPDC) should allow improving displacement capacity by 20%. This last point is difficult to assess as the total displacement depends on deformation mode, and respective contribution of elastic and plastic displacements. An assessed impact of this process on the cost of the part is included in the two bars “crash 2” and “crash 3”. More details will be given in annex 1.

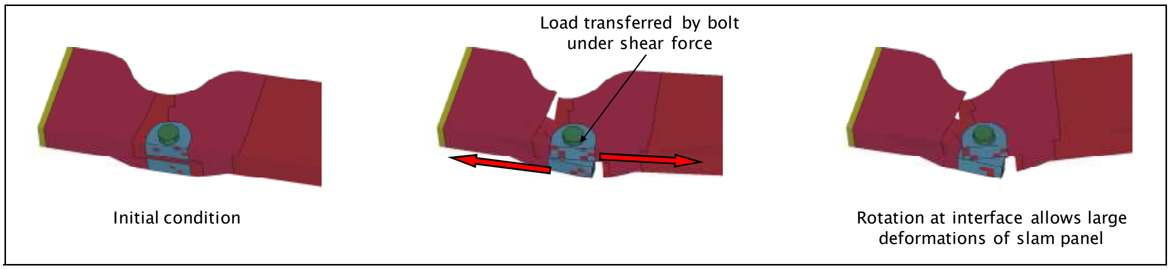


Fig. 5.11 Schematic of hinge mechanism

Increasing of integration is here considered as an improvement of 20% of the number of integrations to grab. Assuming that similar types of integration are considered, this only affects the cost of the final part in terms of metal content. As a note, it must be mentioned that on this type of component, adding integrations with fixings can be affected by screw coating costs. It follows that, at the system level, the cost of integration vary widely depending on the function to achieve and the product. It can also be seen how the machined integration cost more than the “as cast” one. Still, when some machined integrations are already present, the building of the tools and the cycle time necessary to position the component in order to have it machined are already necessary. Hence, in general, adding other integrations has a limited impact on the cost. Even if screw coating has to be added, it is worth highlighting that 20% extra integration, i.e. 8 extra integrations, costs 4£, meaning less than 0.5£ each.

The last two functions to discuss are the cosmetic and galvanic performance for magnesium casting and screws; this topic is very specific as the target is set by the customer and depends on its validation methods. Each customer has developed its own corrosion tests on one hand and, on the other hand, the overall market experience about corrosion of coated magnesium parts is still low, and no clear fail-pass criteria has really been established. The fact that the solution meets requirement is actually a judgment of damage observed through defined accelerated tests, no connection yet has been established with the real use of the vehicle. A requirement for higher performance would only be linked to customer fears, but no evidence of real need would be established. If cosmetic corrosion had to be improved, that would imply to improve the adhesion between coating and magnesium (conversion coating or other solutions), and/or increase actual coating resistance to creep corrosion and increase coating resistance to avoid electrolyte to reach magnesium.

Changing adhesion layer would first mean testing market solutions and eventually push suppliers to develop other solutions. Improve coating resistance could mean improving the type of coating, the thicknesses, the amount of layers (providing interlayer adhesion is not affected). In the lack of connection to real use and of request of the customer, but also not to raise fears, focus should not be put on this topic at this stage.

For screws similar considerations can be made. The risk here would lie in getting the rust to contaminate magnesium and develop galvanic cells in specific areas. Available solution did not show any issue, hence an improvement of properties does not appear as a priority at this moment.

DECREASE VALUE BY 20%

As per an improvement of 20%, the results of a reduction of performance of 20% have been gathered in a Pareto chart (see figure 5.12). On the right hand side, 70% of the functions (11 groups of functions over 16) are offering less than 1,5£ saving per part each. All together it would represent only 8£. These savings would probably be grabbed through the engineering development process, hence it does not seem interesting to focus efforts in lowering performance for these low cost items.

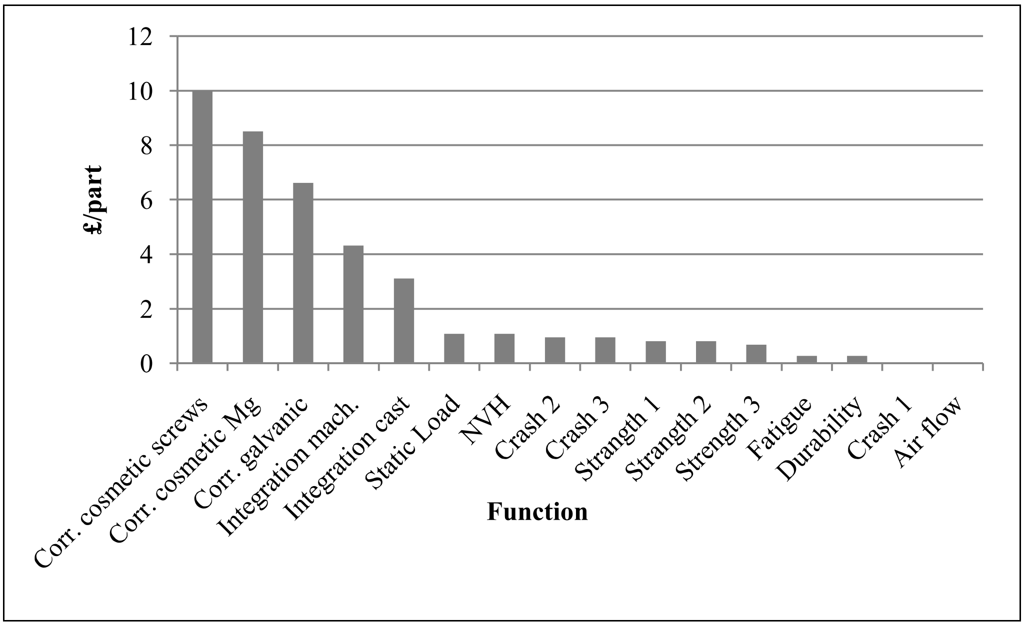


Fig. 5.12. Pareto of savings per function decrease.

Similar consideration can be made with regards to integration: as said above, “integration” gathers together many functions, hence the impact for a single action on a specific feature would have a non significant impact.

The situation is different for the last remaining three functions on the left hand side of the Pareto. These are the galvanic corrosion (spacers is the key cost driver) and the two cosmetic corrosion targets for the part and for the screws, the cost been the coatings.

For the spacers, a lower performance is not likely to be acceptable as it would lead to the failure of the part by local galvanic corrosion.

For the screw coating (costing 23£ for all the part), there are actually two functions: the first one is cosmetic, the second one is the fact that a massive failure of the coating leading to strong rust on fixing could affect part integrity if rust drains on it. Still the issue has not been found yet on coated parts, hence cheaper and eventually lower performing coating could be tested; it must be reminded that a loss of performance would depend on customers' tests. R&D activity could consist of testing existing and new solutions through customer's tests.

Coating (31£ on the part) has only a cosmetic function. In a similar manner than for the screw coatings, it is difficult to evaluate the significance of a 20% loss. If several coating systems are considered, there is not such a big difference between most adhesive layers and types of powders. Hence it cannot be foreseen the achievement of significant cost reduction by testing different combinations. For specific cases, where an e-coat is required, it could be removed; still, it implies to find a cost efficient supplying source having the process without the e-coat. The route to save cost could be to remove completely the coating. The AE44 alloy showing both high ductility and high potential cosmetic corrosion could be used, eventually improving it by an etch to remove process iron contamination. If a high visual standard is required (requirement above what a bare light alloy power train part would be capable of) a plastic vanity cover could be used. The loss in magnitude of value is difficult to assess, and may raise concerns. The R&D activity would consist of testing these solutions through key market tests back to back with coated reference and present the results.

In the case of the FEC, the sensitivity study on value mostly showed that lots of functions could still be improved with minor impact on cost and that engineering still offers good potentials. The limits of the technology would only be reached in the case that high elongation is required, which would trigger R&D on material and process, or validation on innovative engineering solutions. Only a few functions offer an interesting saving to the customer if function magnitude is lowered, these are the ones related to the cosmetic appearance of the part. This loss in magnitude been difficult to quantify, proposed solutions need to be validated (no major R&D) and submitted to the customer.

5.4 CONCLUSIONS / AND HOW AN FEC COULD BE PERCIEVED OR PRESENTED

The analysis on cost reduction raised six potential R&D projects. The approach on value analysis has allowed identifying another topic on cost reduction. This topic has actually been individuated for the matured part of the technology and could have not emerged from cost analysis.

Value analysis allowed highlighting the functions that drive cost and the ones having a minor effect. In some cases, functions are perceived as expensive as they are difficult to achieved, while, though they require big engineering efforts, they actually have a low impact on the final product cost.

The analysis on costs, showed how a magnesium FEC is likely to have a premium cost of about *x* € per kilogram saved, compared to a steel solution. This premium price is likely to include other values than a high weight saving at the front of the vehicle.

The sensitivity study on value mostly showed that many of the functions could still be improved with minor impact on cost and that engineering still offers good potentials. These functions are most of the integrations and many of the pre-requisites. The limits of the technology would only be reached in the case that high elongation is required, which would trigger R&D on material process, or innovative engineering solutions.

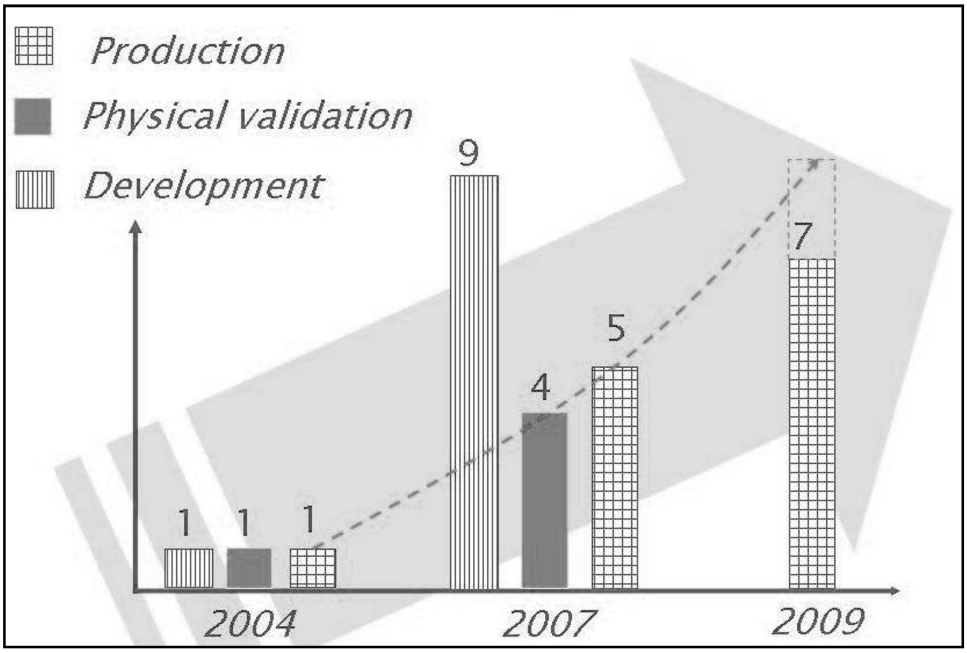


Fig. 5.13 FECs developments and production trend

Only a few functions would offer an interesting saving to the customer if are removed or if their magnitude is decreased: these are the ones related to the cosmetic appearance of the part. However, the loss in magnitude been difficult to quantify, and proposed solutions need to be tested and submitted to the customer.

As a note, from the previous analysis, the FEC could be described as below.

The global Meridian's market for FEC is 800000 parts per year. There are currently 6 FECs in production and 13 components under development and/or validation (figure 5.13).

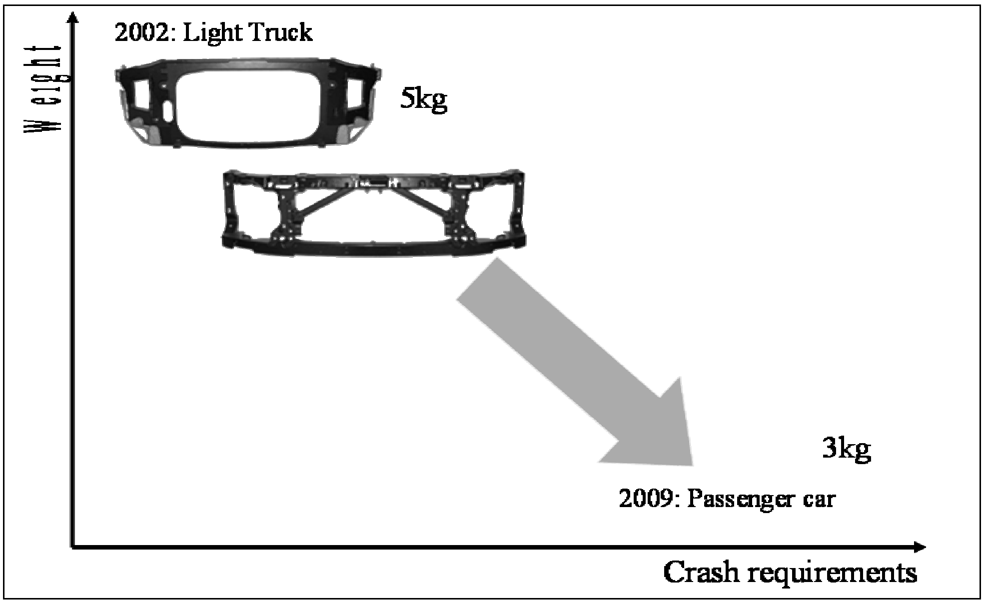


Fig. 5.14 Evolution of FEC weight and performance

Application is extending from light truck to SUV and then to passenger car (figure 5.14). Today the main application for magnesium front end carriers are the high-end vehicles but new applications are now aiming mid range vehicles.

The features that costumers value for magnesium front end carriers are:

- weight saving versus steel (40 to 50%), i.e. 3 to 9 kilograms depending on the type of vehicle; the typical weight of a magnesium FEC is in the order of 5 kilograms on a light truck and 3kilograms on a passenger car; figure 5.13 gives an example of the evolution of FECs typical performance and weight over the last seven years. The weight saving lies not only in the use of Magnesium, but also in the fact that compared to steel, there is less impact on mass when trying to address stiffness or fatigue issues.
- induced weight saving: the reduced weight at the front of the vehicle reduces load on the body in white;
- high stiffness achievable, hence potential to redistribute stiffness target at the system level;
- Compared to steel:
  - o better fit and finish performance compared to steel when requirements increase;
  - o higher integration offered by the foundry compared to welded technologies;
- Compared to plastic:
  - o higher mechanical properties and possibility of achieving crash requirements;
  - o better air flow management offered by foundry shape;

Key features achieved on the current produced FECs are:
- Weight from 2.5 to 5kg.
- NVH 100Hz to 155 Hz, higher targets achievable with minor cost impact.
- Latch strength 8 to 16 kN.
- Bumper abuse 1.25 kN.

- Torsional stiffness 11kNm/deg.
- 1000 hours salt spray ASTM B117.
- 12 week humidity / salt spray tests.
- 12 week mud tests.

6. DEFINITION AND RENKING OF R&D PROJECTS

The analysis run in the previous chapter has highlighted 10 potential R&D topics. 6 emerged from the cost analysis, 1 from the analysis on cost reduction of the values, and 3 from the analysis on value change. 8 of these topics target cost reductions, 2 target a change in value level.

A selection has to be made to identify the topics offering the highest potential for the company, in accordance with the resources available.

Literature offers many methods to rank projects [35, 36, 37]; since the activities found are mostly based on cost reduction and since assumptions on their impact can be made in order to calculate the cash flow, the decision has been made for this study to rank the projects first on the base of the net present value (NPV), then taking into account the cash flow payback period in order to prefer the short payback projects. Since this study focuses on short – midterm activities, the NPV have been calculated on the basis of a five-year period.

The NPV of a cash flow is defined as

$$NPV = \sum_{i=0}^{n} \frac{F(i)}{(1+r)^i}$$

With *F(i)* the net cash flow at time *i*, *r* the discount rate per period and *i* the time of the cash flow.

The selected method does not take into account the risk of the investments, and two aspects are to consider in the present case. The first aspect lies in the probability of success of each project, the second aspect has to consider possible evolutions of the raw material market price, whenever raw material is involved.

For each project a probability of success has been assigned, and then in case of success another probability level has been assigned to the achieved result. For example, project A, 40% chance of failure, hence 60% chance of success split into 20% chance to save 5%, 15% chance to save 10% and 5% chance to save 15%. This scenario will be detailed below for each topic.

For each of the scenario (4 in the example above) a cash flow profile is calculated.

In the same manner, if raw material price has an influence, 6 hypothesis on price ranging from 2 to 4.5€/kg have been set with the associated 6 probability of occurrence. In the present case these 6 scenarios on price would be applied to each of the scenario on project success. Taking the example given above, 24 scenarios would then be generated.

The value used for the ranking is then the NPV corrected by risk factors, it is called expected cash flow as per Martino [36]; it is calculated by multiplying each possible cash flow profile by its probability and summing the products (i.e. to obtain a weighted average).

The actual Expected Net Present Value (ENPV) considered in the final ranking table presented below is extended to the portfolio share on which the improvement could be applied, so that the relative influence of transversal and specific topics is revealed. The header of the table is reported in figure 6.1.

Activity	£/kg max	£/kg exp	£/part max	£/part exp	% of portfolio	ENPV	PBP	Score	PM

Fig. 6.1 Header of the table for project ranking

To be able to evaluate the impact of the activities on a single product and in order to allow evaluating the extension of some activities to whole portfolio, depending on the topic the calculation had to be based either on a cost saving per part (£/part exp. in figure 6.1), either on a cost saving per kg (£/kg exp.). In order to compare activities, the cost savings per kilogram have been turned into cost saving per part considering an average product weight of 5kg.

For information, in order to evaluate the impact of the activity on the midterm period, the effect of the most probable profile has been considered and reported in the column "£/part max", still considering a 5kg part when required.

The column "% of portfolio" reports the percentage of portfolio on which the activity is expected to have an impact, different values could be considered.

The factors included in the cash flow are the initial investments (tools, software...), the cost for development, the cost for implementation, the person months (PM in table), the expected cost reductions, the additional costs (maintenance, energy, personnel…). When cash flows are not easily computable, some assessments on costs and savings have been done on the basis of previous experience.

The payback period can help further to rank topics, and it is used here to put more focus on the short term activities. The cash flow payback period (PBP) is defined as the period of time required for the return on an investment to "repay" the sum of the original investment. Scoring can then be assessed as follow:

$$Score = \frac{ENPV}{PBP}$$

6.1 ASSESSMENT OF THE POTENTIAL R&D TOPICS

This section aims at defining the scoring of each of the research topics identified, and complete the table base given above. If required, more details are given, with regards to the actual work to achieve. Project costs, resources, and risk are assessed; if no topic has been identified, assessments are made on the potentials.

Results of the analysis are reported in table 6.1 at the end of this paragraph.

6.1.1 MC-HPDC (COST REDUCTION AND VALUE CHANGE TARGETS)

This activity has emerged from both cost and value analysis, and this topic was already in the basket of activity.

The technology can be seen as a simple piece of equipment added to the die cast machine, introduced between the furnace and the shot sleeve, which allows to change material structure and hence properties. This device shears the molten metal, increasing the genesis of nuclei and generating a fine and homogeneous microstructure. Mechanical properties are improved showing very high ductility levels (see fig. 6.2), stress levels remain unchanged. The technology could open the door to new applications that could not be considered so far with die casting. New applications could be the suspension area as properties achieved are similar to the ones of the aluminium alloys used in vacuum die casting. More details will be given in annex 1.

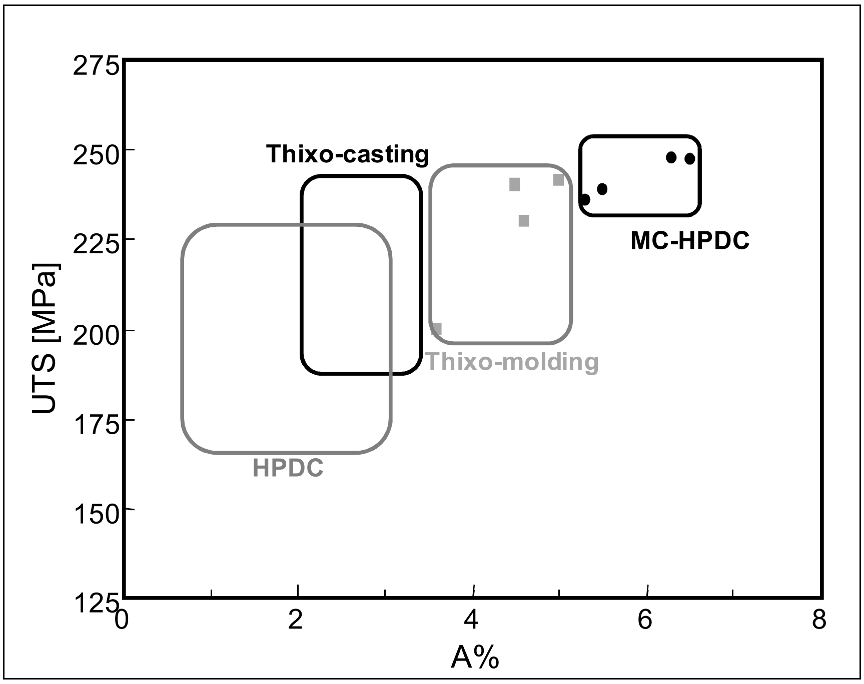


Fig. 6.2 Mechanical properties (Ultimate tensile strength vs. elongation) of AZ 91 processed through different technologies.

It must be reminded that, if properties are improved, casting conditions remain equal as the metal is processed 100% liquid and the approach on defects [27] will remain unchanged.

The challenge lies in the validation costs to implement the device to verify that laboratory results can be reproduced on larger parts, i.e. that there is no scale effect on the nucleation mechanism.

At the laboratory scale only small parts or tensile bars have actually been cast. Meridian products are generally about 6 kg meaning a shot weight of about 12 kg. For cost reason the validation cannot consider directly the manufacturing of a 12kg shot slurry maker. Assessment of the technology will be done with a 3 kg slurry maker, allowing manufacturing a 1,5kg seat frame already in production.

The acceptance of a new technology by a customer is a long process when associated risks are high. It is often easier to introduce an innovation driven by cost reductions than a change to higher performance. It has then been decided to develop the validation in two steps: the first one targets small inner parts that could be done with recycled metal on the 3kg-shot slurry maker, to prove out the technology in production and demonstrate higher properties prior to target larger parts still using recycled metal or stretched applications in terms of performance. In the present study the assessment is then limited to the cost reduction validation of production parts below 1,5 kg, by the use of recycled metal. The potential of this technology to move product values to higher levels is then to investigate afterwards.

The validation work lies in implementing the slurry maker on a 1500 Ton production cell, cast seat frames, and verify that performance is at least equal to the one of the current part, but using recycled metal.

The cost of the 3kg shot slurry maker prototype is 220 k€, 60k€ are required for installing the prototype on the die cast cell, 15k€ for component testing and resource requirements have been estimated in three person months.

If the technology will be validated, the slurry maker would probably have to be moved to China where most of the small parts are produced; this transfer would cost another 35K€.

As a start, the volume to produce with this technology will be low, the parts will be below 3kg shot, and the need in recycled material will far below the current tonnage production of rigging systems and scrap parts. Hence, over the first few years, it will not be required to re-use gates and runners of the MC-HPDC process. The cost reduction will then lie in avoiding recycling the 1,5 kg contained in a part; the gates and runners would have to be recycled.

Three scenarios have been considered:

1. Failure after first stage, probability 50%
2. Failure after slurry maker moved to China 10%
3. Success, slurry maker implemented and capacity of one cell filled in two years time. 40%

6.1.2 REDUCTION OF RUNNERS WEIGHT (COST REDUCTION TARGET)

The term runners is here adopted to indicate all the rigging system which is, according to Campbell, *the word for the various appendages of runners, gates and feeders* [41]. In the case of large thin-walled magnesium die-castings, the amount of material necessary to feed the die including runners, gating, feeders and overflow can be as much as 50% of the total shot weight. The cost of this item lies in the fact that metal has to be re-cycled in order to be used again; over that there is an energy consumption to melt more material than the strictly necessary amount to feed the die. The optimization of rigging has been studied for a long time [42, 43] and the current situation is likely to be close to the optimum; however the continuous improvement of flow simulation software and the development of materials could potentially reduce the amount of material necessary to feed the parts.

As example, a possible activity could consist in working with software supplier to tune the available tools to optimize the rigging design; another one could include the use of ceramic insert to reduce the heat exchange in the runners in order to allow smaller sections.

No activity or real study has been done in the timeframe of this work; the topic would deserve to be brainstormed with the specialists, especially as the impact would be all over Meridian's production.

In order to avoid discarding the potential of the topic, assessment has then been made with relatively optimistic figures on a **non defined activity**. It has been estimated that a weight saving from 2 to 5 % on the rigging system could be achieved. A relative risk of failure of 40% has been considered. 12 person months plus software licenses are necessary to complete the study.

6.1.3 REDUCE MAGNESIUM COATING COST (COST REDUCTION TARGET)

As detailed in paragraph 5.3.3, coating cost is mostly driven by purchasing and potential technical cost reductions first imply to develop the correlation between accelerated tests and real life exposure. Potential study would lie in testing different paint systems to customers' requirements. Hence, here also to avoid discarding the potential of the topic, assessment has then been made with relatively optimistic figures on a **non defined activity**.

Five scenarios have been considered:

1. Failure, probability 35%

2 to 5. 5 to 20% cost reduction

The potential cost reduction has been assessed to 5-20%, as the technology is not matured. The risk level covers both the technical feasibility and the fact that the solution may not satisfy all customers.

6.1.4 VALIDATION OF CHEAPER SCREW COATINGS (COST REDUCTION TARGET)

The activity on fixings is limited here to the screw coating; it might also be of interest to search for other existing types of fixing solutions, exploring the market and analyzing if the current solutions are not over designed.

The activity on coating consists of testing cheaper screw coatings available on the market. The evaluation needs to be done during a development as corrosion tests and targets are customer-specific. The task is limited to the actual corrosion tests and the preparation of the samples.

The resources required have been estimated in two person months and 4,000€ budget for testing. The probability of success has been assessed to be 50% and, here again, it covers both the technical feasibility and the fact that the solution may not satisfy all customers.

Five scenarios have been considered:

1. Failure, probability 50%

2 to 5. 5 to 20% cost reduction

As a note, this work is not been reported in annex, but has been completed. Five coatings have been tested back to back the current solution, through 1000h salt spray tests. Beside the base propose solution, one of new solutions met the costumer's requirements. **The cost of fixing could be reduced by 42%, i.e. 4,25 Euros for the specific product.**

6.1.5 CHANGE OF SPACERS MATERIAL (COST REDUCTION TARGET)

This activity aims at replacing the Aluminium spacers by a cheaper material offering comparable or lower galvanic potential and that could be engineered to withstand temperature as high as 120°C for the FEC application. The concept of a foil is maintained as a substitution by a coating would raise some risk if it had to be injured. Initial corrosion tests on cardboard sealing has showed interesting potential; however if tooling is almost insignificant, raw material cost is actually high. Initially plastics have not been selected due to relaxation issues, however if designed as described in figure 5.8, the solution gathers several potential improvements. The galvanic potential could be brought down to null if distances are respected, raw material and tooling cost would be much lower compared to aluminium, also simple clips could be integrated to the spacer to hold it to the FEC instead of using adhesives. The validation would lie in performing the conventional corrosion tests on plates, replacing the aluminium washers of the joints by plastic materials.

The resource requirements have been assessed to be one person month; a budget around 4,000€ would be required for testing. **Considering both tooling and material, the saving per FEC has been assessed to 1.5€ in initial assessments**. The probability of success has been assessed to be 60%.

6.1.6 REDUCTION OF SCRAP THROUGH STATISTICAL PROCESS CONTROL (COST REDUCTION TARGET)

As explained above, large thin wall parts are difficult to cast and scrap levels as high as 12% can be reached. Initial studies have proven the efficiency of DOEs to reduce scrap [39]. The principle of the method is to test a limited amount of specific combinations of process parameters. In simple cases these parameters are set at two levels (low or high). For each tested combination the scrap rate is measured. A specific post analysis allows identifying the best set up of the process, i.e. the level of each of the parameter investigated. As further detailed in annex 4, these methods can yield more potential. The advantage of the method is that it can be run within or close to the process window so that it can be applied without disturbing the production.

Initial work tend to show that a computer self adjusting system could be developed, the machine could automatically generate combinations of process parameters, associated scrap rate could be measured using a traceability system between the shot number and the part number, and a software optimizer could reset the machine to the best set up.

As a first step, the potential could be assessed as follow: manual generation of the DOE runs on the machine, implementation of a marking system on the part, optimization with software. Further implementation would consist in a self-adjusting system and in an interface to allow the operator to indicate the presence of the scrap part and the part number.

Three person months have been assessed for this activity. An initial cost of 7,000€ will be necessary for installing a marking system; further investment would be necessary to put in communication the operator with the system (interface plus software): 20,000€ investment is assessed. Initial experience tends to show that scrap could be reduced by 30-60%; a 30% reduction would representing a **saving of 0,10 per kg cast**. Risks have been ranked at 70% possibility of success.

Four scenarios have been considered:

1. Failure, probability 30%

2 to 4. Scrap rate at 4, 6, 8%

6.1.7 WEIGHT REDUCTION THROUGH CONCEPT OPTIMISATION (COST REDUCTION TARGET)

It has been said above how the design of the part is done using optimizers on CAE tools for mechanical targets (NVH, stiffness…) and then *filling simulation* verifies the feasibility. The fact that these functions have limited impact on cost could indicate some over engineering. The hypothesis is made that, though extensive use is made of software optimizers, these do not fully interact with the initial definition of the shape. Initial definition is in fact done by experience to integrate key functions and insure castability.

The proposal is to try to design for functions using the minimum packaging space, but also optimizing projected surface area as this drives the machine size and hence transformation cost. No data are available to quantify this benefit; however assuming 5% weight reduction will represent a **potential of 0,15 €/kg** that could potentially apply to many products. 12 person months assessed.

Five scenarios have been considered:

1. Failure, probability 50%

2 to 5. Average weight reduction 3, 7, 11, 15%

In this case some scenarios have been considered to evaluate the variations of raw material price: 6 hypotheses on price ranging from 2 to 4.5€/kg have been set with the associated 6 probability of occurrence. More details are given in annex 3.

6.1.8 HINGE MECHANISM (VALUE CHANGE TARGET)

The “hinge mechanism” is a smart design developed by AE to allow high intrusion (see figure 5.11). Validation implies the tuning of the geometry to adjust and insure the robustness of the fuse mechanism and the corrosion behaviour. Such a validation would imply the manufacturing a die or at least major modifications of an existing die. Associated costs are high, hence the system should only be considered if a project gets to the limit of the technology. For this reason it will be kept as a shelf solution and not further analyzed in that study.

6.1.9 BARE FEC, REMOVE COATING BY USING AE44 (VALUE CHANGE TARGET)

The need for coating is only driven by the cosmetic requirements, and part integrity is not bound to coating, if these were not to achieve the coating cost could be removed. After long time exposure, the appearance of the part would be similar to the appearance of a Magnesium transmission part. Though the surface is contaminated by iron during the casting process, some alloys have higher cosmetic resistance potential; these are the AZ91 and the AE44. Since ductility is required, only AE44 could be considered for FEC. AE44 is an alloy containing Aluminium and Rare Earths; it has been developed as a ductile magnesium alloy with a high creep resistance and is currently used for the Corvette Z06 Engine Cradle. This component is working at a temperature above 140°C and is exposed to severe condition being at the bottom of the vehicle. AE44 has shown good aesthetic corrosion resistance, similar to AZ91. If coating costs could be removed, AE44 is more expensive than AM60 (about 0,4 Euro per kg).

The adoption of this solution would imply for the customer the **acceptance of a lower standard** for visible corrosion. If a higher standard is required, a vanity cover would be needed. The costumer has to balance the reduction of the “cosmetic corrosion” function in exchange of a price reduction.

Such validation needs to be done during a development as corrosion validation tests and pass/fail criteria are customer dependant. The work would consist in preparing bare AE44 samples to be tested at the customer, and costs would be limited. If assessed, acceptable validation costs would raise with the need to cast AE44 front ends for the vehicle field tests.

Table 6.2 Ranking of the activities

	£/kg max	£/kg exp	£/part max	£/part exp	% of portfolio	NPV	PbP	Score	PM
Bare FEC, remove coating by using AE44	10	5	50	25	6%	**90**	**1,6**	**100**	2
Reduction of scrap through statistical process control	1,1	0,7	5,2	3,4	80%	**93**	**1,9**	**87**	3
Weight reduction through concept optimisation	3,9	1,2	19,4	6,0	50%	**100**	**2,2**	**81**	12
Change of spacers material	3,9	2,1	19,4	10,4	12%	**63**	**1,5**	**74**	2
Validation of cheaper screw coatings	2,6	1,2	13,1	6,0	12%	**41**	**1,3**	**56**	4
Reduce Magnesium coating cost	3,8	2,0	18,7	10,0	12%	**52**	**2,6**	**35**	4
Reduction of runners weight	0,2	0,1	1,4	0,5	100%	**26**	**3,2**	**15**	12
Reduce material cost using recycled metal in MC-HPDC	4,9	1,2	24,5	5,8	10%	**22**	**3,2**	**12**	3

The information gathered in the last section allows establishing the ranking given in table 6.2. Decisions on projects to launch have to be taken at the corporate level. Decisions can be made on the ENPV, with more or less focus on the payback period, and obviously in accordance with available resources. Further considerations should also be made.

The ENPV is assessed for a given share of the portfolio however, for most of the project, the implementation will follow the future developments and productions, and hence the actual share of the portfolio will only be completed after a while. The assessment of the ENPV could then be better tuned including a calendar with hypothesis on potential future program. This works has to be done at a corporate level, however the assessment as described in table still ranks potentials, and for this PhD, three topics have been selected and developed. These topics are given below and detailed in the annex.

Two projects do not need to wait successive productions to be widely applied. The first one is the work on scrap reduction by statistical process control as it can be implemented immediately on the production. The second is the one on plastic spacers. Though it should be first proposed on future projects, it could also be worth to assess if it could not be implemented on current projects as a cost reduction activity.

As a general comment, it is interesting to note that all projects related to the non mature side of the product (cosmetic and corrosion), count altogether for 55% of the total scoring, and that project on the mature HPDC count for 45%. Non matured aspects are specific to the product, while matured aspects are transversal; hence apply to a larger part of the portfolio.

This aspect appears clearly in figure 6.3, when plotting both potential cost saving per part and portfolio share versus the development time. Activities triggered on components in production, i.e. on process improvement, have a small impact on product cost but are transversal. Activities identified for initial stages of the development show high cost reductions but are more specific to a non matured product.

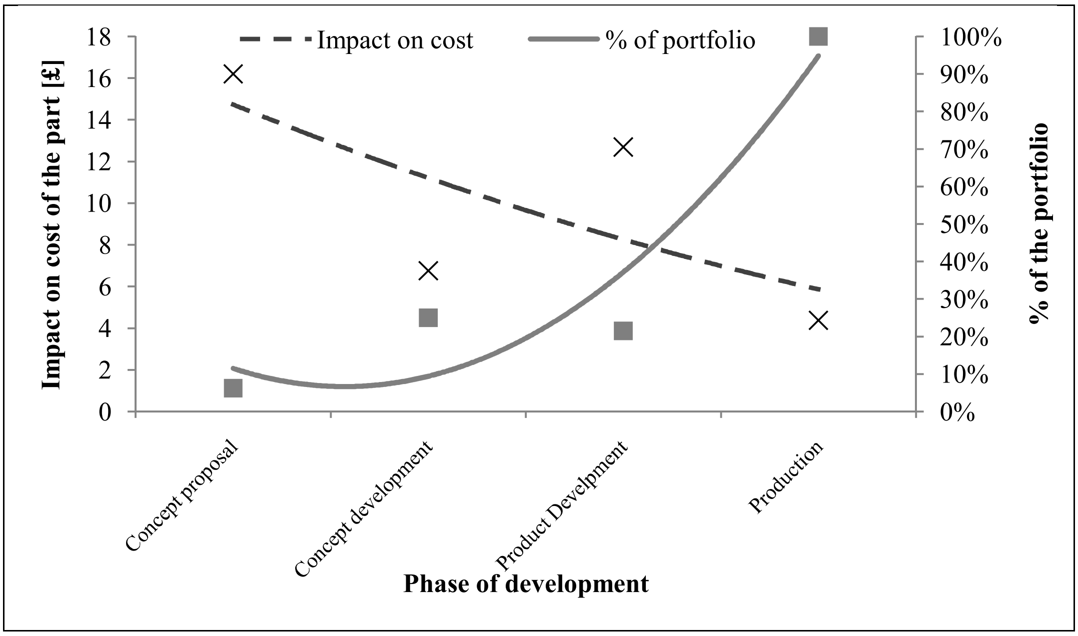


Fig. 6.3 Impact of activities on product cost and share potentially involved

Another general consideration that has also to be made is that, considering the current automotive environment, the approach has been more focused on cost reduction. For example, the MC-HPDC project has the lowest score because the study only aims at getting the validation work refund, remaining on 1,5kg parts. If the analysis had been done for a longer term, larger parts would have been targeted, the portfolio share would have increased and the ranking would have probably been one of the highest. The picture drawn can then seriously change depending on the time considered to deliver results.

Within this PhD, projects have been selected and developed. The first one is the reduction of scrap by the use of optimisers, this projects gathers ranks second in ENPV, requests low resources and can be implemented immediately. Results are presented in annex 4.

An attempt has been made to start the activity having the highest ranking project, i.e. the assessment of the use of bare for FEC with AE44. Though initiated on corrosion plates, the customer has abandoned the project for priority reasons. The project with the third scoring, i.e. the Concept optimisation has then been selected for this PhD, it is presented in annex 3.

The projects ranking 3rd in terms of ENPV has been selected. This project on Weight reduction through concept optimisation is presented in annex 4. If focus has been made on short term, a share of the R&D activity should still be dedicated to new markets. For the purpose of this work, activity has been selected out of the automotive market. As seen before, when it comes to very innovative projects and products out of the portfolio, supplier's capability to analyze potential values is very limited, and the approach has to be opportunistic. In such cases, possibilities to target products can hardly be structured, very general considerations have to be made, and risk of failure is very high.

The decision has been taken to investigate the potential use of magnesium for aircraft seats. Though magnesium is banned in the cabin due to 30 years-old tests, weight saving is highly valued by airways company. Indeed, 1 kg saved represents a fuel saving of 1000 $ per year. On the base of Boeing data [44], the potential market has been assessed to 250000 seats per year over the next 20 years. Capturing 5% of this market would represent 12500 seats per year, where a higher profit could be done since this product would imply coating protection for flammability and the use of MC-HPDC for isotropic properties. More details on the study carried on the flammability assessment for aerospace applications are given in annex2.

As a final comment, the application of the proposed method to the FEC case, ended up with more proposals on cost reductions, eventually identified through value analysis and very little on value change proposals. Most proposals on value change have been discarded along the analysis.

Several factors can explain this result. The first one lies is the fact that the move to other values can be achieved in most cases through engineering work.

However, it may also be that too much focus is put on costs to be more open to work in the perspective to move far above current performance.

7. CONCLUSIONS

An attempt has been made to improve the identification of R&D projects to better support corporate growth of an automotive die casting supplier.

It has been identified that R&D should improve both its capability to reduce product cost and its capability to identify activities to move in product function levels that the costumer values.

The difficulty lies in the B2B environment where, in order to protect prices, OEMs do not communicate on what they value on the products. Major innovations that opened new market have been identified as always triggered by the customer. Major market innovations are triggered by OEM having a good knowledge of the supplier's technology. For short term growth, R&D should focus more on spreading recent innovation rather than searching for new ones.

The approach implies to develop the flux of information on values from the customer to the supplier. In the prospective to capture customer's values, a proposal is made. For each new development, the price could be presented not only for the level achieved for each function, but also with information on how it would change if the level of each of these functions was lowered or improved by a defined percentage.

Such an approach can suits challenging technologies as both the customer and supplier can find an interest in moving towards different products levels and cost.

To be able to establish such a price variations, all functions have to be listed and their cost evaluated. To run this cost evaluation, a method based on assessing the cost by removing the function has been developed. Ideas have to be brainstormed to find technical solutions to move to higher or lower function level. R&D activities have also been identified through cost reduction analysis. One analysis has been done on the product/process, and another one on the cost of the functions.

To assess the efficiency of the combination of these three analyses to identify R&D projects, the method has been applied to magnesium Front End Carrier. A list of projects has been generated and ranked on the base of Expected NPV. Both the analysis and the final selection should be done at the corporate level.

The application of the method has shown that for value changes, most of them can be achieved through engineering work, and that the need for R&D is limited to a few topics. More R&D activities are required for cost reduction, and the analysis of function value has allowed further R&D activity identification. The highest cost reductions were found for the non matured part of the technology, however their impact is limited as they are specific to some products; these cost reductions have to be addressed in the development phases. Cost saving identified on the matured die cast technology are less impressive when reported to the part, but these apply to the whole portfolio.

The proposed approach needs to be extended to other products. It could be also of interest to apply it at the costumer, at a higher system level integrating different parts and eventually different competing technologies. Assuming that each supplier could list function levels and cost associated with function level changes, an approach with optimizers could be developed to assess the cost benefits if function levels were balanced from one side of the system to another.

ANNEX 1: MELT CONDITIONED HIGH PRESSURE DIE CASTING

Melt conditioned high pressure diecasting (MC-HPDC) process, previously named rheo-diecasting (RDC) process, is a combination of a MCAST (melt conditioning by advanced shear Technology) machine for melt conditioning with a standard high pressure diecasting (HPDC) machine for component shaping [1]. Figure 1 shows schematically the complete system.

The technology can be seen as a simple piece of equipment (slurry maker) added to the die cast machine, introduced between the furnace and the shot sleeve, which allows to change material structure and hence properties.

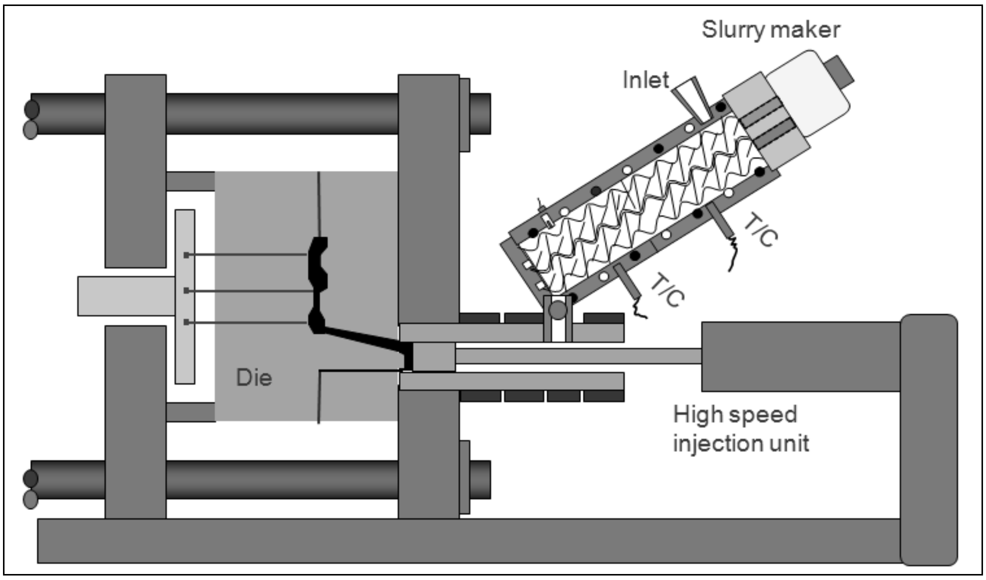


Fig. 1 Schematic of the MC-HPDC system

The slurry maker is a barrel containing a couple of counter rotating screws; the liquid flows inside the slurry maker and is subjected to a high shear rate and an intense turbulence [1]. The initial function of the slurry maker was to convert the liquid metal into a semi-solid slurry; recent studies [2] showed that the system can be used to conditioning liquid metal prior to solidification processing. The MCAST device imposes to the melt high shear rates and an intense turbulence. The consequence is that the molten metal has uniform conditions in terms of chemical composition and temperature; above that, oxides are well-dispersed, wetted and with a fine size.

Extended work on this process has shown that the MCAST machine is actually mostly acting as a grain refining device and that it could be used with 100% liquid, meaning that all process parameters can remain unchanged compared to conventional HPDC process.

Laboratory trials show that the MC-HPDC process is capable of producing close to zero porosity samples with a fine and uniform microstructure throughout the entire component (figure 2). MC-HPDC process provides samples with improved ductility in the as-cast condition, compared with HPDC or other available semisolid processing techniques as shown in figure 3 for AZ91 and in table 1 for AM50 and AM60. Initial tensile test have shown elongations up to 20% on AM50 test sample [3]. The elongation been improved, the ultimate tensile stress increases consequently.

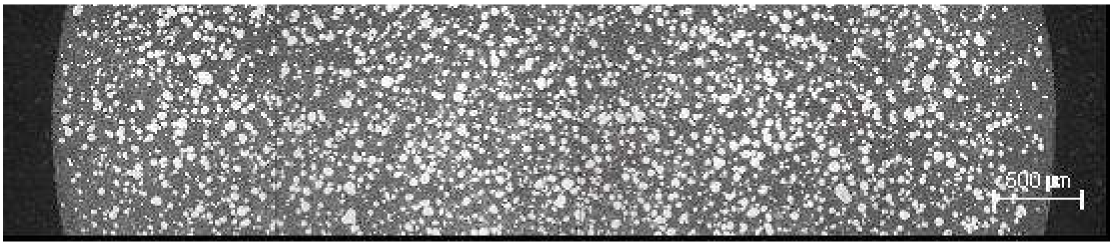


Fig. 2 Microstructure of AZ91 alloy bar (6mm diameter) produced by the MC-HPDC process showing fine and uniform microstructures and close to zero porosity (<0.2%).

The grain refinement is achieved through an enhanced heterogeneous nucleation rate and an increased nuclei survival rate during the subsequent solidification processing [2]. The modification of the melt induces a fine and homogeneous structure after solidification. The structure is found isotropic, consistent not only through the casting wall but also all over the casting, from the gate to the last filled areas [1]. The decreased in elongation with increased wall thickness could be less important than what is achieved with other die cast processes. Interesting results found in laboratory studies [1] with regards to structure homogeneity will have to be proved at industrial scale with a full-scale MCAST unit.

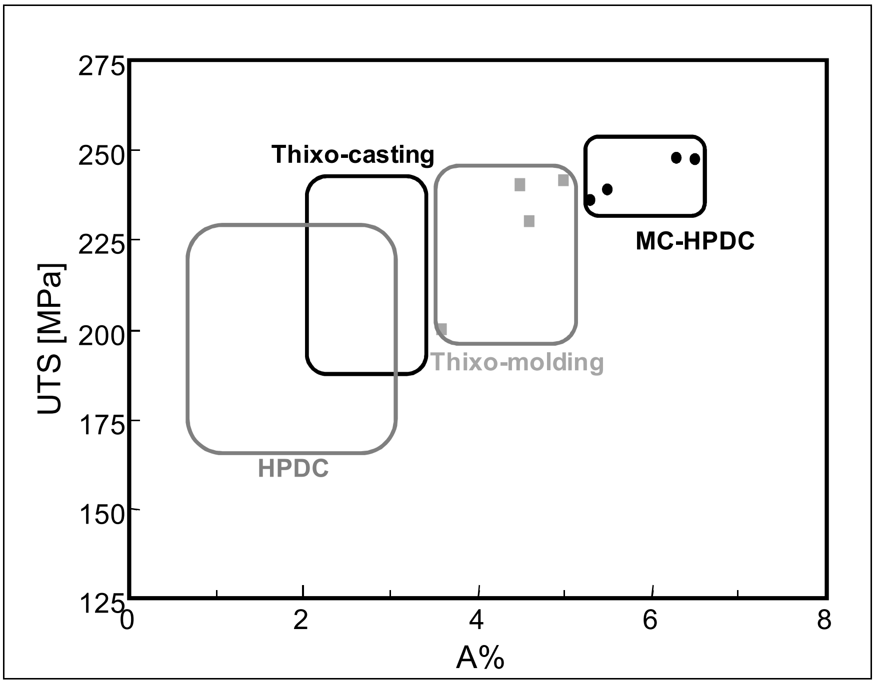


Fig. 3 Mechanical properties (Ultimate tensile strength vs. elongation) of AZ 91 processed with several technologies.

Magnesium alloys processed with MC-HPDC show properties similar to the ones achieved with Aluminium vacuum die casting, hence applications in the suspension area could be possible.

The addition of this single piece equipment to an existing HPDC machine would limit investment and permits new applications. Potential applications could be in the suspension area, together with AE44 showing high temperature resistance, very good corrosion performance and increased ductility [4, 5].

Table 1. Properties of AM alloys processed through several technologies [6]

Process	Alloy	YS [MPa]	UTS [MPa]	A%
MC-HPDC	AM50	122	249	20
Thixocasting	AM50	108	220	7
Thixomolding	AM50	140	269	20
HPDC	AM50	128	241	12
HPDC	AM50	129	195	6,7
HPDC	AM50	120	204	6,9
HPDC	AM60A	125	237	13
HPDC	AM60	142	230	8,7
Thixomolding	AM60B	129	229	7,5
Thixomolding	AM60	150	278	18,8

Another interesting characteristic of the MCAST machine is the fact that it breaks up oxides in small round-shaped particles well dispersed through the entire components [7]. This characteristic opens another potential that is the possibility to use scrap parts and runners systems for specific internal applications, leading to interesting cost savings. Figure 4 compares the mechanical properties of AZ91 alloy produced by the MC-HPDC process using different amount of scraps.

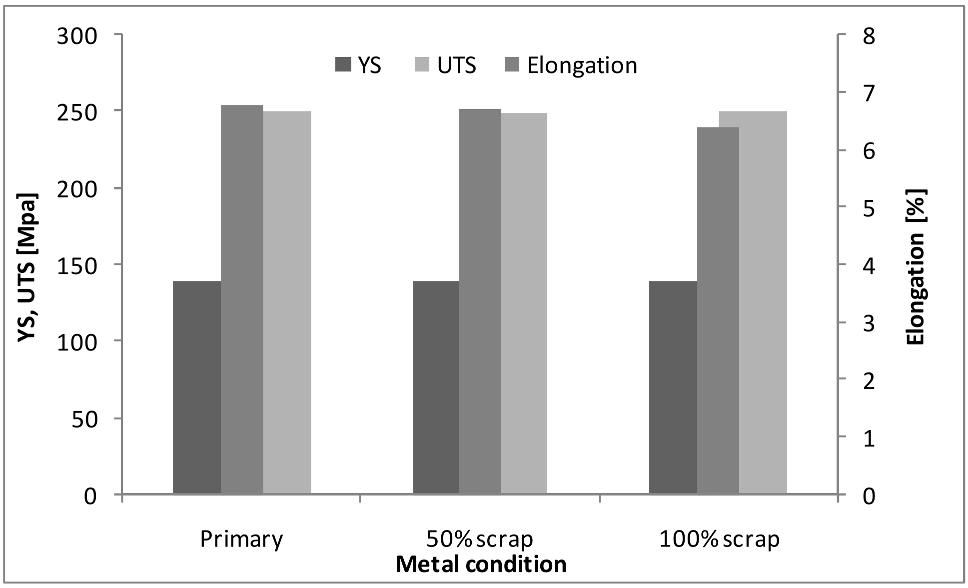


Fig. 4 Comparison of mechanical properties of AZ91D alloy with different levels of scrap addition produced by the MC-HPDC process

The validation of this technology will then lie in two phases: the first is aimed at verifying that laboratory results can be reproduced on larger parts, i.e. that there is no scale effect on the nucleation mechanism. It will be verified if small inner parts could be cast with recycled metal on a 3kg capacity slurry maker. A current production seat frame will be cast to verify that performance is at least equal to the one of the current part, but using recycled metal.

The success of the first phase would open the discussion on the evaluation of the potential of this technology to move product values to higher levels or to open new markets.

ANNEX 2: FLAMMABILITY ASSESSMENT FOR AEROSPACE APPLICATIONS

INTRODUCTION

Being the lightest structural metallic material, and having good strength/density and stiffness/density ratio magnesium is already used on military and commercial aircrafts. Applications are mostly on engines, airframes and landing wheels. Some alloys with good corrosion and creep resistance are commonly used: WE43 (Mg-4Y-3.25Nd-0.5Zr), ZE41 (Mg-4.2Zn-0.7Zr-1.3MM), QE22 (Mg-0.7Zr-2.5Nd-2.5Ag). Aircraft makers and commercial airlines are more and more searching for solutions to reduce weight in order to address energy consumption and emission reductions. Indeed, for commercial aircraft, the cost saving in fuel consumption is assessed at 1000$ per kg saved per year (customer data). For this reason, the interest in magnesium alloys is growing. Potential applications for the die casting process requires minimum volumes to be competitive in terms of price and seat structures appear to be the only parts offering both sufficient part size and volumes for a company like Meridian. Unfortunately, according to the SAE Aerospace standard AS8049 [1], the use of Magnesium alloys is banned for cabin applications: “Magnesium alloys shall not be used” [1, item 3.3.3, pag.11].

The ban followed flammability tests carried out 30 years ago at FAATCO [2], but no information is available. Magnesium burns extensively and requires specific extinguishers; hence aircraft fires could be seriously perturbed if Magnesium is introduced.

No flammability standard and pass fail criteria exist for the use of metals in the cabin, though general guidelines are given in the SAE Aerospace standard AS8049 and in the Aeronautical Design Standard Handbook [3]: “Magnesium alloys shall not be used” [2]; “materials used in aircraft should be selected to provide a fire-retardant capability (…)” and “ should be self-extinguishing” [3, item 3.3] and “In general, non-flammable and self-extinguishing materials are required in aircraft” [3, item 6.6.7.1.6.1].

Other materials used in the cabin are under strict regulation. This regulation is: Part 25: “Airworthiness standards: transport category airplanes - fire protection § 25.853 “compartment interiors”. Thus according to materials and environment several sections are applicable. Appendix F of Part 25: part I, II, IV and V is used to validate non-metallic materials in cabin.

- Part I: vertical test, horizontal test, forty five degree test. Though the standard does not apply, for information, Meridian and Sicma aero seat have tested the AM60B alloy in 3mm thickness, as it would be the solution considered for seat applications, this AM60 die cast alloys with a 3mm thickness, the alloy exceed requirements [6].

- Part II: flammability of seat cushions (A severe oil burner test).

- Part IV: test method to determine the heat release rate.
- Part V: test method to determine the smoke emission characteristics of cabin materials.

The topic has then been brought to FAA and other parties like Magnesium Elektron (Magnesium supplier) are now also working to insure that safety would not be reduced by the use of Magnesium. A policy statement available at FAA website [7] is here reported:

> *Use of Magnesium in Airplane Cabins*
>
> *The FAA has had several recent inquires regarding the use of magnesium in airplane cabins. Specifically, magnesium alloys have been suggested as substitute for aluminium alloys in seat structure.*
>
> *The FAA's central concerns regarding the use of magnesium in the cabin is the flammability, the current regulations do not address the potential for flammable metal to be used in large quantities in the cabin. Therefore, if such a material were introduced to the cabin, the FAA would have to be convinced that the level of safety was not reduced. Special conditions may be required to establish appropriate criteria. While we are aware that there have been changes in magnesium alloys over the years, magnesium remains a material that, once ignited, presents a fire hazard that is almost impossible to cope with.*
>
> *If there is widespread interest in assessing the potential requirements and data necessary to demonstrate that the level of safety is not reduced, the FAA will work with industry to do that. Both the post crash, as well as in-flight, fire scenarios should be addressed. At this point, the FAA does not have any research underway to address the use of magnesium in the cabin.*

The use of magnesium is now currently the subject of a task group of the International Aircraft Materials Fire Test Working Group.

POTENTIAL APPLICATIONS AND WEIGHT SAVING

T. Marker reports as possible applications in the inner cabin air distribution plenum, miscellaneous hardware, escape doors, seat tracks and seat structures [2]. For diecasting applications, minimum volumes are required and only seat frames appear of interest.

A study on some components of the seat structure has been carried on by Meridian and Sicma Zodiac, reporting a potential weight saving of 140kg for a 250 seats aircraft by substituting Aluminium with magnesium die-castings. The structural parts that could be made of magnesium are the armrest, the legs, the seat cushion and the seat back (see figure 1).

For these applications the annual production volumes for Sicma could lies between 4000 to 10000 parts per year.

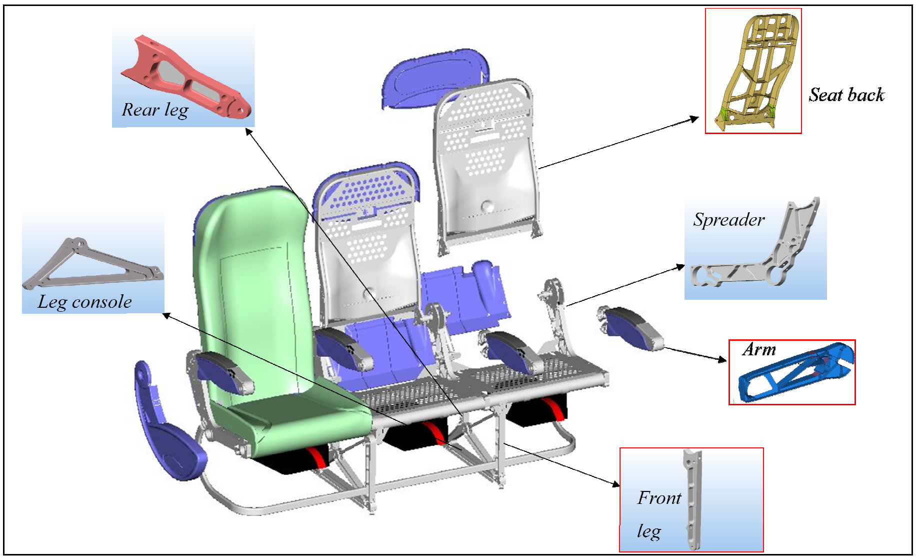


Fig.1 Potential applications of magnesium in the seat structure.

As a note, it must be mentioned that, because of internal porosity, security factors have to be applied when designing aerospace cast components. For this reason semi-solid technologies, i.e. MC-HPDC, show interesting potential as isotropic structure are generated together with low porosity levels compared to conventional die casting.

EXTINGUISHING MAGNESIUM FIRES

Magnesium and its alloys present specific problems with regards to fire protection. Magnesium combines readily with oxygen; under certain conditions, temperature is so high that the water applied to extinguish magnesium may react with magnesium forming magnesium hydroxide and hydrogen (1). Hydrogen reacts with oxygen in the air to form water with a strong energy release (2).

$$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2 + 2{,}9 \text{ MJ/kg} \quad (1)$$

$$2H_2 + O_2 \rightarrow 2H_2O + 24.7 \text{ MJ/kg} \quad (2)$$

None of the commonly available gaseous extinguishing agents are suitable for extinguishing magnesium fires [8]: for example, the affinity of magnesium for oxygen is so great that it will burn in an atmosphere of carbon dioxide. With the high temperature due to magnesium combustion, the environment allows magnesium to also burn in an atmosphere of nitrogen to form magnesium nitride (3).

$$3Mg + N_2 \rightarrow Mg_3N_2 + 1{,}4 \text{ MJ/kg} \quad (3)$$

For these reasons, the common extinguishing methods which consist on water, water solutions, or inert gas are not effective on magnesium fires. Extinguishers in aircraft contain halogen extinguishing agents; they react violently with burning magnesium because the chlorine or other halogen combines with the magnesium. However, flooding with noble gases (e.g., helium or argon) will extinguish burning magnesium. Also flooding with excess of water at the base of the flame (not sprayed), after an initial increasing on fire intensity, will remove heat, cool down the magnesium still un-burned, and stop the combustion.

FLAMMABILITY ISSUE / DEFINITION OF A PASS / FAIL CRITERIA

Regarding commercial aircraft flammability issues, two scenarios are to address: the in-flight fires and the post crash external fuel fires [9].

In-flight fire could be triggered by an electric arc or a hidden fire adjacent to magnesium-alloy component; post-crash fire could start from threat of fire entering cabin, passengers and fire-fighters protection has to be addressed.

Once ignited, magnesium burns intensely and extinguishers currently available on aircrafts are not appropriate because they contain halogen gas which would violently react with the magnesium fire. The possibility of using different type of extinguishers on board to address different types of fires is too hazardous. Flame temperatures of magnesium alloys can reach 1,371 degrees C and an energy of 4,8MJ/kg of burnt magnesium is developed (4).

$$3Mg + O_2 \rightarrow MgO + 4{,}8MJ/kg \quad [10] \qquad (4)$$

The heat released by a magnesium fire could bring surrounding material to higher temperatures and break the flame resistance equilibrium developed so far. Magnesium parts have then to be ignition-proof for in-flight fire and to have to start burning after all the people escaped the aircraft in case of post-crash fire. In addition to that, fire-fighters need to develop specific approach to address magnesium fires.

The development of new flammability target is quite a complete task to achieve. It goes through a clear definition of the threat(s), the correlation with results of full-scale testing and the lab-scale replication of as many aspects of threat conditions as possible.

Flammability describes the ability of a material to burn, flammability characteristics are the properties that define, describe, or measure the behaviour of a material when it is exposed to heat or fire [9]; .In the present case, the two key aspects are the time to ignite and the heat released. Other characteristics can also be taken into account like the burn rate, time to self-extinguish or drip time.

As a preliminary approach, the FAA has decided to proceed in two steps. The first consists of testing magnesium samples according to FAR §25.853 appendix F part II [4] with a target of no ignition after 5 minutes exposure time; this target is much longer than any other requirement.

If the solution meets requirement, a full scale test would be run to assess actual performance and tune a lab test to define a standard.

In the present case, magnesium resistance to flammability will mostly depend on the alloy, the thickness of the specimen and the potential flame retarding coatings that can be used.

MAGNESIUM FLAMMABILITY

Literature reports how different magnesium alloys have different susceptibility to ignition [8]; on the top of that, the ease of ignition of magnesium depends upon its size and shape, i.e. on its minimum thickness and on the area-to-volume ratio as shown on graphs in figures 2 and 3. In order to ignite magnesium, it is usually necessary to raise the entire piece to the ignition temperature: it follows that, because of the high thermal conductivity of the metal, small pieces, such as ribbons, chips, and shavings, may be ignited easily whereas castings and other large pieces are much more difficult to ignite.

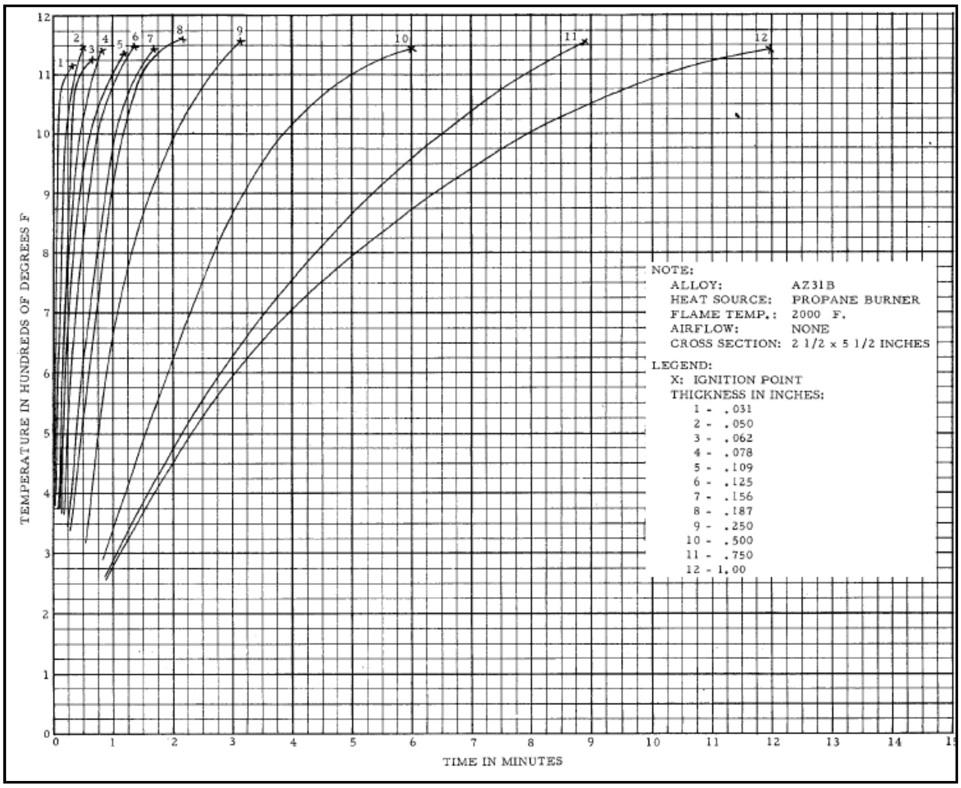


Fig.2 Flame resistance of AZ31B depending on sample thickness [10]

The combination of chemical composition and shape factors makes that, in specific cases, ignition of magnesium may occur at temperature as low as 510°C for ribbons and shavings and as 482°C for finely divided powder [8].

The effect of chemical composition of the alloy on ignition temperature, i.e. the effect of alloying elements is still under investigation. The addition of aluminium was reported to reduce ignition temperature: this effect is likely to be due to a decreasing of the solidus temperature. Addition of other elements as Calcium, Yttrium, Beryllium or Rare Earth mixtures seems to increase the ignition temperature: this is attributed to an improved oxidation resistance and/or a change in the oxide morphology and consistency [11-16].

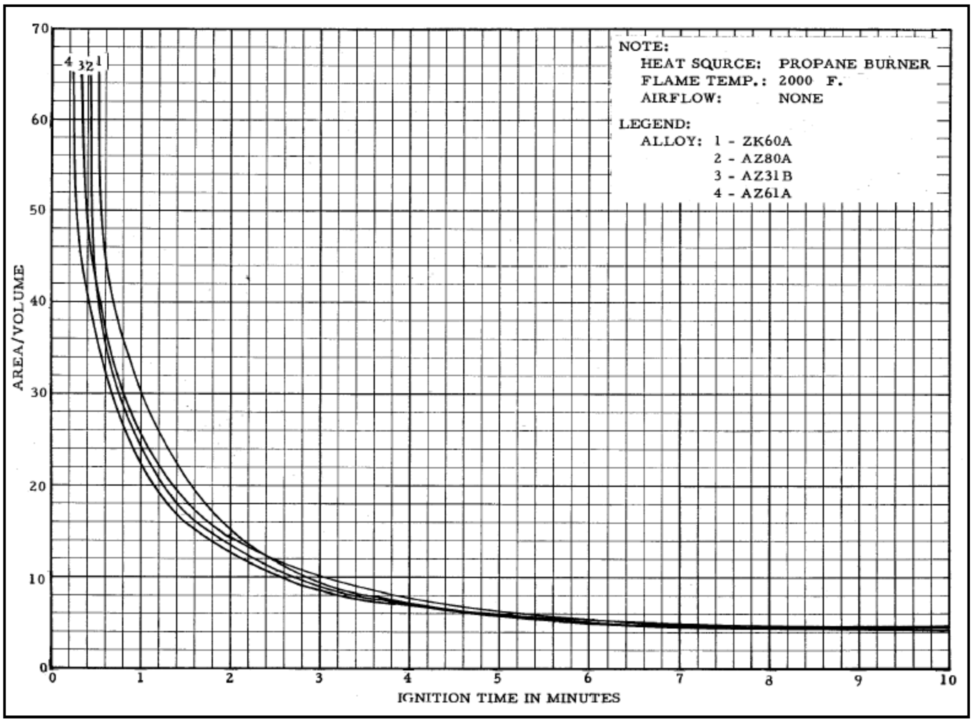


Fig.3 Effect of area/volume ratio on ignition time for several Mg alloys [10]

Blandin, Ravi Kumar et al carried on activities on ignition temperature by continuous heating tests [11, 16] showing that pure magnesium starts igniting at a temperature lower than the melting point whilst for the AZ91 alloy, the ignition temperature (580°C) is between the solidus and the liquidus temperatures, suggesting that a certain amount of liquid phase is required to initiate burning. WE43 alloy, which contains Yttrium and Rare Earths, did not ignite up to a temperature significantly higher than the liquidus (750°C) and consequently, this alloy has been considered as *an ignition-proof magnesium alloy.* [11, 16]

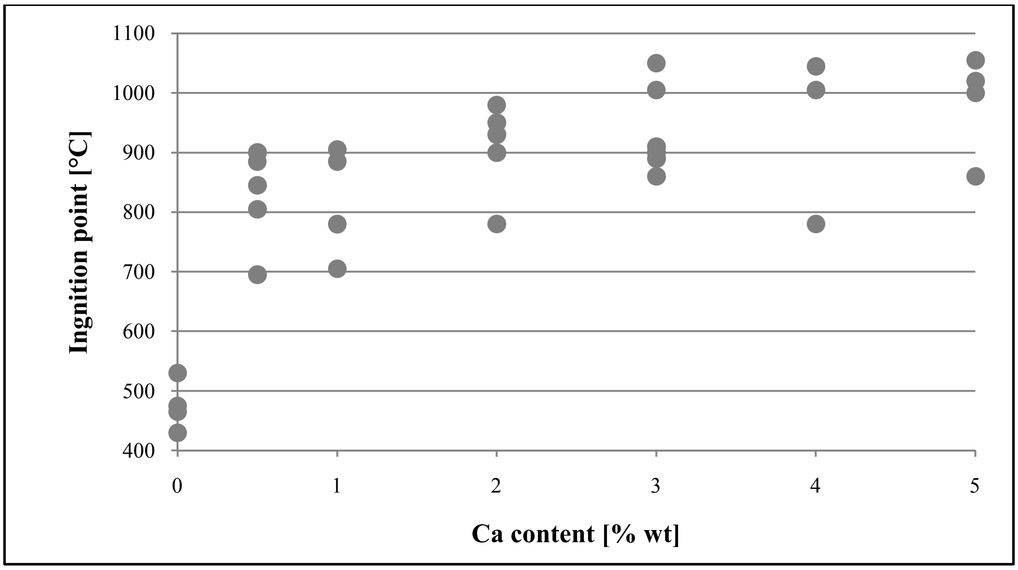


Fig. 4 Effect of Calcium addition to AZ91 on ignition temperature. [15]

The effect of Yttrium and Calcium on the ignition temperature seems to be linked to development of a protective oxide layer (Y_2O_3 or CaO) which are likely to be self healing [15, 16]. Similar effect of Ca has been shown in high-temperature oxidation of Magnesium based alloys, with the formation of a thin and compact layer formed by MgO and CaO [17]. Works on Calcium addition in AZ91 alloy reported values of ignition temperature dependent on the Ca content and reaching magnitudes in the order of 800-1000°C with 2% to 5% of Calcium [15]. Figure 4 shows how the addition of Calcium has interesting benefit even with small concentration (0.5%); the effect seems to stabilize between 2 and 3% addition. Further addition is not affecting ignition temperature.

Though self ignition temperature performance achieved in an oven might not be sufficient as the actual tests lies in exposing the solution to a powerful flame, it is important to define which alloying element provides the highest improvement in ignition temperature. Then, it must be understood if the achieved performances are compatible with a real aircraft temperature fire. Even in case of ignition, a target could be set to a time that does not reduce safety.

AEROSPACE FLAMMABILITY DATA ON MAGNESIUM ALLOYS

In the early stages, Sicma/Meridian carried out initial tests at to assess where magnesium alloys stand compared to the 5 minute target given by the FAA. These flammability tests have been conducted at CEAT (Centre d'Essais Aéronautique de Toulouse, France) on common die-cast magnesium alloys (AZ91, AM60 and AE44) [18]. Tests have been done on sand cast plates with thicknesses comparable to diecast process (3 and 6mm), and using a kerosene burner as per FAR §25.853 appendix F part II [4] (see figures 5 and 6).

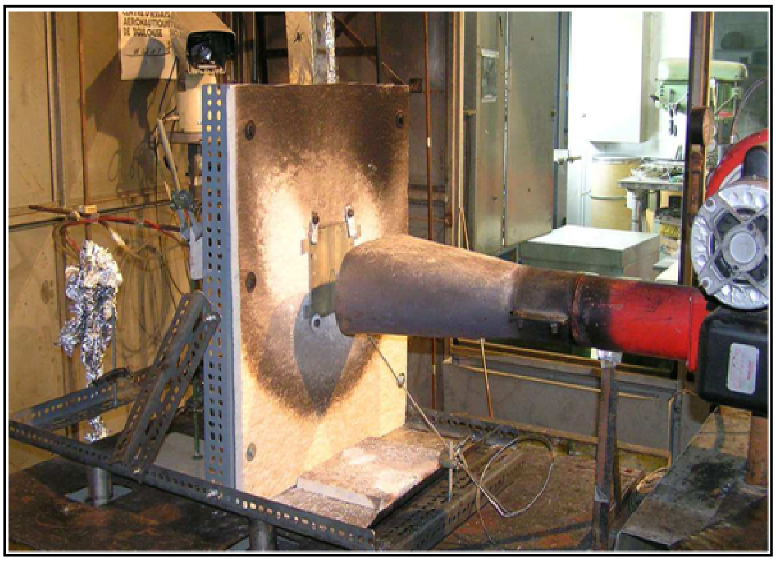


Fig. 5 Test apparatus view, burner side [15]

It appeared clearly that the current die cast alloys would not meet the target. In the best case, sparks initiated at about 2'30" with a full ignition at 3'50". This could be achieved with the AE44 alloy, with a 6mm thickness 3mm and the use of an intumescent coating [19]. It must be mentioned that the efficiency of this protection could not be fully demonstrated across all tests done. This initial testing showed that other diecastings alloys have to be considered for aerospace applications.

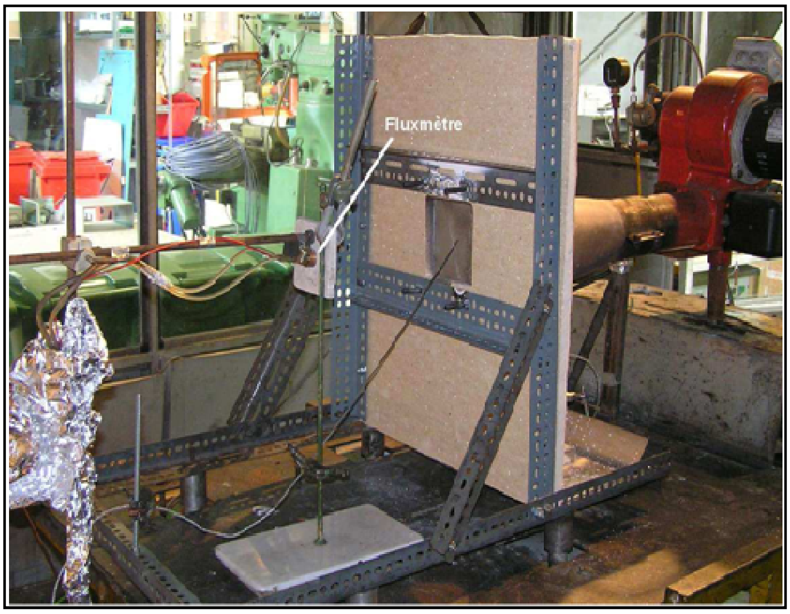


Fig. 6 Test apparatus view, back side [15]

Federal Aviation Administration Tech Centre carried out other tests on different magnesium alloys, still in accordance with FAR 25.853 [4]. The tests have been made on AZ31, AZ80, ZE41, ZE10, WE43 and Elektron21 alloys, using sample with a minimum thickness between 10 and 15mm [20]. All alloys have first been tested bare.

All the samples passed the requirements of FAR 25.853; alloys WE43 and Elektron21 (containing Rare earth and in particular Yttrium and Neodymium plus Gadolinium) performed best and showed no signs of burning, while AZ31 and AZ80 were worst. All bare samples melt in a time ranging from 1'58'' to 3'51''. Samples ignited in a time ranging from 3 to 5 minutes after the application of the flame. 15mm thick samples of WE43 and Elektron21 in most cases showed no signs of burning, while 10mm thick ones showed some degree of burning before self-extinguish of all the alloys. For all of them the molten metal that fell out of the flame into a catch pan kept burning for several minutes, except WE43 and Elektron21 for which the metal did not burn.

The effect of an Intumescent paint has been tested for WE43, it increases the melting time by a factor of four [20]. The selected paint has been supplied by Indestructible Paint Ltd. and consists of several layers for which reference is given below:

IP9064 - 4853 /4854 etch primer - 10 microns
IP3064-6500 primer - 25microns
IP9189 Intumescent - 500 microns
IPFP 8000 Flame resistant enamel - 25 microns.

Test showed that there are some alloys with enhanced flammability resistance due to the addition of Rare Earths. The AE44 die cast RE alloy tested at CEAT showed an improved performance compared to common die cast alloys, but none of the tested cast samples was capable of achieving the 5 minutes target. Samples made with WE43 and Elektron21 alloys met the 5 minute target; however the tested thickness was much higher (15 vs. 6mm).

Calcium, Yttrium and Rare Earth addition appear to be the first driver for flame resistance; if those elements are not present, the time to ignition is bound to the melting point of the alloys. Die casting alloys containing these elements have to be tested.

To identify the best potential Magnesium die cast allows, Meridian and Sicma have decided to act in two steps: in a first phase, magnesium alloys will be tested for self ignition temperature, to identify the best performing ones. To assess if at least one die casting solution can get close to the FAA target, the alloy showing the highest self ignition temperature will then be tested with the oil burner [4], for a thickness of 6mm and using a flame the intumescent coating identified by Magnesium Elektron [20].

SELF IGNITION TESTING OF MAGNESIUM ALLOYS

To assess self ignition temperature a selection of die cast alloys has been made first on the base of Calcium, Yttrium or Rare Earth addition but also verifying the melt temperatures. Been a simple and not expensive test, the investigation has been extended to other alloys for reference. The selected alloys and their composition are presented in table 1, melt temperatures can be found in figure 12.

Table 1: Chemical composition of tested alloys

	Al	Zn	Mn	Ca	Sr	Nd	Y	Zr	RE	Mg
AZ91D	8.3 - 9.7 %	0.35 - 1.0 %	≥ 0.13 %	-	-	-	-	-	-	balance
AM60B	5.5 - 6.5 %	≤ 0.22 %	0.24 - 0.6 %	-	-	-	-	-	-	balance
MRI153	7.5 - 8.3 %	≤ 0.08 %	0.15 - 0.35 %	0.75 - 1.2 %	0.05 - 0.35 %	-	-	-	-	balance
MRI230	6.4 - 7.2 %	≤ 0.08 %	0.17 - 0.4 %	1.8 - 2.6 %	≤ 0.4 %	-	-	-	-	balance
AJ62*	6%*	-	-	-	2%*	-	-	-	-	balance
AE44	3.6 - 4.4 %	≤ 0.2 %	0.2 - 0.5 %	-	-	-	-	-	3.6 - 4.6 %	balance
WE43	-	≤ 0.2 %	≤ 0.15 %	-	-	2.40 - 4.40 %	3.70 - 4.30 %	0.40 - 1.0 %	-	balance

The self ignition test measures two parameters: the first one is the temperature at which the first shiny points appear Ts; these points consist of small sparks that appear on the sample surface and that self extinguish. The second measurement is the ignition temperature Ti, at which the sample starts burning with a low temperature flame (slow and orange) or with an intense flame (bright white). Two definitions of T_i are proposed in literature: it corresponds either to the lowest temperature associated with the observation of a flame or to the temperature at which an exothermic oxidation reaction becomes self sustaining at a rate which causes a significant temperature increase. In this work Ti is the temperature at which the flame appears.

For each alloy a sample sized 3x3x3 mm has been cut and introduced in a muffle furnace (figure 7) pre-heated to 500°C. The temperature has then been increased at a rate of 0.1°C/s and the sample and the sample has been kept under observation through a peephole in the furnace door (figure 8).

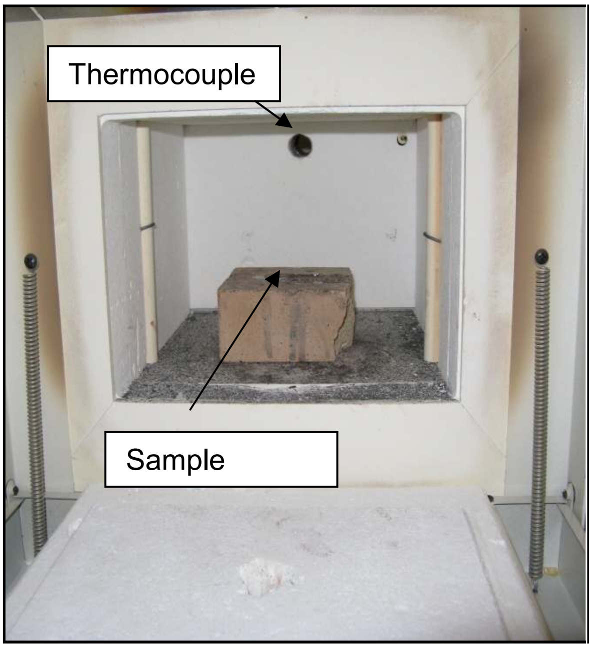


Fig. 7 Test device; inner of the muffle furnace with sample position and internal thermocouple position indicated

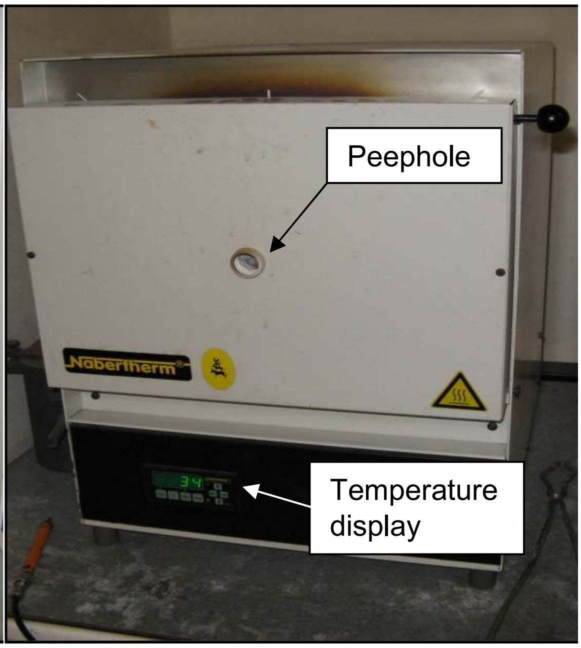


Fig. 8 Muffle furnace; exterior image showing the peephole and the temperature display

After every trial, the furnace has been cooled down to 500°C; all tests have been done three times; temperature has also been measured with a type-K thermocouple positioned in the area of the sample.

DISCUSSION

The chart in figure 11 reports the results of the tests: the given values are the average of three tests, both Ti and Ts are reported.

Ti is compared with incipient melting temperature and liquidus temperature [21] in figure 12. Three groups of alloys can be differentiated when comparing melting and ignition temperatures.

1) AZ91D and AM60B have similar Ti between 570 and 575°C; both ignite below the liquidus temperature as shown in figure 12. AM60 does not produce shiny points before ignition, while

AZ91 produces sparks 3°C below Ti; the difference is not significant for the purpose of this work.

2) Compared to the first group, AJ62 and AE44 show an extra resistance of 40°C on Ti, reaching respectively 611 and 621°C. This behaviour could be explained by the higher incipient temperature compared to AM and AZ alloys. Ignition occurs very close to the liquidus temperature (slightly above or below, depending on the sample; measurement accuracy is not high enough to understand more). The effect on oxidation with the rare earth elements present in AE44 does not reveal an improvement as high as calcium based alloys, though incipient temperature is high.

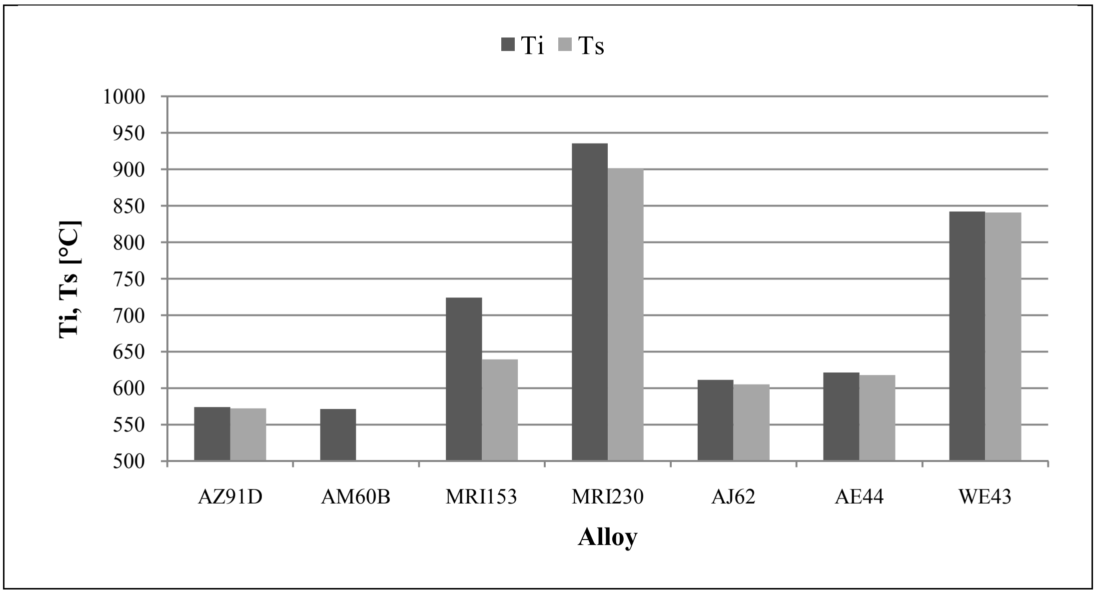


Fig. 9 Ts and Ti for tested alloys

3) In the third group ignition temperatures are far above the melt temperature. MRI153 ignites above 700°C (average 724°C). During testing, a layer becomes visible on the surface in proximity of 650°C, this layer breaks at intervals of circa 10 seconds, small shiny points appear but immediately the layer self heals and shiny points self extinguish. WE43 and MRI230 show the same phenomena, a layer is forming on the surface acting as a barrier between molten magnesium and air. The layer has also a mechanical function as the small sample keeps the cubic shape up to the ignition, while the whole sample is 100% liquid. In comparison with the layer seen on MRI153, these result to be more resistant. WE43 ignites at 840°C and MRI230 at 935°C. Both show some shiny points but just 3-5 °C below the ignition temperature. These results are in line with literature, the development of a protective oxide layer (Y_2O_3 or CaO) acts as a self healing barrier to air [15, 16]. In the case of MRI 230 the effect of Strontium is likely to be negligible as AJ62 which contains 2% of Sr performs much worse than MRI 230.

It is interesting to note that an addition 2% of calcium have more effect than a 4% of Yttrium in increasing the injection temperature, this is a good point as Calcium is much cheaper than Yttrium.

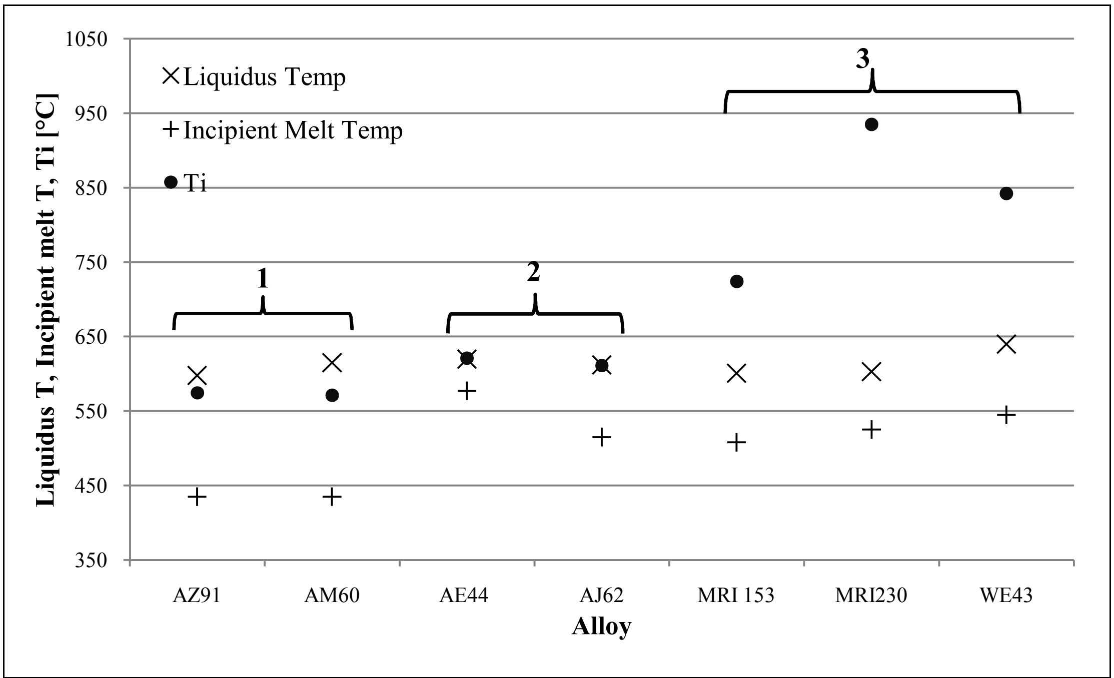


Fig. 10 T_i compared with incipient melting temperature and liquidus temperature [21].

T. Marker [2] reported the temperature achieved during a full scale test to simulate a severe fire inside an aircraft cabin. The plots of temperature in the most severe areas are shown in figures 11 and 12. It can be seen how the maximum temperature is below 760°C (1400°F) and 815°C (1500°F) for mid cabin temperature and seat frame respectively. For information, in the oil burner test [4], the minimal average flame temperature is 982°C (1800°F).

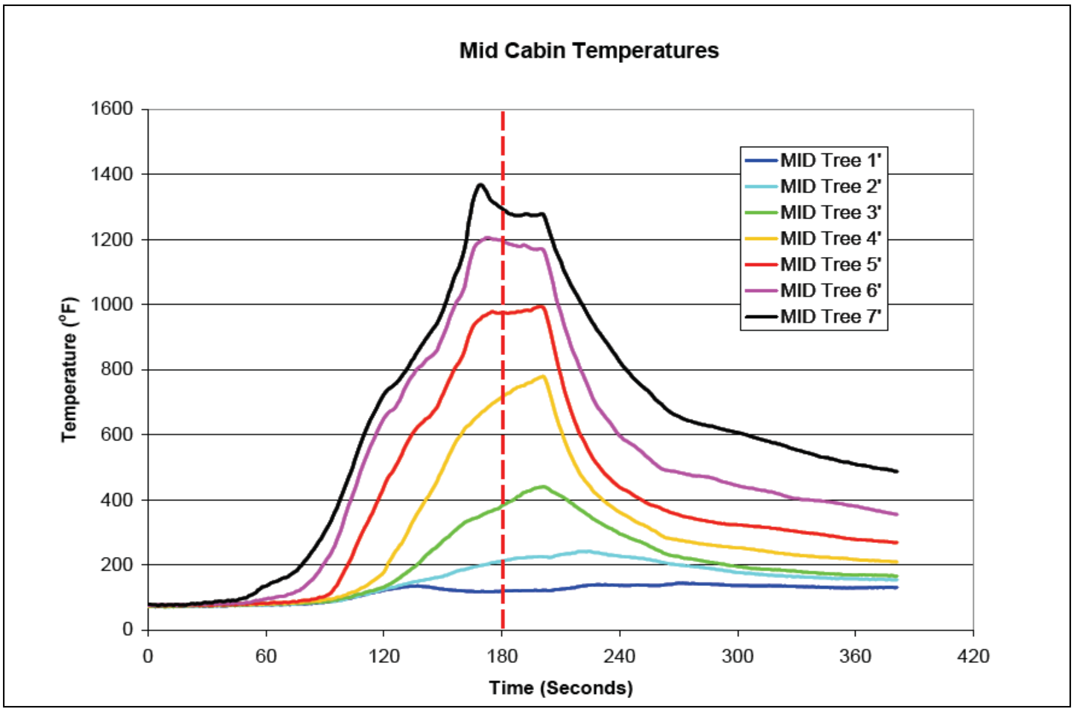


Fig. 11 Temperature trend measured during full scale test, Mid Cabin area [2]

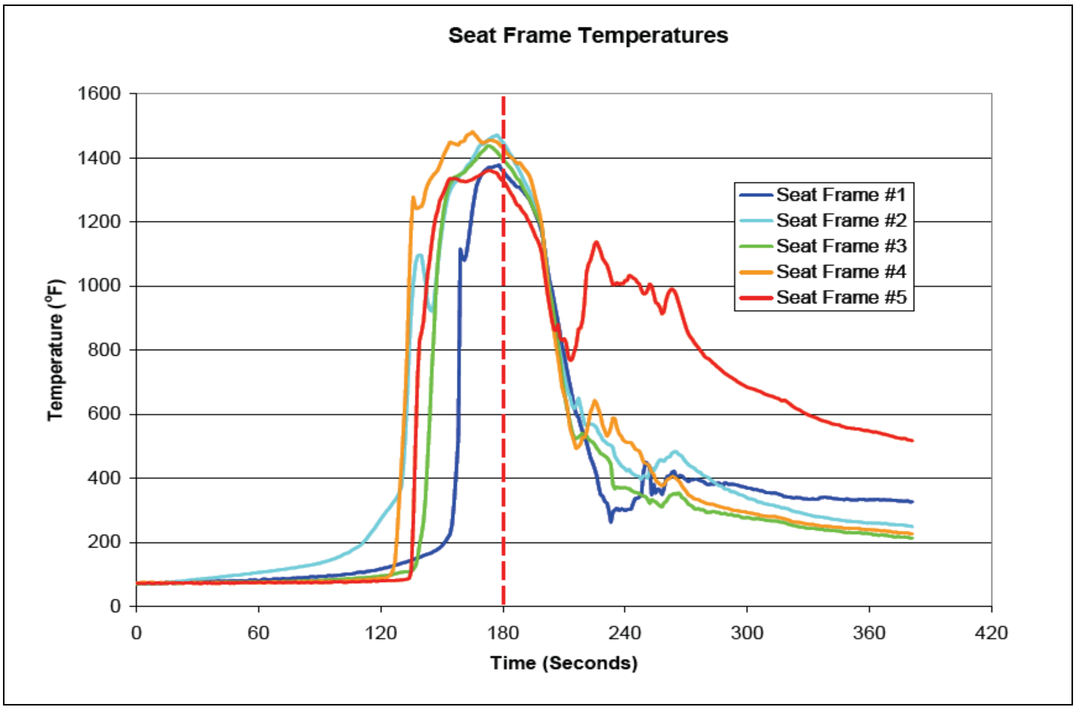


Fig. 12 Temperature trend measured during full scale test, Seat frame [2]

Full scale flammability test, oil burner FAR §25.853 flame test and tests measuring temperature at which self ignition appears, cannot be compared directly as tested shape and size are different, and since a flame of a more or less high intensity can be present or not. Still, just for information, self ignition temperatures of the present work, together with the ones reported by AIST [15], are compared with the maximum temperature measured during the full scale test in figure 13.

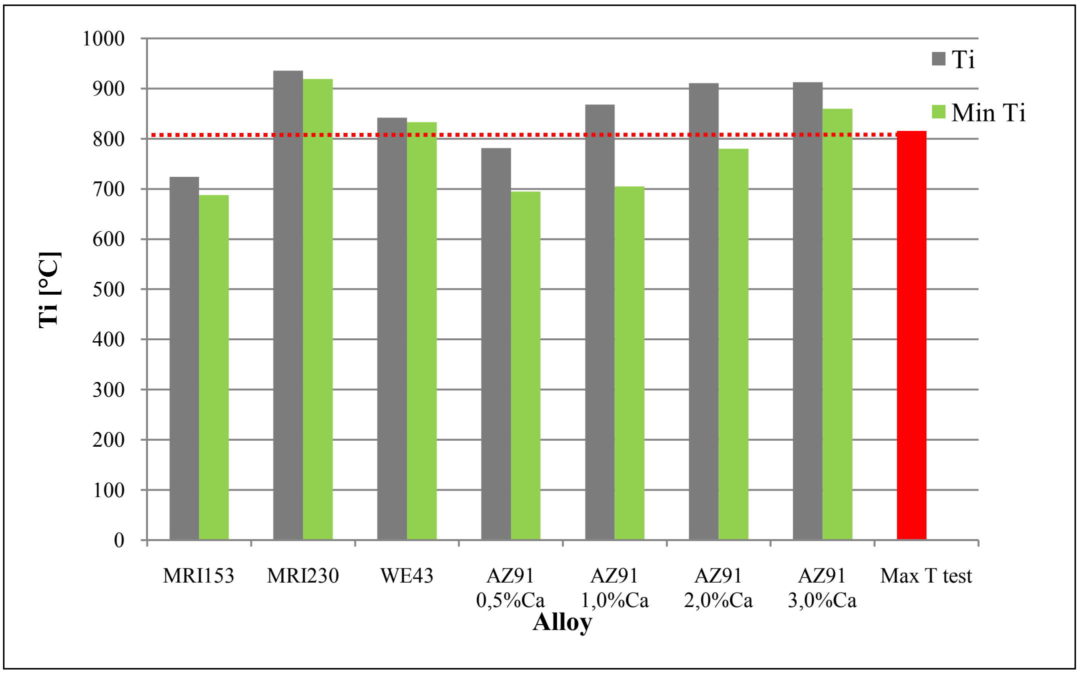


Fig. 13 Average and minimum measured ignition temperature of best-performing alloy compared with the maximum temperature achieved during the full-scale test

The red bar on the right represent the maximum temperature achieved in the full scale test, horizontal dotted red line is drawn to give a reference.

Blue bars represent the average Ti measured in tests, green bars the minimum observed Ti. Among all alloys tested, MRI230 shows the highest resistance; when it comes to commercially available alloys both MRI 230 and WE43 ignite at a temperature higher than the maximum temperature achieved during full scale test.

All testing done, confirms the important role of Calcium addition to improve the self ignition temperature, only alloys with more than 2% Calcium self ignite above 900°C. The observations made on MRI153, having a Ca content is between 0,75 and 1,2%, indicate that the lower performance could be linked to a more instable oxide layer as seen with the appearance of shiny point.

On the base of these ignition results, MRI 230 has been selected to be tested to the FAR 25-853. This test been expensive, validation has been limited to 6 mm sand cast plates Two specimens have been covered with the intumescent paint identified by Magnesium Elektron [20, 22],and one has been tested bare.

The bare plate started melting after 4’15’’, the painted ones after 4’45’’. None of them burnt after 5 minutes test, even at the molten state: both the coated and uncoated solutions were capable to meet the 5 minutes requirement.

CONCLUSIONS

FAA now reconsiders the potential use of magnesium in aircraft cabin. To insure that safety would not be reduced a specific validation for flammability is to develop. FAA has decided to proceed in two steps. The first test consists of testing magnesium samples according to FAR 25.853 with a target of no ignition after 5 minutes exposure time. Second step is to investigate full scale flame test behaviour on aircraft and eventually set standards and pass/fail criteria for magnesium.

Common die cast alloys, including some of the high creep alloys (AE44, AJ62) ignite at a temperatures much lower than the temperatures found during an aircraft fire.

Resistance to self ignition with temperature is best indicator for magnesium flammability resistance. Laboratory experiments confirmed that Calcium and Yttrium additions increase the ignition temperature of Mg alloys. Calcium addition is efficient starting from low concentration (0.5% in weight), addition above 2% do not further improve ignition temperatures.

Commercially available MRI230 (1.8 to 2.6% Ca) and WE43 (3.7-4.3% Y) alloys ignite at a temperature higher than the maximum temperature achieved during full scale test 815°C. WE43 burns at 840°C; MRI230 performs better with an ignition at 935°C.

When it comes to the burner tests [4] the 5 minutes target can be met.

WE43 was tested by Federal Aviation Administration Tech Centre with thicknesses of 11 and 15mm, and some of the 15mm thick samples passed the 5 minutes target.

Meridian and Sicma tested the MRI 230 to the same test standard with 6mm thick cast plates, bare and coated with an intumescent paint provided by Indestructible Paint Ltd. Bare MRI230 plate melted after 4’15’’, the painted ones after 4’45’’. None of them burnt after 5 minutes test, even at the molten state: both the coated and uncoated solutions were capable to meet the 5 minutes requirement.

FAA has decided to move to full scale testing on plane. For these tests, the selected alloy is WE43. The reason with FAA has selected WE43 and not MRI230 is unknown but may lay in the fact that prototype magnesium seats are easier and cheaper to manufacture by machining WE43, than by sand casting MRI 230. A full scale test has been carried out on Aluminium seat frames for reference in 2008 [23], the tests on magnesium are pending. After scale flammability tests, a simplified test and target could be defined to allow the validation of other Magnesium solutions.

ANNEX 3: CONCEPT OPTIMISATION

The review of the engineering of the part revealed that for some products, it might be interesting to try to design for functions using the minimum packaging space, but also optimizing projected surface area as it drives the machine size and hence transformation cost (see paragraph 5.3.2).

Meridian's Advanced Engineering department already applies an innovative method to optimize the design of the part by the use of advanced FEA software including the possibility of doing topology optimisation, free-size optimisation and shape optimisation [1].

After an initial shape is drawn, the optimisation work follows the steps below:

1. Achieving of NVH target (first vibration mode above a set target)
2. Achieving targets for quasi-static load cases (Tension, buckling, compression).
3. Achieving targets on dynamic load cases (insure no failure at a certain displacement or full scale done by the customer)
4. Optimization of local stiffness
5. Definition of interfaces with other subsystems of the vehicle
6. Prevention of galvanic corrosion issues.

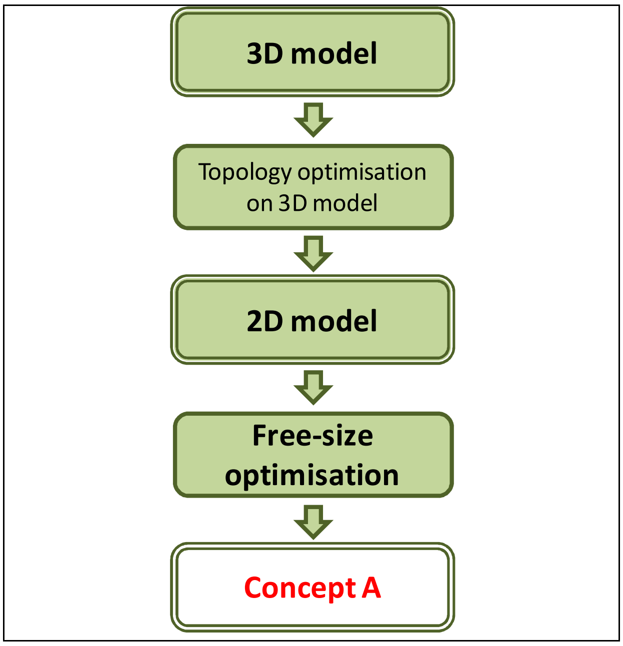


Fig. 1 Generation of the initial concept

The generation of the initial concept follows the stream shown in figure 1:

1. An initial shell (fig. 3) is modelled into the given space design (fig. 2). The thickness is set to a determined value and it is constant for the entire model.

2. A solid model is designed filling the initial shell.

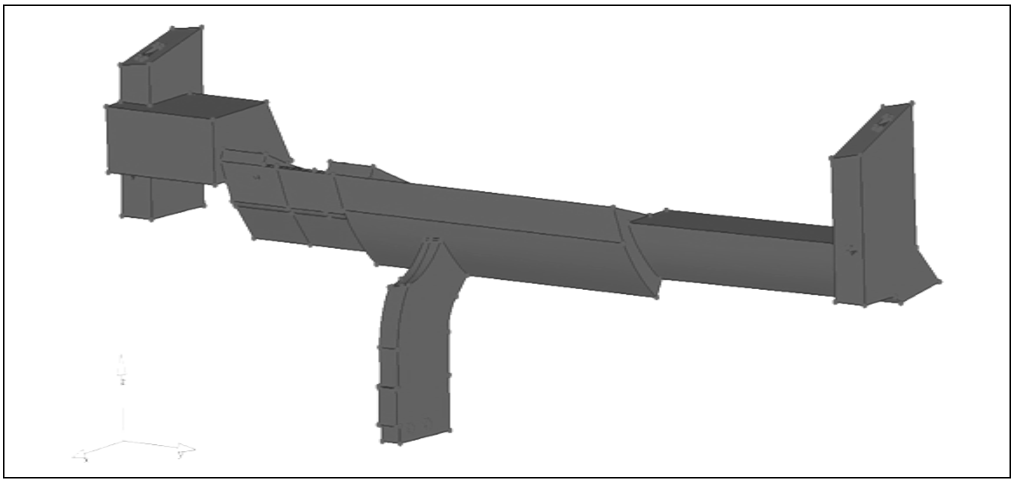


Fig. 2 Example of design space

3. A topological optimisation is run on specific load cases. The target is to minimise the mass respecting the constrains given by the load cases (minimum vibration frequencies, stiffness requirements...). The software is then removing mass where it is not necessary for the load cases.

4. The initial shell is reinforced with ribs positioned according to the results of the optimisation. An example is given in figure 4. The thickness of the ribs and the external shell is constant.

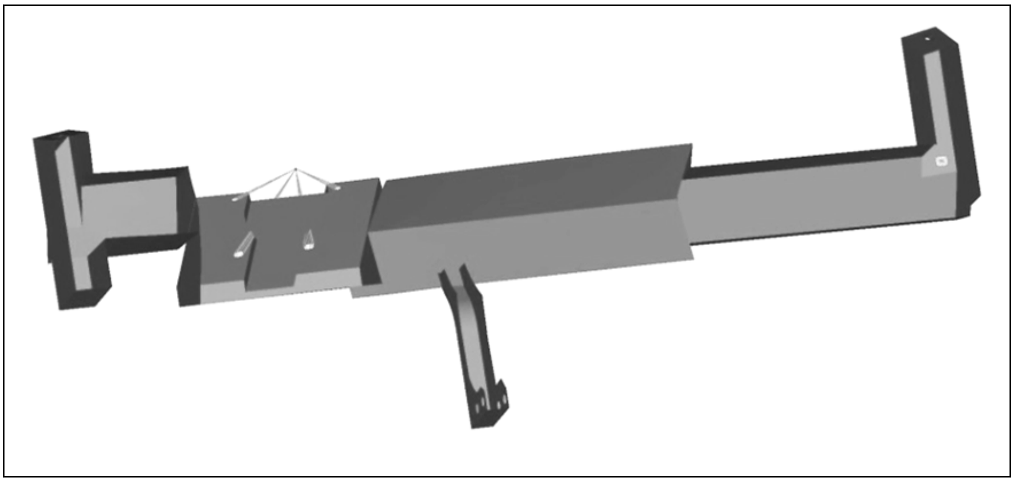


Fig. 3 Initial shell model

5. An optimisation on the thickness is then run. The target is to minimise the mass respecting the constrains given by the load cases. The output here will be the final model with different thicknesses dependent on the area.

It can be seen that hypothesis driving the shape and the size are then made right from the beginning of the design (before step 1) and usually the choice is to use the full space design provided by the customer.

The optimisation is currently done with the target of minimising weight with the advantage of reduce the amount of magnesium in the part Production costs are not been taken into account in this analysis.

The proposal is to try to design for functions using the minimum packaging space, but also optimizing projected surface area as this drives the machine size and hence transformation cost.

The decision has then be taken to consider new parameters when working on the initial concept, in order to work inside the space design and to evaluate the production cost due to the mass of the part and to the projected surface (which is bound with the size of the press to use).

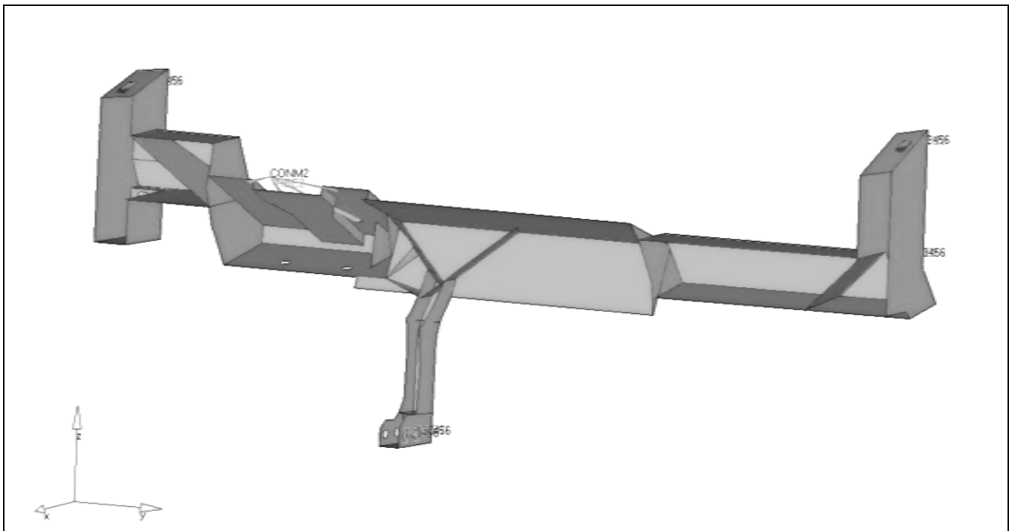


Fig. 4 Model reinforced with ribs according to topology optimisation outputs

The idea at the base of this work is to constrain the projected area to some levels in order to allow the component to be cast in a certain size machine.

For this analysis just the NVH has been considered as function to achieve. An IP has been selected as this type of component offers the highest level of knowledge of pre-requisites (mechanical characteristics).

Given the design space, shown in figure 2, one initial concept has been developed with the currently used method per reference.

Two other concepts have been developed constraining the projected areas to a level compatible with a 900 and with a 1500 Ton machines. This activity requires adding some steps before the normal procedure shown in figure1. It necessary first to generate a parametric 2D model, to implement a function measuring the projected area and to run a shape optimisation aimed at maximising the NVH within the area constrains by varying the parameters of the 2D model.

Figure 5 schematizes the adopted procedure. It can be seen that a shape optimisation is run before the current procedure shown in figure 1.

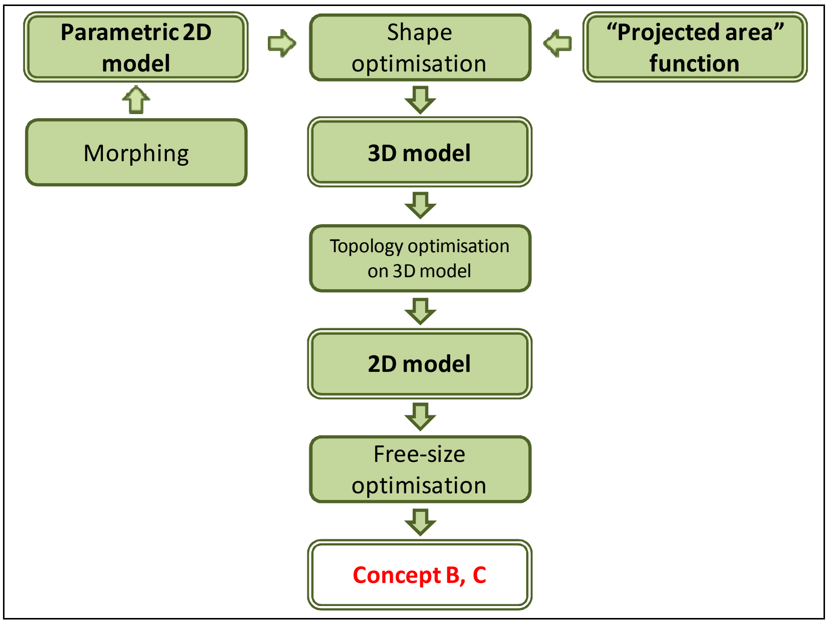


Fig. 5 Modified procedure for generating of the initial concept

The first concept has been parameterized using the z-coordinate of 12 nodes (see figure 6). The "projected area" function has been implemented (1) in the software and it has been used as project variable; in particular it has been set as constrain with different magnitudes in order to allow casting the IP in a 900 or in a 1500t machine.

(1) $$Area = f(a,b,c,d,e,f) = 56874 + 358a + 445b + 136c + 52d + 52e + 113f$$

Where: $a= x_1 - x_2$; $b= y_1 - y_2$; $c= z_1 - z_2$; $d= p_1 - p_2$; $e= w_1 - w_2$; $f= q_1 - q_2$;

and x_1, x_2, y_1, y_2, z_1, z_2, p_1, p_2, w_1, w_2, q_1, q_2, are the z-coordinates of the respective points.

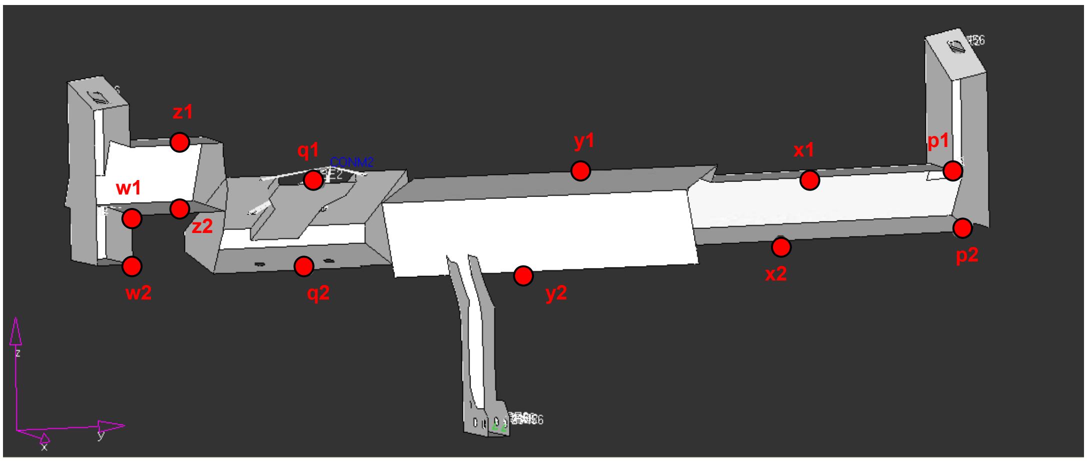


Fig. 6 Nodes on the concept for parameterisation

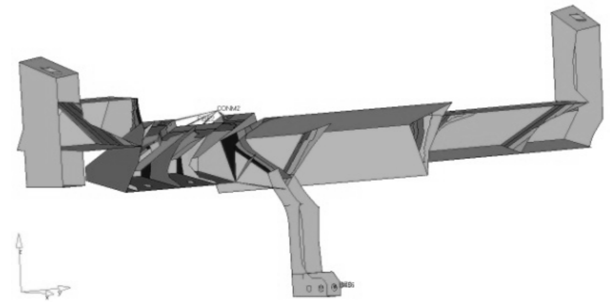
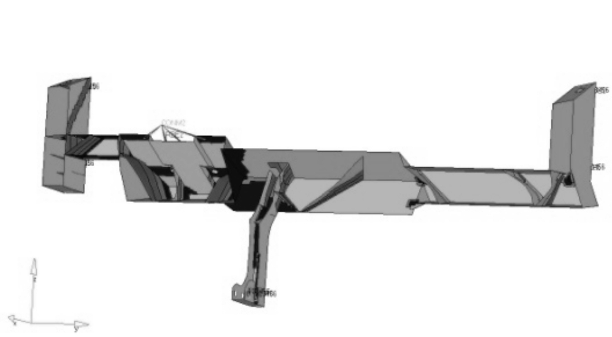
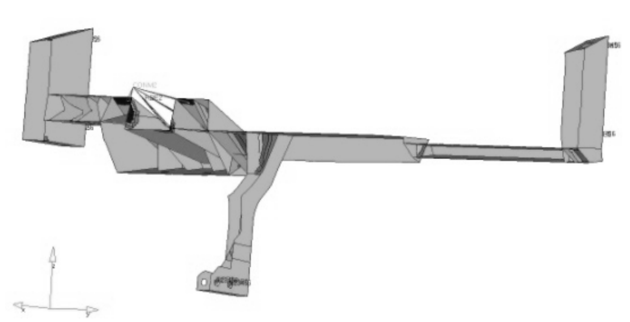
The optimization has been run with the target to maximize the modal frequency related to first vertical mode; this can be seen as an optimization of the function NVH described in chapter 5.

After this step, a 3D model has been generated and the normal procedure of topologic optimisation and free-size optimisation has been run. Table 1 reports the developed concepts: as a reminder, A is developed with the current method, B and C with the optimisation considering projected area and cost. B and C are based on the best response of the shape optimisation.

The base concept for calculation of cost is to separate the cost due to raw material and the cost due to process, including the amortization of the die cast cell. The cost of the raw material has been considered proportional to the mass and included also the cost of recycling runners and scrap and the melting cost. The production cost has been parameterized considering the mass of the component and the size of the machine to use that is, in turn, bound with the projected surface.

It can be seen how, for the selected optimisation target, the shape optimisation with constrains on projected area led to interesting results for both weight and potentially to cost savings allowing to use a smaller diecast machine.

Table 1 Results of the optimisation of concepts with different constrains on projected area

Concept		Weight [kg]	Area [mm^2]	Cost [€]
A		2.75	196351	20.83
B		3.03	150000	19.65
C		2.1	109000	15.15

Concept B is 10% heavier than the concept A but 6% cheaper. Concept C is 24% lighter than the concept A and 28% cheaper. Further analyses will have to be done to assess the effectiveness of this method taking into account all the load cases and integration of functions.

As a comment, the fact that a customer is likely to accept a cheaper but heavier solution will depend on how much he is ready to pay for weight saving. This fact depends on the value to the customer of weight saving, hence on the details of the business case which must be considered in any concept study evaluation.

It must be highlighted that other load cases have not been considered at this stage and that the necessity to achieve other targets will implicate an increase of the weight and, probably of the projected surface and the cost. In addition to that, the addition of other functions such as integration will certainly require adding some material. It is then not known of the initial potential achieved will then be affected when designing for the successive targets.

It must be said that this activity is time consuming and if the experimentation will succeed, it would be necessary to develop an automatic procedure, in order to extend the approach to all products.

More details on the cost model have been published in a Master Thesis in 2007 [2].

ANNEX 4: STATISTICAL PROCESS CONTROL

The parts manufactured today are challenging to cast, especially when considering that for such large parts the thickness is as low as 2,3mm. In such circumstances, scrap rate can sometime reach 12%. The use of DOE (Design of Experiments) has proven its efficiency to reduce scrap rate [1-3]. The principle of the method is to test a limited amount of specific combinations of process parameters. In simple cases these parameters are set at two levels (low or high). A statistical software analyses the scrap levels, across the tested combinations, defines the best set up of the process parameters and the expected scrap rate. In this section, the works aims as identifying the most efficient way to spread the use DOE for scrap reduction.

As a first step it should be understood which type of analysis has to be done on scrap to get the highest efficiency. A way of analysing scrap can be to consider every single defect and size, this could allow getting the better response from the optimiser, but it would be time consuming and difficult to apply over the production. Another analysis could only be based on fact that a part is good or bad, without considering if the defects are far above the standard, or if the part should be scrapped due to many defects. Though the optimiser's response could be not as efficient as per the first approach, the analysis would be less time consuming, hence easier to spread over the production. The two approaches will be compared to identify the most efficient one. To simplify this chapter, only the results will be given.

Once the method is defined, the objective is to apply it as widely as possible over the production. Die cast cells can both acquire process data and be monitored by computer. The idea is then to implement a tool that, once triggered on the machine, would set production parameter according to a factorial experiment design, to acquire the scrap rate for each of the runs generated, and to reset the process parameters to best configurations. The self adjustment would then be transparent in production. This approach implies to be able to trace back the process setting for each scrap part. In this work a marker has been installed in the diecast cell to engrave on every part a code related to the counter of the diecast machine.

General considerations have to be made when studying the scarp rate:

The defects analyzed are the visual defects induced by the shrinkage of the metal during solidification and the filling conditions. These defects are:

- Cracks
- Cold shots
- Lacks of fill
- Shrinkages

Inner defect are not considered in the quality check inspection. The influence of the inner defects produced in die casting has been quantified and properties have been modified accordingly. Design is then made with conservative data [4].

Visual defects change in size, but their nature and their localisation over the part remains the same. A part is a scrap if the defect appears and exceeds the size defined in the quality specification.

Generally, quality specification defines two types of areas on the casting, the critical and the non critical areas (for structural or cosmetic reasons). For each type of defect, different maximum sizes apply depending on the area.

Structural critical areas are usually the areas that need to be deformed in crash, these areas are the ones identified in FEA where yield stress is exceeded. In non critical areas, where the material remains in the elastic condition, it has been demonstrated that, to a certain extent, casting defects have no influence on the performance. Hence defects can be accepted in non critical areas.

The setting of the process parameters can change the percentage of occurrence of defects. It has been demonstrated that only one process parameter can change material properties [1, 2]. This parameter is the melt temperature. If this temperature is too low, pre-solidification of primary magnesium Alfa phase is produced and elongation is reduced. [1, 2]

Process parameter can then be adjusted to reduce scrap, as long as a minimum melt temperature is guaranteed.

The process parameters found to have an effect on defect formation are:

- Lube ratio
- Fast shot velocity
- Hot oil temperature
- Dwell time
- Metal temperature

These parameters interact strongly in the creation of defects. The factorial experimental plans are generated around current process values, and can be run without disturbing the production.

These considerations been made, the study on the type of analysis to consider (per defect, or good/bad part) and on the potential use DOEs on more die cast cells can be addressed.

The analysis has been done on a large scale DOE with a factorial plan set on 7 parameters; each parameter having two levels. The study has been done on the Alfa Romeo 159 IP, as this part belongs to the 4 components giving 80% of MPI’s turnover.

The following parameters have been taken into account:

- Melt temperature
- Die conditioning temperature
- Lubricant concentration
- Intensification pressure
- Second phase velocity

- Dwell time

The following system has then been generated:

- 32 combinations of process parameters;
- a minimum of 150 parts have been cast for each combination (4 hours of production)
- all the parts have been marked with an univocal code to insure traceability with the shot number and hence process parameters and side data recorded on the diecast cell
- one piece over 30 minutes has been taken for the analysis of defects (independently from the fact that it was good or scrap)
- all the parts have been recorded as good or scrap; trim defects were not considered
- every hour a thermograph of the die has been shot

Altogether 4897 part have been cast, 159 of them were scrap. The scrap rate ranged from 0 to 20%.

The analysis on defects has been done on the measurable output given below:

- % of scrap
- Average length, per defect, hence per location
- Maximum length, per defect, hence per location
- Total length per type of defects (sum of the length of all defects of the same type over the part)

These measurable have been further investigated mostly setting different filters to the minimum size to consider, and changing the size of the standard to lower or higher values.

At the opposite of previous studies, on this large scale study, the optimiser could not identify any process parameter having statistically significant effect, whatever the measurable considered. Further analysis showed that machine stops can actually affect the analysis. Machines stops above 1 minute have been identified as long enough to affect the thermal equilibrium of the system. It has been assessed that seven parts have to be cast after a stop to recover a steady condition [3, 5]. During the first seven shots after every machine stop, in fact, the system is not stable and the optimal combination of parameters could differ from the steady-state one.

It has been found that the scrap rate decreases when removing the start-up parts from the analysis up to the seventh shot; after that it stabilises. Optimiser is also giving a stable response if the first seven parts after every machine stop are removed from the analysis. In this way the steady state phase of the system has been optimised.

As a note, in that large scale study 13% of the parts have been cast between a stop and the successive seven shots; 25% of the scrap has actually been generated within these periods. The following considerations have then to be made:

- traceability is key to filter shots in order to understand if parts have been cast under thermal equilibrium conditions or in a start-up phase
- the response of the optimiser hence the expected scrap rate only applies to stable periods
- further analysis should be developed to address machine stops and start-up phases

The analysis done considering defects size could not lead to any satisfying optimisation. Whatever the measurable considered, if it is easy to optimise to process considering only one defect, process set up can completely differ if another defect is to address. In some cases, it has even been found that 2 defects of the same type, but appearing at different location would require opposite set up to be minimized. If 15 different defects are to consider, weighting the DOE response per defect becomes quite complex. The appearance of a defect is the result of both global conditions set by the process parameters, and of local thermal and mechanical conditions.

The approach using the scrap as a measurable has been found easier and more successful. The optimiser predicted a possible scrap rate at 0 %, while it was currently at 12%. It must be said that the 0% scrap prediction refers to a steady-state process. Due to machine stop the optimised set up led to scrap rate of 3,5% through a 3 days confirmation run.

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