# Innovation and Adoption of New Materials

By

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## Abstract

Many risks stand in the way of introducing a new material into the market place – some technical, some production related, some market oriented and some financial. Over the past 50 years, because of these risks, new material innovations have been commercialised almost exclusively by large corporations, and their development has had a long gestation period. If the risks can be estimated, quantified and managed at an early stage, and the risk-return is sufficiently financially attractive, then the gestation time of a new materials innovation is likely to be shortened. Tools exist for investigating aspects of these risks, but they were not originally developed with materials innovations in mind, nor have they been integrated into a coherent and accessible methodology which combines powerful predictive software tools with business strategy.

For these reasons, the investment methodology for materials (IMM) has been introduced and developed in this thesis. IMM is intended to help identify promising materials innovations at an early stage by adapting existing and emerging predictive tools to materials innovations and linking them to give a practical, comprehensive procedure. The viability of this methodology has been demonstrated both by testing some of its parts through exploration of innovation with light emitting polymers (LEPs), oriented polymers (OPs), and cast octet-truss (OT) structures, and – demonstrating the whole procedure – through a major case study of the introduction of metal foams into automobiles. IMM consists of three interwoven segments: viability, market forecasting and value capture.

IMM is aimed in particular at Small and Medium sized Enterprises (SMEs) which are attempting to commercialise a new materials innovation. Preliminary empirical evidence supports the hypothesis that the structure of the materials industry is changing such that SMEs can now drive a major materials innovation. The most important elements of this change – greater inter-firm connectivity and trends towards collaborative work – have reduced existing barriers to SMEs by improving access to capital and by making it easier to scan the marketplace for suitable applications. It is envisioned that IMM will assist SMEs in obtaining financing to commercialise new materials innovations and/or to refocus their efforts.

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# 1 Introduction

## 1.1 Innovations in the Materials Industry

The commercialisation of technical inventions over the last century has led to an enormous increase in the number of materials and a significant reduction in material production costs. The family of plastics, spurred by numerous material innovations, has been born and grown to a major materials family, enabling or altering products such as: gas pipes, car interiors, packaging and housing for appliances. The traditional material for most of these - steel - has also undergone many developments and innovations, spawning classes such as the high strength low alloy (HSLA) steels and polymer coated steels. Steel remains, by virtue of it high strength, ductility, toughness, and low price, by far the dominant material of engineering. The phenomenal growth of the global production volume of steel,[1] has been driven both by performance enhancements and by dramatic process cost reductions: the cost of structural steels has halved over the past decade.[2] Innovation within traditional materials has also enabled increased energy conversion efficiency, the longer life and lower maintenance requirements of automobiles, and a 10,000-fold improvement in the functionality of silicon computer chips.[3]

High performance or advanced materials[4] are considered a strategic industry for national wealth creation.[5,6] The development and commercialisation of GoreTex™, Kevlar™, FiberGlas™, and carbon-fibre reinforced plastics (CFRPs) has changed the face of the sporting world. Other new materials innovations, such as optical fibres (communications), compound semiconductors (computers and communications), Liquid Crystalline Polymers and Light Emitting Polymers (flat-panel displays), oriented high-strength polymers (light body armour), and hard and soft magnetic materials (motors, power conversion), have emerged, although they have yet to rival the traditional materials in sales volume. Future developments in smart materials and nanotechnologies are anticipated as a new wave or "revolution" in the economy, after the information economy and the bio-economy have run their course.

Two major hurdles must be surpassed in order for a materials innovation to become commercially successful. The first is that of *technical invention*, defined by Freeman as "an idea, a sketch or model for a new or improved device, product, process or system" which must be brought to a first commercial introduction. This might be accomplished by an established company with a large R&D organisation or by a small, entrepreneurial organisation, perhaps forming a company solely focused on the invention. Second, the *innovation*, here defined as "an invention that has been commercially introduced," must go through a process of diffusion into the marketplace, in which the innovation either displaces current materials or processes or enables the creation of new applications.

The title of this thesis is "Innovation and Adoption of New Materials" and I refer often to the "materials industry". The materials industry is here considered to be all companies engaged in the development and commercialisation of new materials. Several industrial sectors belong to this industry, including companies classified as being within the plastics, synthetic fibres, rubber, metals, advanced materials, new materials, engineering plastics, synthetic materials, advanced ceramics, and electronic sectors. The use of this grouping can be justified by considering the factors these companies have in common and the grouping of similar companies in studies such as those by MERIT- CATI[7] and the OECD.[8] Factors common to companies in the materials industry include: high knowledge intensity; significant R&D expenses; production of an intermediate, non-assembled product; need for substantial investment in production facilities; need to interact with designers of downstream companies; ability to protect innovations with patents; economies of scale; and, in many cases, common buyers.

## 1.2 Push-Pull Theories of Materials Innovation

Theories of successful routes to technical innovation are divided into science-push and demand-pull theories.[9] Science-push advocates cite examples such as the laser, nuclear power, personal computers and compact-disc recorders as proof that the market has little if any role in evaluating new products of which it has no knowledge and for which it cannot envisage applications. For these types of revolutionary innovations, if development was contingent on market assessment, the innovations would never have been brought to market. On the other hand, demand-pull advocates cite innovations such as synthetic rubber, chemical cracking processes and photo-destruction of plastics as examples of inventions developed to respond to a clearly defined market need.[10] Rothwell and Zegveld proposed a coupling model which shows an idealised form of interaction between science push and demand pull in the development of technological innovation (figure **1.1**[11]). Most materials innovations fall somewhere between these two extremes, but are biased toward science-push. Materials innovation has been hindered in demand-pull strategies by the lack of predictive power when attempting to create a new material. Emerging knowledge of the linkages between microscopic and macroscopic material properties and the development of software to exploit this knowledge is already beginning to alleviate this shortcoming.

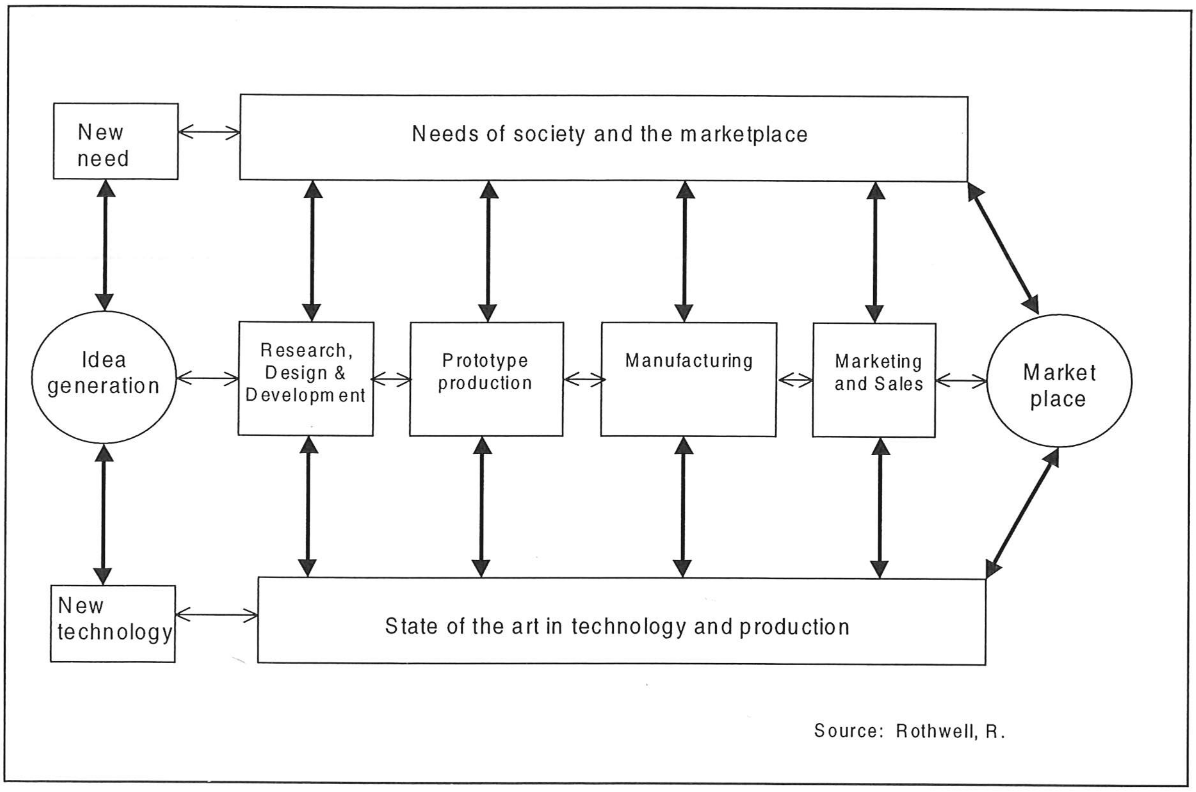



**Figure 1.1: Rothwell's 3rd Generation Coupling Model**[11]

## 1.3 Slow Adoption of New Materials

Innovation in new materials has been characterised by a long gestation period between the technical invention and the first commercial application, and a long substitution period between the first commercial application and the widespread use of the new material. As an example, polyethylene was developed in 1933, a pilot plant was built in 1938, but applications beyond insulation and radar housing did not appear until the 1950s. In fact, production of polyethylene was almost suspended after the Second World War because it was thought peacetime demand would be too low.[12] Today, polyethylene is the most widely used plastic, with annual global production of 130 billion lbs.[13] Another example is that of Sheet Moulding

Compound (SMC), a composite of thermoset plastic resin, chopped glass fibres, and filler material, invented in 1953, not commercialised until 1970, and currently fighting substitution battles in automotive, construction, and appliance markets.[14] Further examples can be found in the substitution histories of such material innovations as Metglasses (amorphous metals), Metal Matrix Composites (MMCs), technical ceramics for mechanical applications (SiC, $Si_3N_4$), and - with the outcome still uncertain - warm superconductors, metallic foams, oriented polymers, and amorphous semiconductors.[15]

Figure **1.2** depicts the adoption rates (by volume) of several materials,[16] with first commercial introduction represented by a time of zero years. This graph confirms the slow rate of industrial adoption of new materials. By the comparatively rapid adoption of synthetic rubber and fibres, the data suggests that the adoption rate is largely influenced by the matching of new technical capabilities with market opportunities. The comparatively rapid adoption rate of synthetic fibres and synthetic rubbers (figure **1.2**) might be attributed to very similar material properties, aesthetic, and manufacturing methods to those of the replaced natural materials.

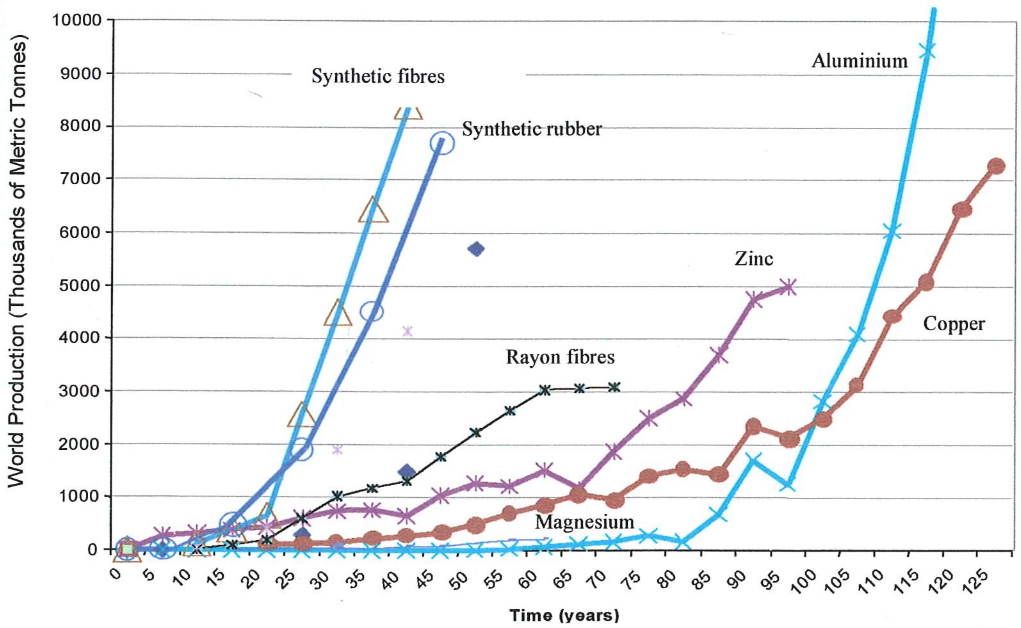



**Figure 1.2: Adoption Rates of New Materials[13]**

When most new materials are created, they have entirely new performance parameters and manufacturing requirements, and there is a long gestation period between the technical understanding of the new materials and the commercial take-up[17] (see figure **1.3**). The research into the developmental material grows rapidly, and then slumps when little interest is shown by industry in using the new material. On a longer time scale (15 years) applications slowly emerge. Early formation of design rules, research targeted at characterising the most useful properties, and demonstrator projects have been proposed as ways to shorten the gestation period.[18]

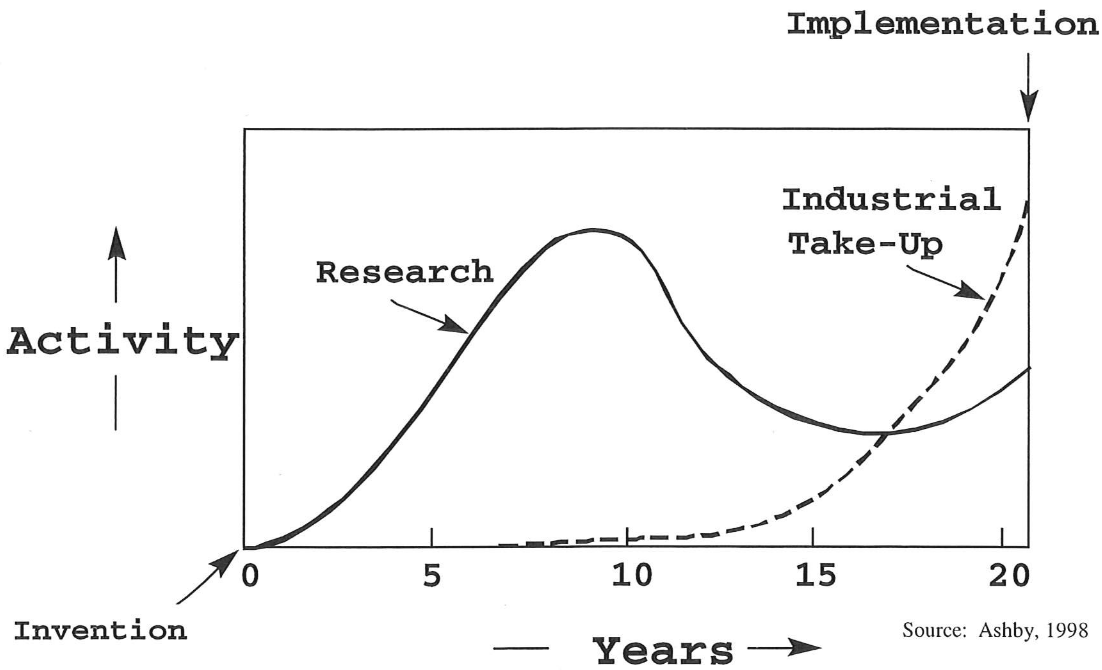
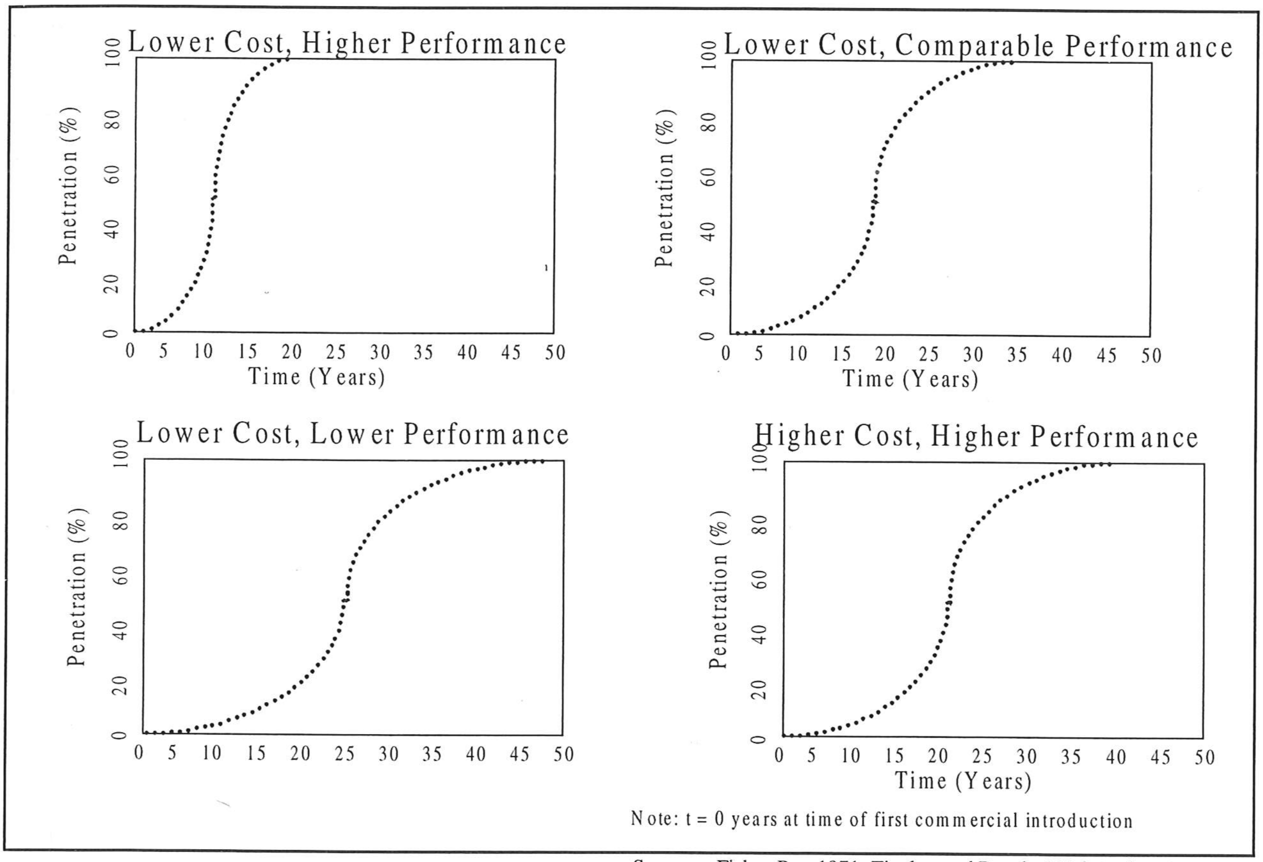



**Figure 1.3: Gestation Period of New Materials**

The length of the gestation and substitution periods of new material innovations can be effected by many factors, including an initially high cost invention, cost barriers to materials substitution from entrenched materials, and, often, insufficient knowledge of market applications by inventors. The substitution period, which is the period of time between first commercialisation and 50% substitution into an established application, can be 20 years or more (figure **1.3**).[19] It is generally believed that the substitution period correlates with price and performance characteristics.[20] Figure **1.4** depicts the substitution curves of four successful combinations of price and performance characteristics: lower cost and higher performance, such as PVC window frames substituting for aluminium window frames; lower cost and comparable performance, such as PVC plumbing pipes substituting for copper pipes; lower cost but lower performance, such as oriented strandboard replacing plywood; and, higher cost but higher performance, such as carbon fibre composite boat hulls replacing wooden hulls. Examination of figure **1.4** reveals that, even for high performance, low price substitutions, there is still a significant substitution time lag. Whether this period between first commercialisation and widespread diffusion can be shortened is of great interest to both economists and engineers concerned with innovation.




Sources: Fisher-Pry, 1971; Tincher and Busch, 1996; Maine, 1997

**Figure 1.4: Types of Substitution Curves for New Materials**

We surmise that this long gestation period is partly due to a mismatch between designers' and entrepreneurs' understanding of market needs and the development of new materials for various applications. This mismatch is exacerbated by the many layers of separation between material and end consumer. Freeman likens the market push and technology pull of technological innovations to a pair of scissors: together, the parts work efficiently; separately, they don't work at all. He writes:

> "Innovation is essentially a two-sided or coupling activity. It has been compared by Schmookler to the blades of a pair of scissors, although he himself concentrated almost entirely on one blade. On the one hand, it involves the recognition of a *need* or more precisely, in economic terms, a *potential market* for a new product or process. On the other hand, it involves technical knowledge, which may be generally available, but may also often include new scientific and technological information, the result of original

research activity. Experimental development and design, trial production and marketing involve a process of '*matching' the technical possibilities and the market.* The professionalism of industrial R&D represents an institutional response to the complex problem of organising this matching, but it remains a groping, uncertain process."[21]

Assuming this matching process is a bottleneck in the diffusion of a materials innovation, a methodology to facilitate the matching of technical possibilities with the market could be of use in shortening the gestation period of materials innovation and substitution.

Adoption of new materials innovations is also slowed by strategic corporate decisions at the firm level. Much of innovation in materials industries has been developed and commercialised by large enterprises with structured R&D strategies. These organisations generally follow some sort of portfolio management system in order to diversify risk in the R&D projects that they fund and develop. However, due to flawed R&D valuation methodologies, the desire to match R&D tightly with current core competencies, and the reluctance to cannibalise current business, some potentially profitable materials innovations are passed over by large enterprises.[22] Small enterprises have faced financial barriers to entry in commercialising a materials innovation over the past several decades, since R&D, manufacturing equipment investments, market information, and distribution channels all benefit from the scale economies of the large materials companies (see table **2.1**).

## 1.4 Forces of Change in the Materials Industry

New materials are developed because of forces for change at the material, product, consumer, and environment levels, whereas the commercialisation of materials innovations is predominantly influenced by forces at the organisation level (table **1.1**).[23] At the material level, a change in material attributes, such as the development of a lower cost or higher performance material, often initiates the drive to commercialise a materials invention. At the product level, a change in design requirements can lead designers to consider developing a new material for their application. At the consumer level, a new material could be developed or a material exploited in a new market in response to evolving market needs. At the environment level, macroscopic shifts in national and international perceptions and standards can alter product specifications or consumer demands. Lastly, at the organisation level, changes in industry structure, barriers to entry, or risk/reward positioning of an innovation can drive the development and commercialisation of a new material. It is at this level that the greatest changes have occurred in the past decade.

Organisational forces for change have such a profound effect because a materials innovation impacts a broad range of end-products and because materials are removed from end consumers by many vertical industry layers. Forces for change at an organisational level could impact both the size of company that can successfully drive a materials innovation and the gestation period of materials innovations.

| **LEVEL OF ABSTRACTION** | **TYPE OF CHANGE** | EXAMPLE | COMMENT |
|---|---|---|---|
| **MATERIAL** | **Change in material attributes**<br>(science push and market pull) | Improved processing.<br>Improved material.<br>New material.<br>Change in availability. | Lower cost and/or improved material<br>Improved material (subsequent processing remains unchanged)<br>Requires new processes and design methods<br>Banned or restricted supply changes relative costs between substitutes |
| **PRODUCT** | **Change in design requirements** | Change in real performance.<br>Change in perceived performance.<br>Product based environmental legislation.<br>Sector maturity. | A lighter, bigger, hotter, more reliable, more efficient, cheaper<br>Add caché, high tech or glam image<br>Lightweighting, energy efficiency., disassembly, recycleability, sustainability<br>Industrial design considerations replace technical considerations |
| **ORGANISATION** | **Change in industry Structure**<br>**Change in barriers to entry**<br>**Change in level of risk required to drive innovation in the materials industry** | Globalisation & Collaborative work<br>Information technology & Predictive tools | SMEs can commercialise a materials innovation, due to reduced effective barriers<br>Manageability of vast amounts of information, along with the development of predictive tools, are changing the way that commercialisation of new materials will occur |
| **CONSUMERS** | **Evolving Market Needs / Wants** | Market desire for a new performance attribute that can be met by an existing material | Established technology applied to new applications in new markets in response to consumer needs (eg. Teflon for frying pans) |
| **ENVIRONMENT** | **Change in perception of goods and services** | Consolidation of consumer society.<br>Dematerialisation. | Replacement of goods by services.<br>Miniaturisation.<br>Developed countries no longer manufacture, but may innovate and develop |

**Table 1.1: Forces for Change in the Materials Industry[23]**

## 1.5 Hypothesis of Thesis

The starting point of this thesis is the following hypothesis, which we seek to confirm or dispute by systematically exploring its implications. It is that organisational level forces have changed significantly in the past decade with the advancement of the capabilities and utilisation of information technology. The structure of the materials industry is changing such that small-and-medium-sized enterprises (SMEs) can drive a major materials innovation today, where they have not been able to do so for the past 50 years. The major elements of this change have been greater connectivity, trends towards collaborative work, and the development of predictive software tools, which are discussed in further detail in section 2.1. These changes have affected many aspects of the process to commercialise materials innovations, including the interaction between the market and design of new materials, the ability of designers to select new materials, the early stage possibility of predicting material viability, and the financing options open to organisations. This hypothesis is developed and tested in chapter 2.

## 1.6 Goals of Thesis

This thesis has three goals. Firstly, I aim to explore the dynamics of the materials innovation process and the current barriers to commercialisation. Secondly, I attempt to highlight the shifts in the structure of the materials industry that could lead to SMEs commercialising key materials innovations in the future. Finally, and most importantly, I introduce and demonstrate a methodology (IMM) designed to help identify promising materials innovations at an early stage.

Key barriers to materials innovation currently are: "long lead times to commercial exploitation…; the requirement for overall very high levels of investment; user reluctance to use new materials without knowledge of performance over long time-periods; a complex innovation environment with a wide range of different agents involved, since materials are largely intermediate goods which downstream have to be further converted to products."[24] All of these barriers can be reduced to difficulties in accessing capital and poor information flow between materials innovators and engineering designers. Any method of reducing the time period between invention, first commercial introduction, and significant marketplace adoption of a new material, would give the company driving the commercialisation of the new material many more financing options due to the shorter payback time.[25]

A materials invention can sit on a side burner for many years as it gradually gains acceptance into mainstream applications (figure **1.3**). A viability assessment such as the one presented in this thesis could shorten the gestation time of new materials innovation through the provision of a staged vetting method for the new material, in the mould of the approval stages for new drugs in the pharmaceutical industry. FDA approval is a major vetting stage for pharmaceutical companies and investors, providing them with an opportunity to discontinue research or enhance investor confidence. Similarly, the stamp of approval of credible technical and economic forecasters could provide a staged investment approach for venture capital companies considering investment in new materials innovations.

Engineering designers have many materials and processes to consider for every component, and will not invest much effort in looking at a materials innovation without solid evidence that it will have a strong performance or a cost advantage for the product that they are designing. There is merit in seeking a methodology which could help materials innovators to identify potential market niches more quickly and to communicate both technical and economic attributes to engineering designers: it could shorten the time lag of materials invention and innovation to industrial diffusion.

## 1.7 Overall Perspective and Scope.

The target set at the start of this PhD program was that of formulating *an overall strategy and methodology to guide innovation with new materials.* To achieve this I have sought to identify each essential step in the progression from the scientific demonstration of technical promise of a new material to its final, successful, commercial exploitation. The steps are explored, seeking strategies for dealing with each and examining the nature of the interaction between them, with the ultimate aim of integrating them into an overall methodology. Some aspects of these strategies are new, others are drawn from general, existing, tools for business planning and strategy. The novel contribution of this thesis is their adaptation to the specialised task of material innovation, and their assembly into a methodology, the use of which is demonstrated.

The emphasis throughout is on *breadth* and *integration.* The successful exploitation of a new material requires assessment of its technical potential, of the cost involved in realising that potential, and of the value the market attaches to the

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The emphasis throughout is on *breadth* and *integration.* The successful exploitation of a new material requires assessment of its technical potential, of the cost involved in realising that potential, and of the value the market attaches to the achievable technical performance. The investment required for commercialisation is influenced not only by this trade-off between performance, cost and value, but also by other aspects of the market (its size, its rate of growth) and on considerations of value capture (IP protection, vulnerability to competition or substitution and overall appropriability). IMM, developed here, is a tool for identifying critical points in this path. Throughout, information has been acquired, and ideas tested, through field-studies. Inevitably, in a project as broad as this, the field-studies are limited – the exhaustive field-studies that would help refine the approach lie far beyond the scope of a single PhD research program (though I hope to pursue them further in the future). None the less, the field-studies of individual steps and the major case study – that of the commercialisation of metal foams, a new class of materials – amply demonstrate the potential of the approach.

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[4] as defined in Williams, 1993. p.7

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[6] Williams, 1993. pp.11-12

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[8] Organisation for Economic Co-operation and Development

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[11] Dodgson, 1994

[12] Freeman, 1982

[13] CMAI, Nova Chemical Investor Relations presentation at http://www.nova.ca/InvestorRelations/presentations/Investor_Relations_Sep_1999/OPO_Business_Strategy/sld005.htm

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[15] discussions with M.F. Ashby

[16] compiled by E. Maine, from a variety of sources including:
Cahn and Bloor, 1994; Freeman, 1982, p.48; London Metal Exchange, http://www.lme.co.uk; The Society of the Plastics Industry, http://www.socplas.org; Association of Plastic Manufacturers in Europe, http://www.apme.org; IISI, http://www.worldsteel.org; Cominco website, http://www.cominco.com; Financial Times website, http://ftdiscovery.ft.com;

[17] Williams, 1993

[18] Ashby, 2000

[19] Tincher, 1997.

[20] Tincher, 1997.

[21] Freeman, 1982

[22] Neely, 1998.

[23] developed by M.F. Ashby and E. Maine in 1999

[24] Wield and Roy, 1995. p. 199

[25] discussions with ADL, CRIL, and 3I

# 2 Changes in the Commercialisation of Innovations in the Materials Industry

## 2.1 Literature Review: Effect of Firm Size on Materials Innovation

There is no consensus as to the effect that the size of a firm has on success in technological innovation across industries. Galbraith and several other economists strongly believe that large firms with established R&D organisations are the optimal vehicle for developing technological innovations. It is argued that only large firms have the technical manpower, information gathering ability, management techniques, financing strength, and ability to deal with government regulations that enhance the success rate of innovation.[1] However, another school of thought sees small firms as the more efficient vehicle for invention and innovation[2] and draws on examples in the electronics, scientific instruments, and computer software industries to back up their theories.[3,4] Rothwell proposes that small firms have advantages in innovation in the areas of flexibility in marketing, flexibility in reacting to technological change, entrepreneurial management, and good internal communication.

Utterback argues that radical innovations are much easier for new firms in an industry or established firms entering a new arena to commercialise than for established competitors in an industry. His argument is that established competitors in any mature industry need to be specialised in their equipment, components and skills: "Thus change in one element, the product, requires changes throughout the whole system of materials, equipment, methods, and suppliers."[5] For this reason, large, established players are unlikely to lead the development of a technical innovation that will shake up their existing business.

Figure **2.1** shows that SMEs have played a significant role in the development of major innovations globally, being responsible for 45% of the major innovations studied. However, this macro level analysis does not give any insight into the types of innovations which SMEs are successful at developing. Rothwell and Zegveld believe that whether small firms are best suited for developing innovation is specific to the technology of the innovation and is strongly dependent on the structure and requirements of the marketplace: "Small firms are therefore unlikely to play an important part in innovation where capital costs are high and where large scale economies are necessary, but may play a significant role in highly segmented markets for specialist products."[6] Table **2.1** summarises the respective strengths and weaknesses of small and large firms with regard to their suitability for developing and commercialising a technological innovation.

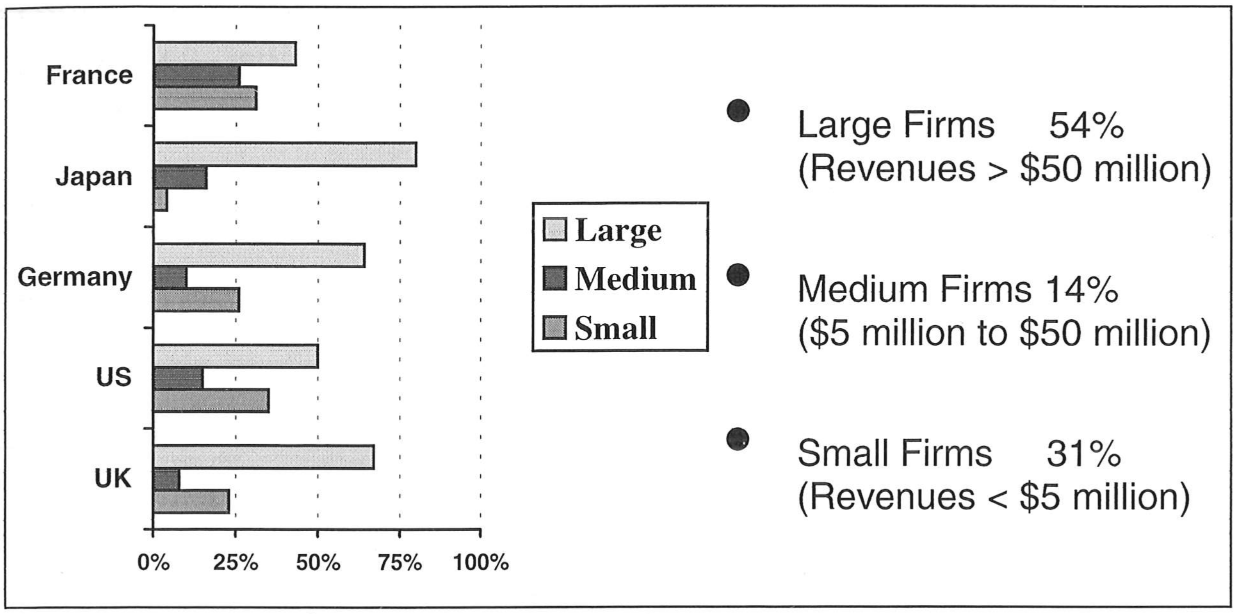


**Figure 2.1: Major Innovations Commercialised by Small, Medium, and Large Firms**

There is, however, a consensus that the impact of firm size on the commercialisation of innovation is industry specific.[7,8,9] Freeman, in a survey of UK innovations from 1945-1970, found that small firms had a negligible contribution to innovation in (among others) the steel, glass, aluminium, synthetic resin, and cement industries.[10] Since the development of mass production manufacturing of materials at the beginning of the 20th century, large barriers to entry have been erected which have effectively meant that only large firms could successfully drive a materials innovation. SMEs generally haven't had the scanning ability that comes with substantial marketing and R&D departments, the capital to scale up manufacturing, the customer and distribution networks to test product concepts and enter the market, or the financial resources to withstand a long payback period (see table **2.1**)

Changes effected by the development and widespread use of information technology and the trend toward collaboration in R&D may have altered the dynamics of innovation in the materials industry. Information technology has enabled scanning the market and R&D literature without a large marketing or R&D department. The ability to manage vast amounts of information has given rise to the development of database scanning and matching software, and the development of predictive tools to link microscopic material properties with macroscopic market needs. Based on these changes, Rothwell has proposed a "fifth generation" innovation process[11] which is essentially the process depicted in figure **1.1** with the addition of systems integration and networking (SIN), allowing for substantial shortening of the time required for an innovation to be commercialised. In addition, the reduction of the "transaction costs" associated with collaborative work due to advances in information technology, has been a major driver in the recent trend towards collaborative R&D and is "having an increasingly important impact on the structure of firms and industries."[12]

| | SMEs | Large Corporations |
|---|---|---|
| CONs | Inability to access capital for large, capital intensive innovations | Corporate bureaucracy and slowness. |
| | No reputational clout for partnering | Lack of motivation / purpose. |
| | Inability to scan the market and technical opportunities with broad R&D and marketing departments | Unwilling to cannibalise existing product offering. Specialisation |
| | Long gestation time of materials innovation endangers cash flow disproportionately | Internal communication often poor |
| | No existing distribution system or customer base | Constraints created by need to satisfy shareholders |

**Table 2.1: SME Disadvantages Versus Those of Large Corporations in Commercialising Materials Innovations**

Collaborative R&D partnerships have also reduced the barriers to entry in the commercialisation of new materials. The entire number of technology co-operation agreements in the materials industry has grow rapidly since the 70s[13] and R&D alliances have tripled in relative importance to that of other forms of inter-company alliances since the 80s.[14] In a survey of 12 large materials innovating companies in the UK, every company was found to be increasing their formal collaborations with other organisations.[15] Freeman believes that technological complementarity and the desire to reduce lead times have been the dominant motives for these collaborative materials technology R&D partnerships to be formed.[16] The technological complementarity driver leads to SMEs becoming more desirable collaboration partners in developing materials innovations. And the partnerships are valuable to SMEs because of the access to capital for development and the reduction of lead times for product applications.

Further literature review, covering the broad areas of the methodology, is contained in sections 3.2 and 3.3.

## 2.2 Methods of Testing Hypothesis

The hypothesis that SMEs can drive a major materials innovation today, where they have not been able to do so for the past 50 years is tested through a deductive approach. Deductive research methods start with a conceptual structure (a "hypothesis" which is often developed through informal observation), translate those concepts into observable variables, and test the hypothesis through empirical observations.[17] By contrast, inductive research approaches begin with formal observations of the empirical world, followed by a selection of relevant variables from those observations, and finish with the development of a hypothesis.

Deductive approaches range from the true experimental, to the quasi-experimental, to action research (see table **2.2**). This research is quasi-experimental, and conducted by the use of a structured questionnaire and case based interviews. The theoretically dependent variable is the environment for successful commercialisation of a materials innovation. This variable can be operationalised, or made observable, through such measurable variables as company revenue, market share growth, or profits, and can be more qualitatively operationalised through survey answers. In this initial survey, all respondents are asked whether the environment for commercialising materials innovation is better today than it was a decade ago.

The theoretically independent variables, which are meant to explain the variance of the dependant variable, include the development of information technology, the greater connectivity of companies due to internet, email, and networking, trends towards globalisation, collaborative research, outsourcing, and the development of predictive tools. The observable measures of these independent variables are summarised in table **2.3**. These independent variables were chosen through literature review, discussions with industry experts, and a brainstorming exercise. Lastly, some controls are made to isolate extraneous variables. In this case the main extraneous variables are the size of the company and the industry, as the hypothesis is concerned with SMEs in the materials industry.

| **True Experiments** | **Quasi-Experiments** | **Action Research** |
|---|---|---|
| Entail the analysis of the direct intervention of the researcher | Entails the analysis of events that have naturally occurred without the intervention of the researcher, i.e. after the fact | Entails the analysis of the direct interventions of the researcher |
| Incidence of the independent variable due to the manipulation of the researcher | Incidence of the independent variable occurs naturally | Incidence of the independent variable is constituted by the actions of the researcher |
| Entail pre- and post- treatment, measurement, and comparison of the dependent variable in both the experimental and the control groups | Entail pre- and post- treatment, measurement, and comparison of the dependent variable in both the experimental and the control groups | Entail pre- and post- treatment, measurement, and comparison of the dependent variable in the experimental group. Availability of an equivalent or non-equivalent control group problematic according to the context of the research |
| Entail physical control over extraneous variables through assignation of the subjects to equivalent experimental and control groups | Since analysis entails naturally occurring events, prior assignation of subjects to control and experimental groups problematic. Instead, control and experimental groups are identified in terms of the incidence of the independent variable and cannot be exactly matched | As the incidence of the independent variable is constituted by the actions of the researcher prior identification of control and experimental groups is sometimes possible. However, their full equivalence problematic since such groups are usually naturally occurring |
| Strengths<br><br>High internal validity | **Strengths**<br><br>High ecological validity. Avoids problems associated with experimental artefacts; can have high population validity | **Strengths**<br><br>Can be very high in ecological validity. Can avoid problems associated with experimental artefacts |
| Weaknesses<br><br>Low ecological validity; often population validity is limited | **Weaknesses**<br><br>Loss of control over extraneous variables | **Weaknesses**<br><br>Population validity limited to those subjects involved; loss of control over extraneous variables |

**Table 2.2: Range of Deductive Research Approaches** (Gill and Johnson, 1997)

| VARIABLE TYPE | VARIABLE | OBSERVABLE |
|---|---|---|
| Theoretically dependent | Better placed to successfully commercialising materials innovation than a decade ago | revenue, market share growth, profits, survey answers |
| causal or explanatory | development of information technology | Survey answers |
| | Greater connectivity | Survey answers |
| | globalisation | Survey answers |
| | collaborative research | Survey answers |
| | predictive tools | Survey answers |
| | Outsourcing | Survey answers |
| extraneous | industry | Advanced materials industry |
| | size of company | Small company |

**Table 2.3: Variables for Testing Hypothesis**

## 2.3 Survey and results

The initial survey conducted to test the hypothesis involved companies which we had already been involved with in case study analysis. The materials innovations of the five companies chosen are summarised in table **2.4**. The questions asked of these companies can be found in Appendix A. In all cases, the respondent was a senior executive in the company and well placed to understand and accurately answer the questions posed. General information was gathered about the company's size, location, targeted industry sectors, type of material innovation, and percentage of the company dedicated to that innovation. Next the respondents were asked "Do you believe that your company is better placed to successfully commercialise your materials innovation today than you would have been a decade ago?" In every case,

| Company | Innovation | Applications |
|---|---|---|
| A | Foamed Aluminium | Automotive energy absorption,<br>Heat dissipation<br>Lightweight structural |
| B | Foamed Aluminium | Loading pallets<br>Lightweight structural |
| C | Octet Truss<br><br>Proprietary database | Lightweight structural<br>Translating market needs into the development of new materials |
| D | Light Emitting Polymers as diodes | Flat panel displays for TVs, mobile phones, computer monitors |
| E | Oriented Polymers | Synthetic hardwood flooring, drumsticks |

**Table 2.4: Companies Surveyed in Quasi-Experimental Hypothesis Testing**

the answer was "yes." Lastly, respondents were asked to identify factors affecting the more successful commercialisation of materials innovations, corporate areas where these factors had impact, and changes in barriers to materials innovation.

The factors effecting successful commercialisation of materials innovations (see table **2.3**) were chosen to be the development of information technology, greater connectivity, trend towards globalisation, trend towards more collaborative research, development of predictive tools, and the trend towards outsourcing. The development of information technology refers to such tools as information scanning software, distribution systems, and the ability to handle large amounts of information. Greater connectivity refers to the development and proliferation of the internet, of emailing as a quick, informal, and convenient means of communication, and the development of networked communities. Globalisation is meant as the internationalisation of companies and the lowering of trade barriers. The trend towards collaborative work is referring to the formation of R&D alliances and distribution alliances. Predictive tools include predictive software for material development, product design, and cost forecasting. Lastly, outsourcing refers to the practice of subcontracting a supplier to manufacture a component or part or to perform another task previously performed inside the company.

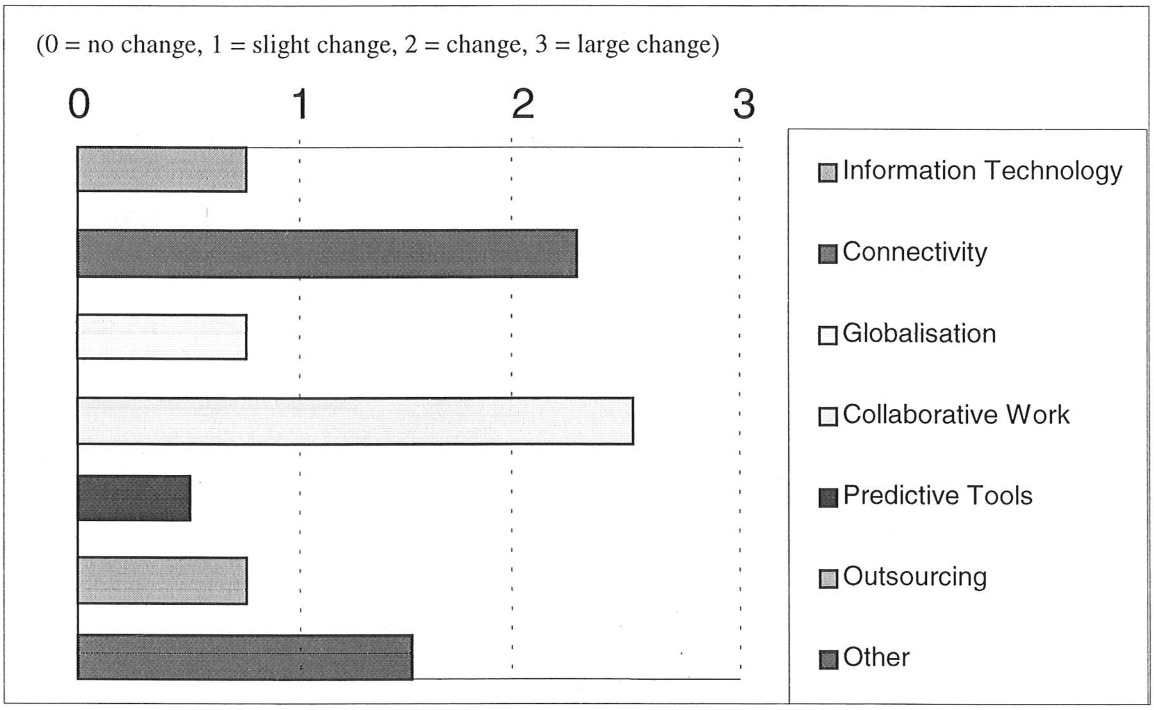


**Figure 2.2: Factors Effecting Successful Commercialisation of Materials Innovations**

Due to the small sample size of the survey, outlying results strongly influence the average response. To mitigate this problem, one outlying result was removed from each average response calculated. The results are shown in figures **2.2** to **2.4**. The average results indicate that small, materials innovating companies perceive connectivity and collaborative work as the factors which have most positively influenced the chances for successful commercialisation of a materials innovation. They perceive access to venture capital to have been highly positively impacted by these factors. They also believe that the manufacturing interface, the market interface, and the design process have been moderately to highly influenced by these factors. Materials industry structure was perceived to have been slightly to moderately influenced in the past decade by these factors. The largest reductions in barriers to materials innovations were perceived to be in reputational clout for partnering, access to venture capital, ability to scan the marketplace. These results support the hypothesis that the environment for SMEs commercialising materials innovation is changing positively due to the dissemination of information technology tools (such as tools for connectivity) and trends towards collaborative work.

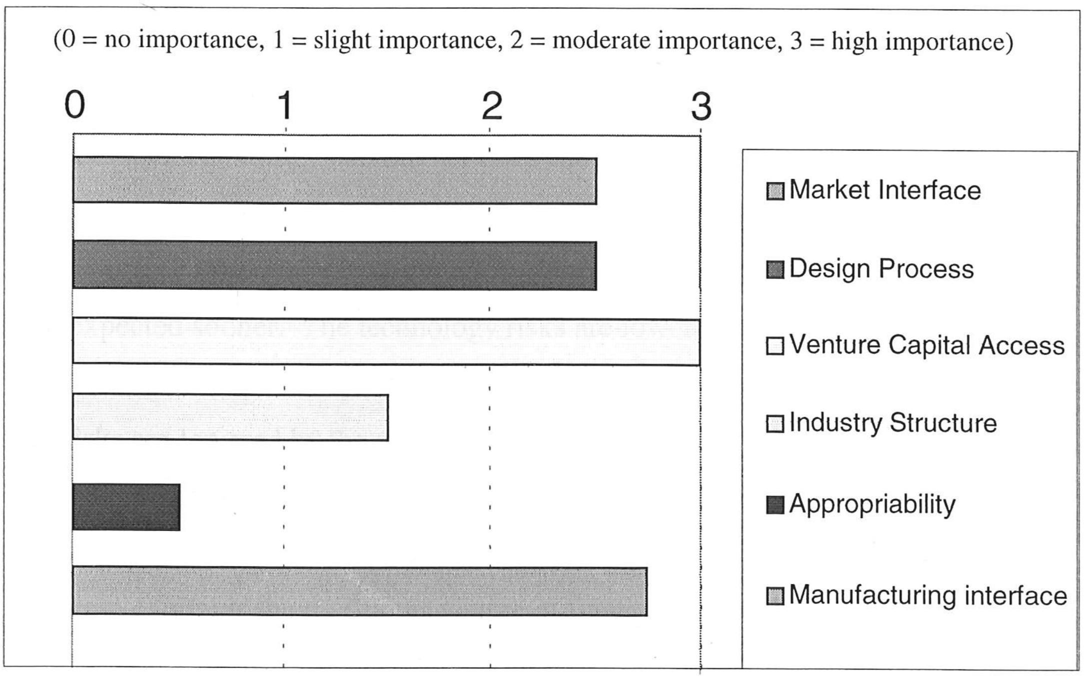


**Figure 2.3: Corporate Areas of Factor Impact**

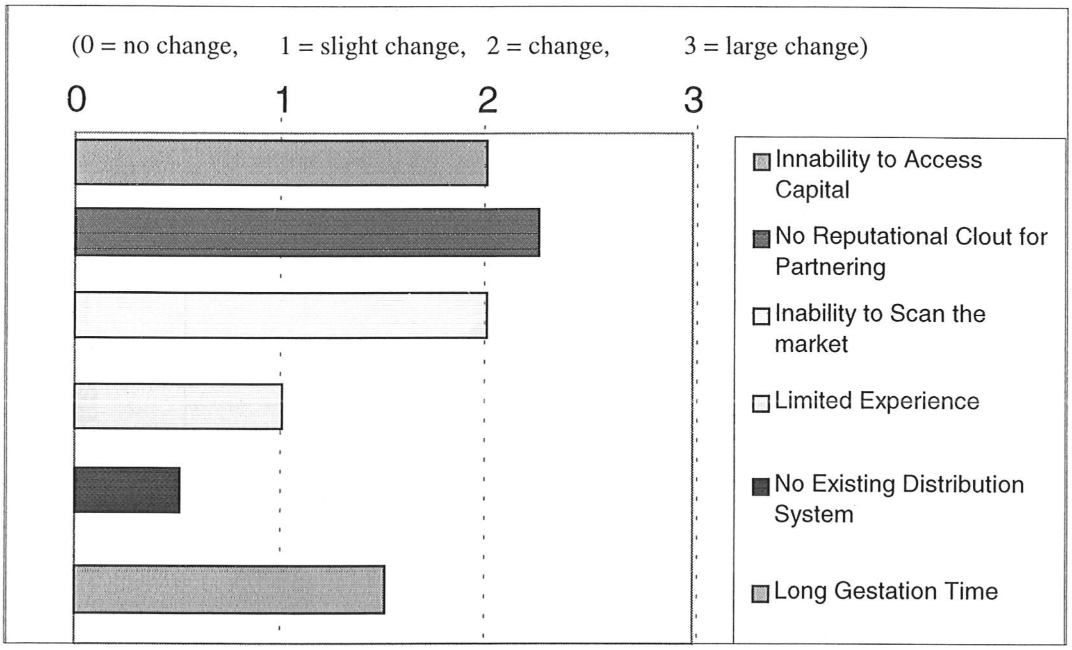


**Figure 2.4: Changes in Barriers to Materials Innovation**

## 2.4 Need for Materials Investment Analysis Tool

One of the main barriers to SMEs commercialising materials innovation has been access to capital for "risky, long-term development."[18] Survey results indicate that connectivity and the trend towards collaborative research are making access to capital less difficult. If the gestation time of a materials innovation can be shortened by these forces and technology and market risks can be lowered by tools and methods of research enabled by IT, the risk/reward position of materials innovation by SMEs will be considerably improved (see figure **2.5**). The potential reward is higher, as the returns are expected sooner. The technology risks are lowered by utilising viability assessment (see section 3.2) for early stage vetting of a materials innovation. The marketing risks are lowered by the use of relevant precedents for market forecasts, by earlier stage access to information about consumer needs, and by predictive tools used to create materials in response to consumer needs.

Venture capital is the traditional source of financing for risky, early stage ventures. Currently, ideas for materials innovations are assessed by venture capitalists in precisely the way that non-technological business ideas are assessed. Business plans are ranked by the following factors, in order of priority: quality of management

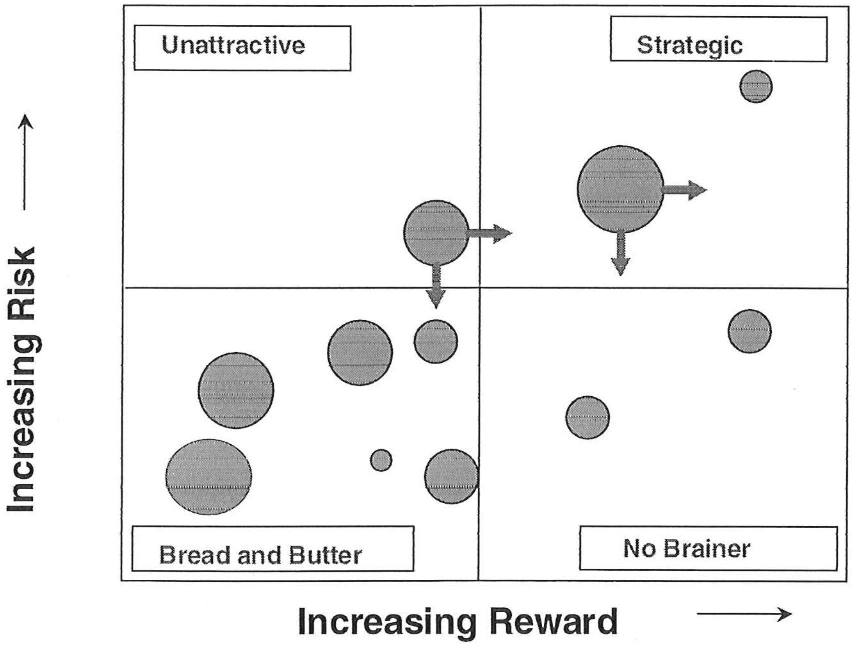


**Figure 2.5: Lowering Risk and Increasing Reward in Materials Innovation by SMEs**

team, size of global market, potential upside revenue, technology assessment (usually through references), geographical location of the firm, and target markets.[19] In this changing environment of connectivity and collaborative work, materials innovations driven by SMEs have an improved risk/ reward positioning and could be lucrative investment opportunities for venture capital companies. However, a better investment assessment methodology is required. Without assessing the technical and economic viability of the materials innovation, investors are either assuming unnecessary risk or missing worthwhile investment opportunities.

Additionally, materials innovating SMEs need to become aware of the strategic positioning of their innovation and of the best paths for commercialisation. By using this methodology, the predominantly science-biased entrepreneurs driving materials innovation in SMEs could make strategic decisions at an earlier stage of development. In summary, this methodology is meant as a tool for venture capitalists, an accepted method of vetting a materials innovation, and a learning mechanism for materials innovators.

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[7] Freeman and Soete, 1997.

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[10] Freeman and Soete, 1997. p.237

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[12] Clemons, 1993. p.219

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[14] Narula and Hagedoorn, 1999

[15] Wield and Roy, 1995

[16] Freeman, 1992. p.108

[17] Gill and Johnson, 1997.

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[19] interviews with Cambridge Research and Innovation Ltd., Arthur D. Little, 3I, Scientific Generics, and St. John's Innovation Centre

# 3 Tool for Materials Investment Analysis

## 3.1 Overview of Investment Methodology for Materials (IMM)

Innovations in the materials industry have in the past been driven by large enterprises,[1] considered a high risk investment,[2] and have been characterised by long gestation periods between invention and widespread market adoption (Figure **1.2**). In this thesis, an investment methodology for new materials (IMM) is developed which could both reduce risk and shorten that gestation time. The risk can be lowered through early *viability analysis* and the gestation time could be shortened, and thus the present value of expected revenues increased, through earlier and more effective information exchange. This methodology, along with structural changes in the materials industry (sections 1.4 and 2.1), could enable SMEs to commercialise new materials innovations in an industry previously dominated by large enterprise.

IMM assesses the technical and economic viability of the materials innovation and also the likelihood that a specific company could capture the value created by adoption of the innovation. Specifically, it is envisioned that IMM should provide a structured, informed procedure for assessing the attractiveness of investing in the industrial scale-up of the production of a new material. IMM can be divided into three segments: *viability*, *market forecasting*, and *value capture* (see figure **3.1**). A material is *viable* in an application if the balance between its technical and economic attributes are favourable. Assessing viability involves: technical modelling of the application, cost modelling of manufacturing, input from the market assessment, and value analysis. The market assessment consists of techniques for identifying promising market applications and for forecasting future production volume. Likelihood of *value capture* is assessed through an analysis of industry structure, organisational structure, IP issues, appropriability, and the planned market approach. If the two metrics of size of viable markets and value capture are used to characterise materials, it is clear that the most desirable investment opportunities lie in the upper right hand quadrant of figure **3.2**. The position of a not-yet-commercialised structural material on these two axes is not easy to predict – polyethylene, at the top left, was at first thought to have only a tiny potential market. Control of intellectual property is a key to value capture in the materials industry (as elsewhere), as the positions of Kevlar™ and of Goretex™ indicate. With functional materials, of which LEPs are an example, the positioning on the figure may be more certain, though still an informed guess rather than a certainty.

A decision to invest time and capital in developing a new materials innovation is a bet that products can be produced, either now or at some specified time in the future, that will be economically attractive in existing applications or will enable new, desirable applications. Such a bet can be made with evidence, gut feel, or it can be simply postponed. This thesis argues that a structured analysis enhances the probability of making a good bet, and can prevent postponement of bets. Evidence is provided through an assessment of viability, analysis of the markets, and an assessment of the potential for value capture (figure **3.1**)

There exists a substantial body of literature and experience on each of the topics listed above, each corresponding to a segment of figure **3.1** and a module of this thesis. The novelty of the methodology proposed here lies in their integration into a concurrent procedure. It may be thought that this step is an obvious one, but the history of materials development suggests that the modules, or the groupings shown in figure **3.1**, are frequently treated in isolation, compromising the effectiveness of the analysis.

The rest of this chapter explains the methodology from a user's perspective. Each segment of figure **3.1** corresponds to an analysis module of the methodology. The inputs and outflow of information from each module are elaborated on in the following.

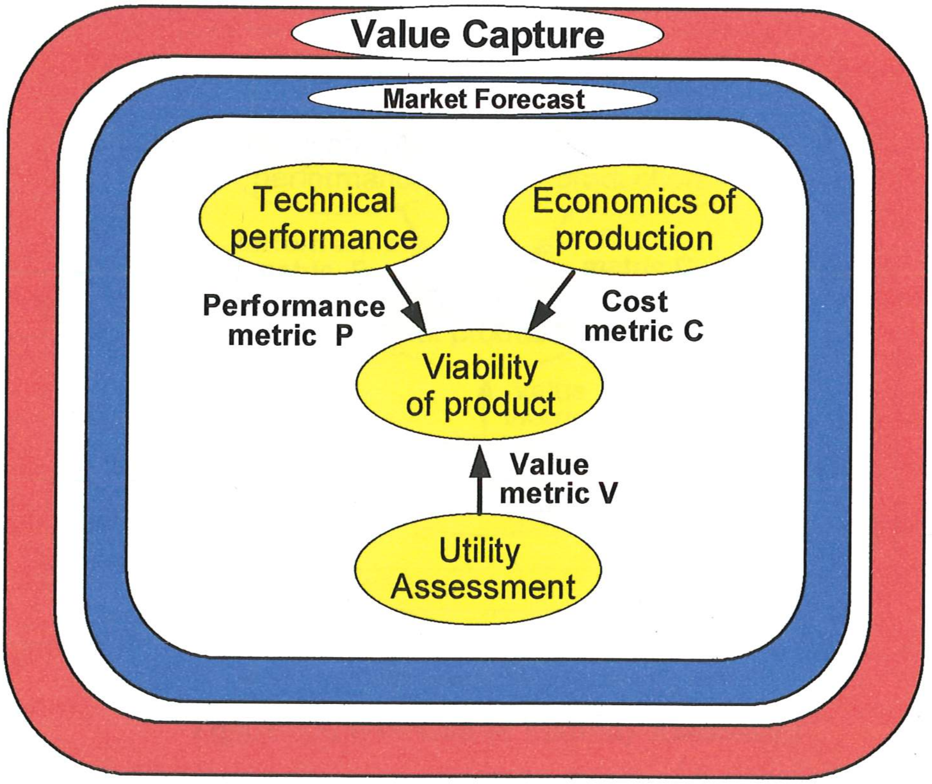


**Figure 3.1: Investment Methodology for Materials (IMM)**

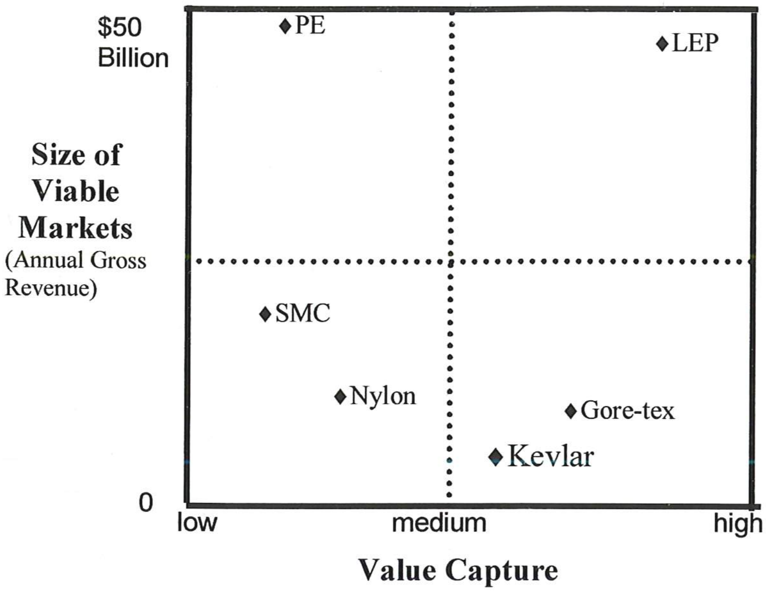


**Figure 3.2: Decision to Invest in a Materials Innovation**

## 3.2 Viability Assessment

The viability of a new material in a given application depends on the balance between its performance, its cost, and its value. There are three steps in evaluating it. The first is the **technical assessment** (Figure 3.3, upper left oval). Performance metrics are identified and evaluated for competing solutions for the design.[3] Each application can be modelled in this

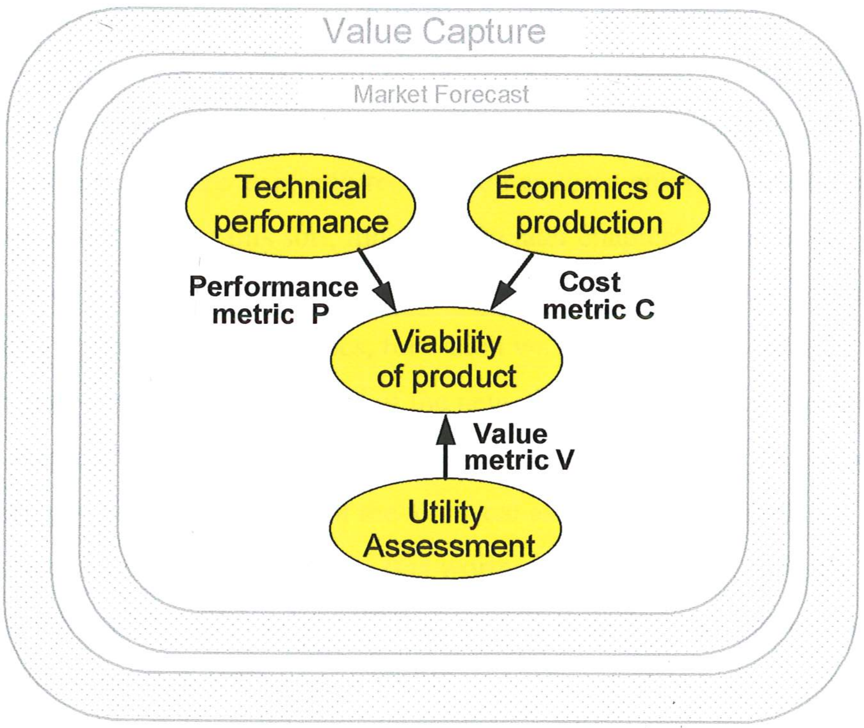


**Figure 3.3: Overview of Viability Assessment**

way in order to provide a basis for performance comparisons between new material solutions and incumbent solutions. The second step is the **analysis of cost** (Figure **3.3**, upper right oval): how much does it cost to achieve a given performance metric? The quantity of material required to meet constraints on stiffness, on strength, on energy absorption etc. is calculated from straightforward technical models. The cost, C, of producing this quantity of material in the desired shape is the output of the cost model, as described in Section 3.2.2. The final step is that of **assessing value** (Figure **3.3**, lower oval): is the change in performance worth the change in cost? Balancing performance against cost and value is an example of multi-objective optimisation. It is discussed in Section 3.2.3.

### 3.2.1 Modelling Technical Feasibility

Before recommending a new material to a designer, or investing in manufacturing equipment to industrially produce a new material, it is essential that the new material be well understood from a technical perspective. The first module (upper left oval of figure **3.3**) of the analysis takes as input the property profile of the new material, allowing its comparison with the profile of existing materials in a range of potential applications. Contemporary software, typified by the Cambridge Engineering Selector (CES), allows the retrieval and comparison of physical, mechanical and thermal properties of thousands of materials. Comparison by function (as well as by simple property), is enabled by using material "indices" that characterise the performance of a material in a given function. Material and first-order processing costs are also captured, as well as some environmental information.[4]

The use of software of this sort, illustrated in later chapters, is the initial, scoping, step in establishing technical merit. Almost always this must be supplemented with more detailed analysis, identifying performance metrics, for which we shall use the symbol P, that measure technical excellence and comparing those of the new material with those of existing materials – in a later example, the performance metric is the *energy absorbed per unit volume* in an energy absorbing system. The output of the technical assessment is a tabulation of these metrics for new and incumbent materials. It is worth emphasising that viability does not necessarily require greater technical excellence, since it is the balance between this and cost (to which we now turn) that determines viability.

### 3.2.2 Modelling Cost

The second step in exploring the technical viability of a materials innovation is that of establishing the material production and secondary processing costs. Most models to predict manufacturing cost as a function of production volume rely on historical data for existing processes. It is common to crudely approximate costs when the process has not been developed past pilot scale, the manufacturing method is untried, and the potential for technical advances exist. Such approximate estimates can be useful, but a predictive cost model which allows for sensistivity analysis on technical uncertainties is better. This is made possible by Technical-economic Cost Modelling (TCM).[5]

TCM enables a cost comparison between functionally similar components or systems made with competing materials and processing methods. Developed at the Massachusetts Institute of Technology over the past two decades, TCM has emerged as an accepted metric for material and process comparison for automotive manufacturers and suppliers. TCM can facilitate credible communication with design engineers about new material innovations and enable the development of product cost scenarios that are based on potential technological changes.[6,7]

The upper right oval in Figure **3.3** represents a technical cost modelling module. The inputs into this module include technical properties of the new material, process information, estimated dimensions and key design features of the desired applications, and desired production volume range. The main output is a comparison between the cost, C, of a part made of a new material and one made of an existing one. Additional outputs are a manufacturing cost estimate over a range of production volumes, cycle time estimates, limiting intermediate variables, costs broken down by accounting line item, and the results of sensitivity and scenario analysis. TCM for two processes of manufacturing aluminium foam parts are developed in Chapter 4.

### 3.2.3 Value Analysis

If the materials innovation delivers products with better performance at lower cost than existing solutions, the innovation is viable. Barriers to entry may delay the substitution, but, eventually, it will occur. Nothing more needs to be considered in this sector. However, it is commonly the case that a new material that is proposed for substitution into a particular application has enhanced performance, but costs more, or is cheaper, but has lower performance than existing solutions. The new material may have a viable market niche, but, to establish this, more information is needed about how the market values performance. The lower oval in figure **3.3** represents a module for exploring trade-offs and assessing value. It utilises the profile of a new material, the economics of production (including scenario forecasting), knowledge of existing products and technologies, and measures of utility for the cost and/or performance attributes of the new material.

Here we have a classic example of the problem of finding a compromise between two conflicting objectives – that of maximising performance at the same time of minimising cost. When a design has two or more objectives, solutions rarely exist that optimise all objectives simultaneously. The objectives are normally non-commensurate, meaning that they are measured in different units, and in conflict, meaning that any improvement in one is at the loss of another. However, some solutions can be rejected quickly because they are dominated by other solutions, meaning that other solutions exist that have better values of both (or all) the performance metrics. The solutions that cannot be rejected in this manner lie on a line called the *non-dominated* or *optimum* trade-off surface.[8,9] The values of the performance metrics corresponding to the non-dominated set of solutions are called the Pareto set (Figure **3.4**).

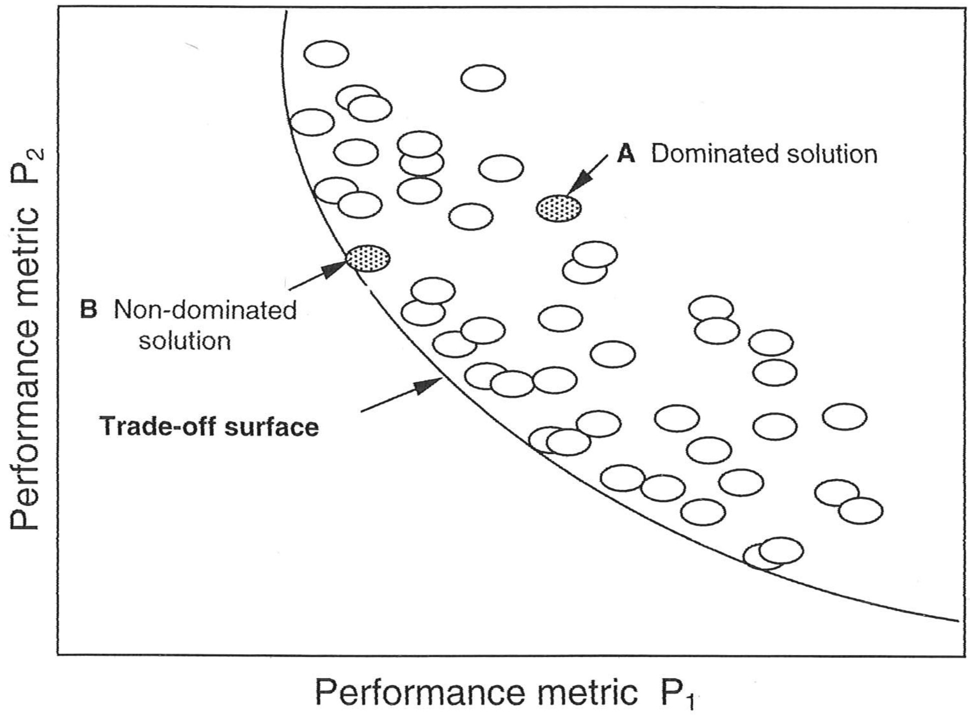


**Figure 3.4: Dominated and non-dominated solutions, and the optimum trade-off surface.**

The trade-off surface identifies the subset of solutions that offer the best compromise between the objectives, but it does not distinguish between them. Three strategies are available to deal with this.

1. The trade-off surface is established and studied, using intuition to select between non-dominated solutions.
2. All but one of the objectives are re-formulated as constraints by setting lower and upper limits for them, thereby allowing the solution which minimises the remaining objective to be read off.
3. A composite objective function or *value function*, V, is formulated; the solution with the minimum value of V is the overall optimum. This method allows true multi-objective optimisation, but requires more information than the other two. It is explored next.

A new material is viable in a given application if, for some range of production volume, it has a greater value, V, than any other material (see equation 1). The value function combines measures of the performance, $P_1$, $P_2$, $P_3$....., with cost, C, to form an overall objective function, V:

$$V = \alpha_1 P_1 + \alpha_2 P_2 + \dots\dots\dots - C \qquad (1)$$

The α's in equation 1 represent "utility" or "exchange" constants, each measuring the change in V for a unit change in $P_1$, $P_2$ etc.. Their magnitudes depend on the application and the value associated with each performance metric – and this involves information from the market assessment module, described in section 3.2.4. Table **3.2** gives examples. In transport systems, different industry segments have different utilities for the reduction of mass. Here the performance metric, P, is mass. The utility of mass savings in a passenger car can be estimated from the fuel savings realised over the life of the vehicle, giving a value of between 2 $/kg and 3 $/kg weight saved. For trucks it is larger: estimates based on payload give utility values, $\alpha_m$ , between 10 $/kg and 20 $/kg. For a military aircraft, the utility of mass reduction would be based both on increased performance and on additional payload enabled, and $\alpha_m$ is estimated at the much higher values of between 500 $/kg and 2000 $/kg. And for aerospace applications, $\alpha_m$ is widely accepted as 5000 $/kg, which is the launch cost per kilogram into space. For applications where utilities are difficult to estimate, approximate exchange constants can sometimes be derived from historical pricing-data; thus the value of weight-saving in a bicycle can be approximated by plotting the price P of bikes against their mass m, using the slope $(dP/dm)$ as an estimate of $\alpha$. Finally, exchange constants can be determined through interviewing techniques[10] which elicit the value to the consumer of a change in one performance metric, all others held constant. Given the utilities of the required performance parameters for the intended markets, the scenario range of costs supplied by the Technical Cost Model, and an adequately represented application, the Value Function approach can be used to show the conditions under which a new material would appear viable for each assessed application.

| Function | Objective (constraints) | Exchange Constant ($\alpha$) |
|---|---|---|
| **Mechanical Systems** | | |
| Transport systems | Minimise weight (at given stiffness, strength) | $ / kg saved |
| Crash protection | Maximise energy absorbed (at given plateau stress) | $ / MJ absorbed |
| Submersible craft | Maximise depth of dive (without failure etc.) | $ / extra m of depth |
| **Thermal Systems** | | |
| Heat exchanger | Maximise heat transfer / $m^2$ (without failure, etc.) | $ / ($MJ/m^2$) increase |
| Thermal insulation | Minimise heat transfer / $m^2$ (without failure, etc.) | $ / ($MJ/m^2$) decrease |
| **Electro-Magnetic Systems** | | |
| High-power magnet | Maximise magnetic field (without failure, etc.) | $ / tesla increase |

**Table 3.1: Assessing Utility**

### 3.2.4 Market Assessment

Science-push innovations require an early stage market assessment to link the worlds of engineering and finance.[11] Without such an assessment, they are doomed to languish in the backrooms of R&D facilities waiting for a market to announce itself. Market assessment involves both the technical inputs of performance metrics and the market inputs of customer requirements and emerging opportunities. Desired outputs include: further information to direct the technical development effort, such as, suitable markets on which to concentrate development, and exchange constants for utility analysis; and information to guide business decisions, such as, segments of the market which are most attractive, sizes of those markets, and anticipated timing and amount of potential revenue flows. These outputs are depicted below in Figure 3.5.

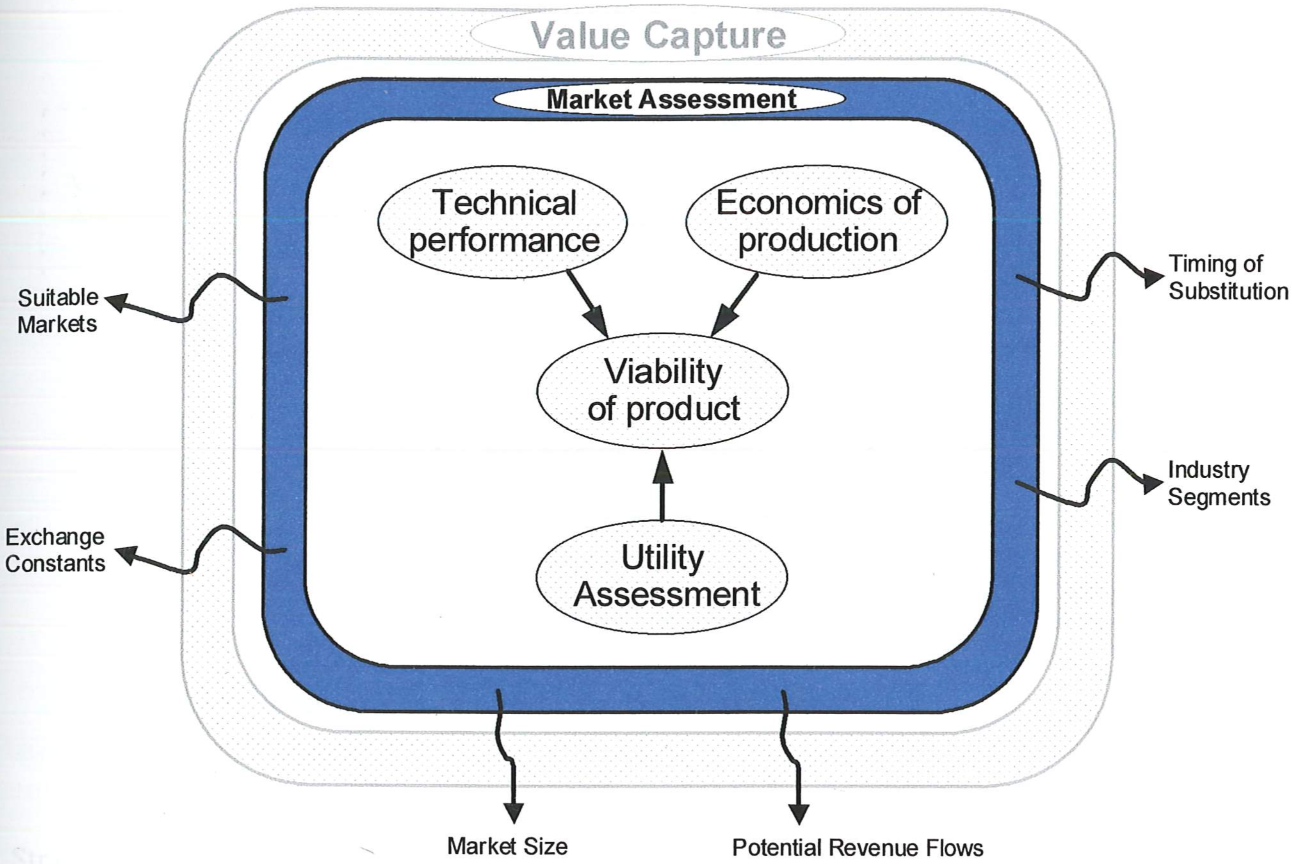


**Figure 3.5: Market Assessment Information Flow**

An early stage, new material-market assessment (figure 3.6) involves the following two strategies, on which this thesis expands in the chapters that follow:

Strategy A: The search for new markets or applications created by the new material. This search is based on the performance attributes of the new material or the new material process and relies on satisfying a consumer desire that is not currently met. Examples of the above include the novel processing of PTFE to create Gore-tex™ offering performance in combined winter/rain/sports/casual jackets; the development of cobalt-samarium magnets, which enabled ultra lightweight earphones and small DC motors; the advances in silicon wafer manufacturing which have contributed to the development of the computer chip industry; and the development of light emitting polymers into diodes (see chapter 7). Success here is difficult to achieve but the potential payoff is large.

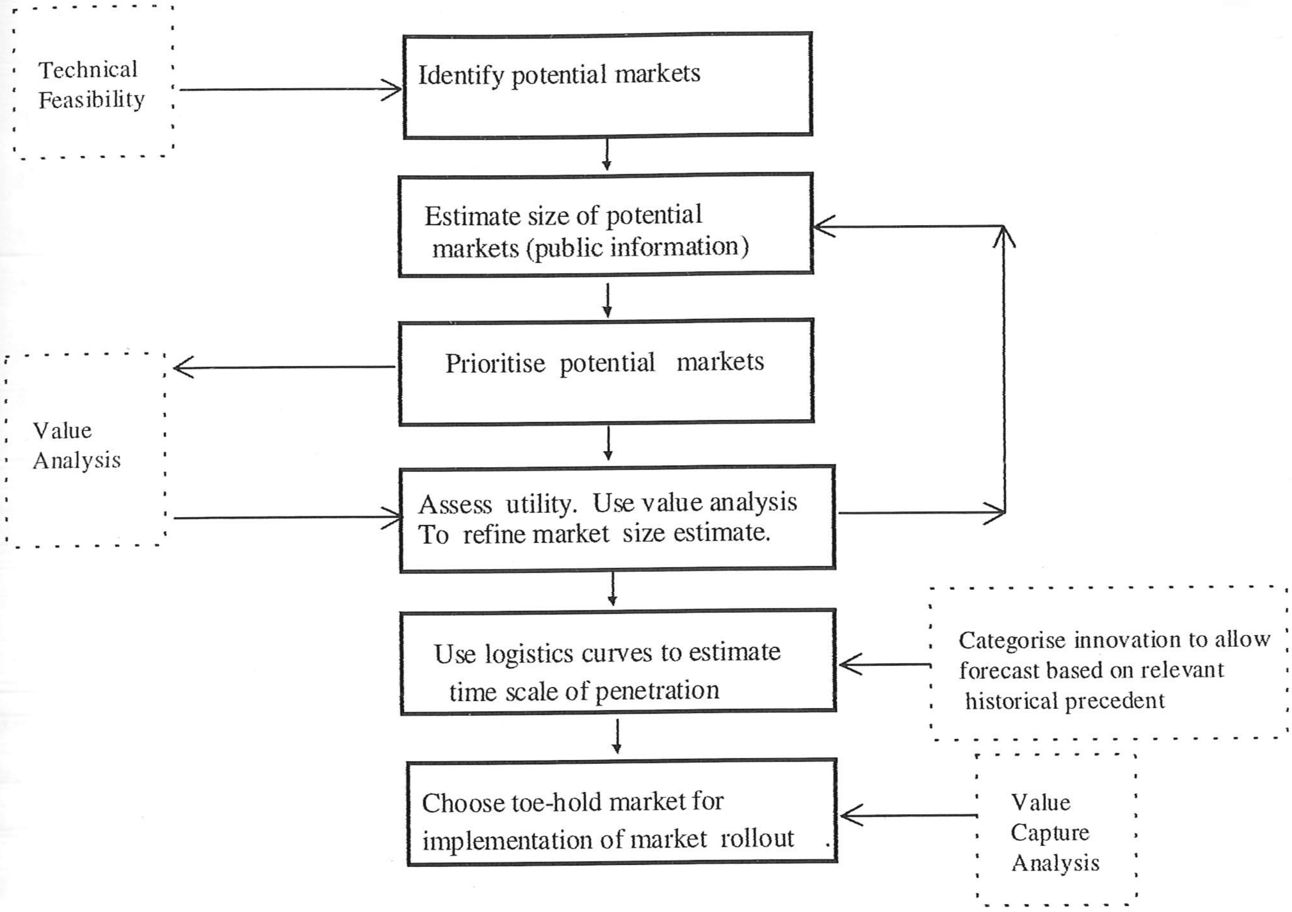


**Figure 3.6: Steps of Market Assessment (Strategy B)**

Strategy B: An exploration of substitution into existing markets.

This strategy involves six broad steps:

1) Potential markets are identified by comparing the properties of the new material with those of existing materials and noting the most promising property combinations of the new material. The established applications of existing commercial materials with similar property profiles are explored as a first estimate of potential markets.
2) The sizes of potential markets for the new material are determined through public information sources (WWW, electronic news search services etc.).
3) The above markets are prioritised according to market size and estimated type of substitution (figure **3.7**). This initial prioritisation step provides input for the technical assessment, cost modelling, and value analysis modules. Market size estimation is an iterative process, with refined estimates becoming possible only after viability analysis is performed.

4) The utility of different markets and/or applications for the performance-cost attributes of the new material is assessed. Utility analysis – techniques for determining the α's of equation (1) – is useful both to screen potential applications and as an input into the value function, which enables material selection based on a combination of cost and performance metrics.
5) Logistics curves and assessed performance-cost attributes are used to estimate penetration into identified markets and applications.
6) An Implementation Plan is created for the order of markets to be entered. Finding an entry market with minimum risk is most important for an SME.

Market demand estimates are always uncertain. If the innovation is deemed viable, performance and cost characteristics can help in estimating penetration rates of the material into the defined markets (figure **3.7**). This is accomplished by forecasting the penetration rates for the new materials innovation based on a historical material substitution curve (see, for example, figures **1.3** and **2.4**) of a material with similar performance and cost characteristics.[12] Lower cost / lower performance innovations serve the minimum requirements of customers for the application. For substitution to occur, this lesser

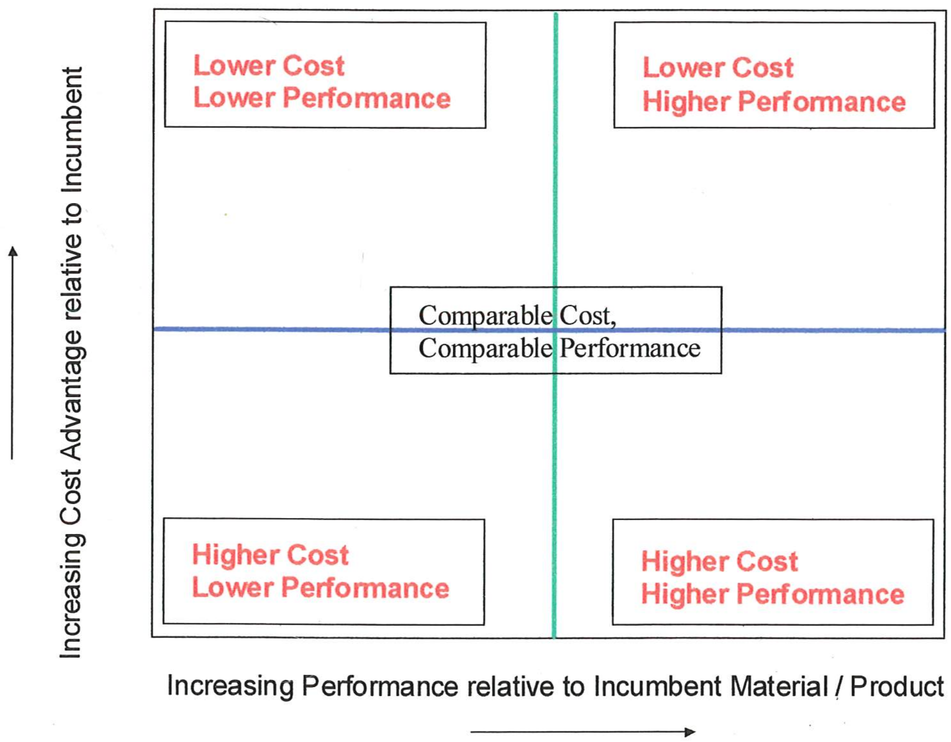


**Figure 3.7: Types of Performance/Cost Based Substitution**

functionality must be provided at a reduced cost. Oriented strand-board substituting for plywood in furniture and construction applications is an example of this type of substitution. An example of technological innovation allowing for performance enhancements but at higher cost is carbon fibre reinforced plastic boat hulls substituting for wood hulls. If the materials innovation enables entirely new applications, it does not need to be compared with an existing product or technology, but, rather, with assessed customer requirements and safety standards

By following the procedure outlined in figure **3.6**, answers to guide further technical and business assessment can be reached. Market assessment is seen here as an interim step, but a vital step in reaching an investment decision. The overall goal is to ensure that the assumptions on which market forecasts are based are sound, and to integrally link the technological innovations strengths and weaknesses with the market dynamics of the industries in which the applications are targeted.

## 3.3 Likelihood of Capturing Created Value

Viability assessment and market assessment may demonstrate that the materials innovation under consideration has the potential to create enormous value. However, a

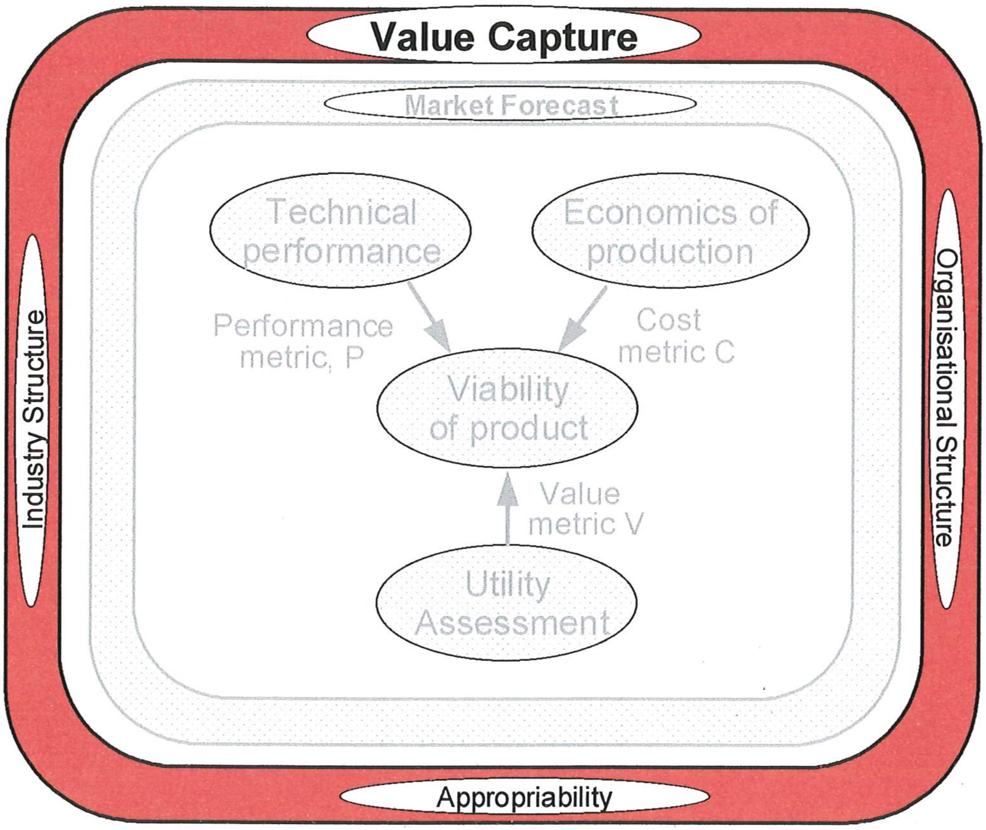


**Figure 3.8: Overview of Value Capture Analysis**

company may be persuaded of this assessment and still decide not to invest. In order to invest, a company must be convinced that they will be able to capture a significant portion of the value created by the innovation. The concepts of appropriability, industry structure, competitive advantage, and organisational structures are utilised to predict the likelihood of capturing value.

### 3.3.1 Industry Structure

Michael Porter's methodology for assessing *industry attractiveness* provides an inter-industry attractiveness rating, ranging from low to high. Porter assesses the attractiveness, or potential for profitability, of an industry by examining the rivalry of competitors in the industry, supplier power, buyer power, barrier to new entrants to the industry, and the threat of substitute products, as depicted in figure **3.9.**[13] Technological innovation can alter the attractiveness of an industry by changing one of the above factors, for example, by raising or lowering the barriers to new entrants to the industry. The process innovation of continuous casting of aluminium is an example. Continuous casting took away the scale advantage that large semifabricators had with capital-intensive hot mill plants. This innovation brings a strong manufacturing cost advantage, but also lowers the barriers to new competitors entering the industry by lowering the minimum capital investment required to compete. Thus, Porter's methodology can help inform investors whether a selected industry is competitively attractive and whether the technical innovation is likely to increase or diminish this.

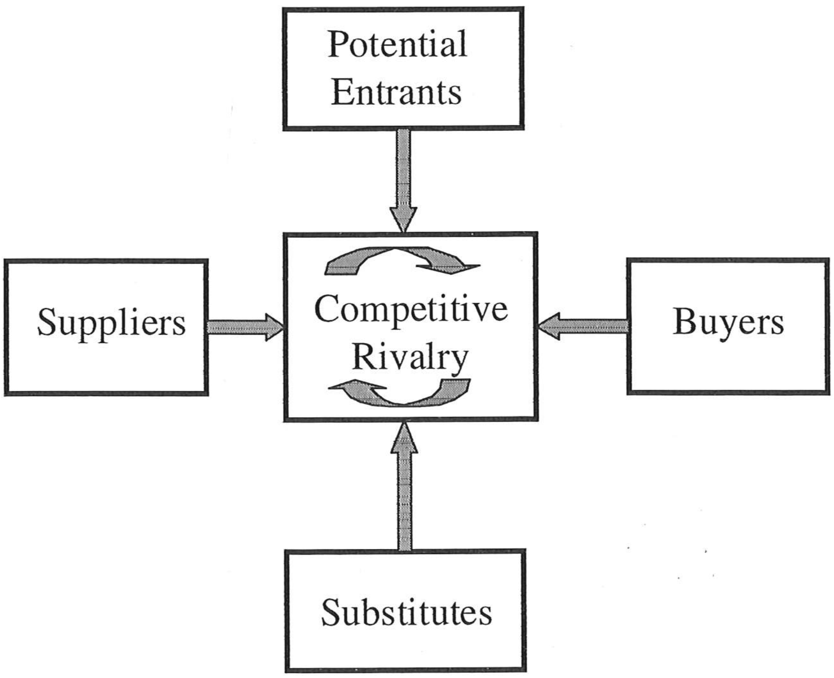


**Figure 3.9: Porter's Five Forces as a means of Assessing Industry Attractiveness**

### 3.3.2 Appropriability of Profits

Ownership of Intellectual Property (IP) is of high importance in extracting value from commercialising a materials innovation. Without patent or trademark protection, it is difficult to maintain a profit margin in mass production of any product. The concept of *Appropriability* was developed[14] to measure the degree of IP protection and, further, the ability of the innovating firm to capture the profits from commercialising a new technology.

Teece divides appropriability regimes into tight, where strong patent or trade secret protection, asset type, and the type of innovation combine to enable the capturing of innovation profits, and weak, where information about the innovation is not well protected and the innovator has difficulty capturing innovation benefits (see figure **3.10**) Tight appropriability regimes are very desirable as they allow for monopoly conditions for a period of time.

| | Innovator | Follower - Imitator |
|---|---|---|
| **Win** | • Pilkington (float glass)<br>• Dupont (Teflon) Tight<br>• G.D. Searle (Nutrasweet) | • IBM (P.C.)<br>• Matsushita (VHS video recorders)<br>• Seiko (quartz watch) |
| **Lose** | • RC Cola (diet cola)<br>• EMI (scanner)<br>• Bowmar (pocket calculator)<br>•Xerox (office computer) | • Kodak (instant photograph)<br>• Northrup (F20)<br>• DEC (P.C.)<br>Source: Teece, 1987 |

**Figure 3.10: Examples of Innovators with Tight Appropriability Regimes**

The type of assets necessary to manufacture or provide an infrastructure for the innovation effects appropriability through creating barriers to entry and/or exit from an industry. Teece divides these assets into the categories of generic, specialised, and co-specialised.[15] *Generic assets* are manufacturing, distribution, marketing, or infrastructure assets that are widely available: an example would be stamping presses for making either steel or aluminium car body panels. *Specialised assets* are assets that are not generally available and need to be tailored to the innovation: an example would be custom-made capital equipment for manufacturing. *Co-specialised assets* are assets with bilateral dependence with the innovation diffusion. For example, a fleet of cars powered by natural gas needs a network of natural gas fueling stations for the innovation to be successful. The fueling stations would exist solely because of the natural gas powered vehicles and the vehicles' market success would be dependent on an acceptable re-fueling infrastructure. Specialised and co-specialised assets act both as barriers to entry for would-be imitators of the innovation and as the cause of potential irreversible commitments which can lock an innovator into a chosen strategy before a dominant design has emerged.

Categorising past innovations can provide a method for selecting relevant historical precedents to help with predicting market substitution and appropriability. Abernathy and Clark's framework for innovation provides such a categorisation. Innovations can be divided into one of four quadrants, shown in figure **3.11.**[16] *Regular innovation*, found in the bottom left quadrant, refers to incremental technical change that builds on established technical and production competence and that is applied to existing markets and customers. This type of innovation incrementally reduces cost, improves performance or improves reliability, while strengthening existing technological and marketing competencies and linkages. *Revolutionary innovations*, such as transistors replacing vacuum tubes and jet engines replacing reciprocating engines in aircraft, are innovations that overturn established technical and production competencies, but allow a manufacturer to sell to their existing markets and customers. *Niche Creation innovation* is the application of existing technologies to new market applications. Lastly, *Architectural innovation* involves new technology that disrupts existing competencies and a product that disrupts existing market and customer linkages. Examples of architectural innovation include the creation of the radio and the development of the Ford Model T. Abernathy and Clark use these four types of innovation to mark the extremes of what they term a Transilience Map (Figure **3.11**). Transilience is defined as "the capacity of an innovation to influence the established systems of production and marketing."[17]

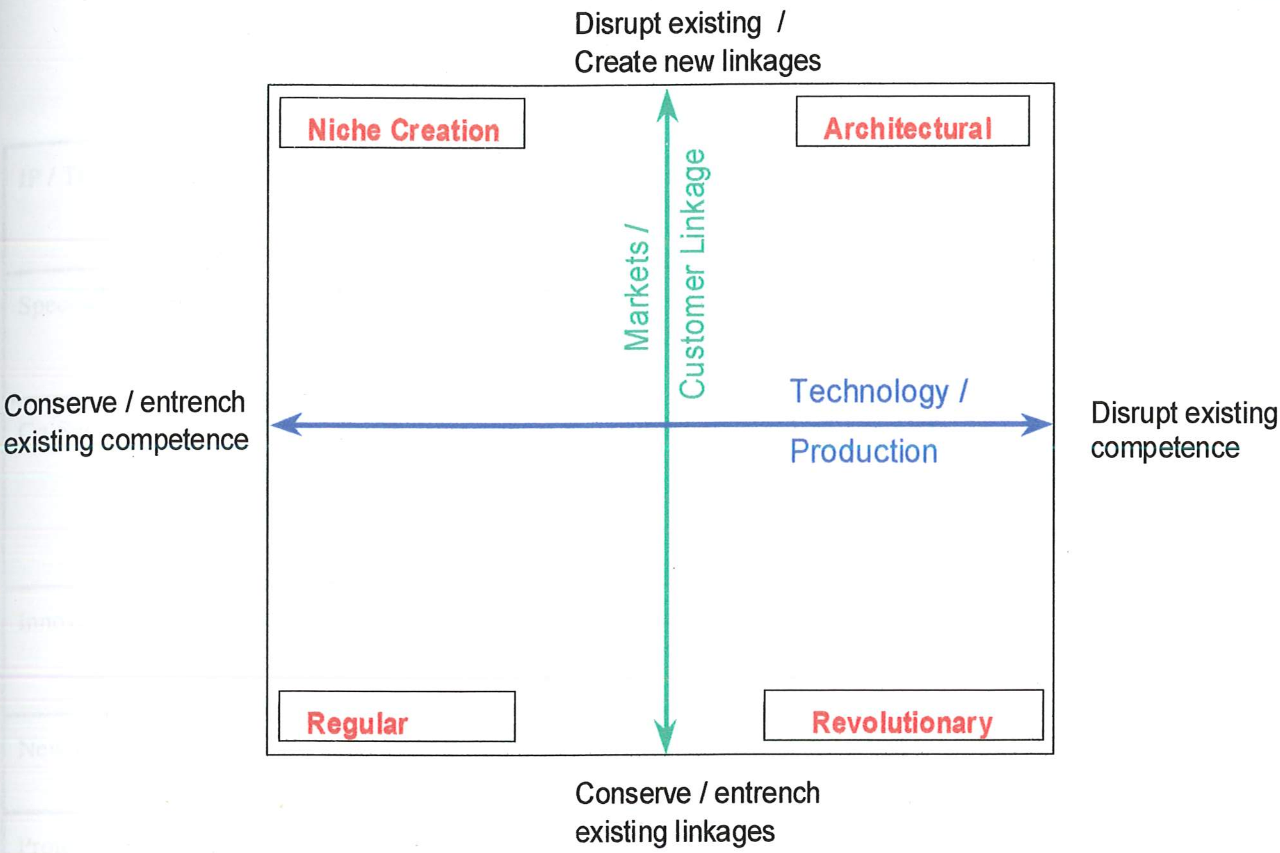


**Figure 3.11: Abernathy and Clark's Transilience Map**

Categorising the type of materials innovation under consideration according to this Transilience Map can help in locating an appropriate historical substitution on which to base both market forecast and appropriability comparisons. For more guidance on assessing the appropriability of an innovation, we have developed table **3.3**. Generally, a tighter appropriability regime will exist to the left hand side of the table.

← Tightening Appropriability Regime

| | | | | |
|---|---|---|---|---|
| IP / Trade Secret Protection | High | Medium | Low | None |
| Specialised Assets | High | Medium | Low | None |
| Co-Specialised Assets | High | Medium | Low | None |
| Innovation Type | Architectural | Niche Product | Revolutionary | Regular |
| New Product Cycle Time | Slow | Medium | Fast | Continuous |
| Protectable Industry? | High | Medium | Low | No |

**Table 3.2: Appropriability Guide**

← Tightening Appropriability Regime

| | | | | |
|---|---|---|---|---|
| IP / Trade Secret Protection | Composition of Matter Patent | Contestable patent / well protected trade secret | Penetrable trade secret | Competitor holds key patent |
| Specialised Assets | chemical manufacturing complex | T.V. manufacturing plant | Foundry | Lemonade Stand |
| Co-Specialised Assets | Natural Gas fuelled vehicles and N.G. fuelling station infrastructure | CD-ROMs and Personal Computers | Transport ships configured to carry oil and a business that relies on that oil supply | Straw Doormats |
| Innovation Type | Ford Model T | CFRP monocoque for race cars | GFRP fenders | High strength steel automobile body |
| New Product Cycle Time | Aerospace | Automotive | Computer Software | Information Content |
| Protectable Industry? | Pharmaceutical | Computer Hardware | Publishing | Computer Software |

**Table 3.3: Examples Corresponding to the Appropriability Rankings of Table 3.2**

### 3.3.3 Organisational Structure

The most attractive innovation opportunity can be squandered by a company without an effective organisational structure.[18] In the materials industry in particular, organisational competencies are required to interchange knowledge across disciplinary fields, functional roles, organisational boundaries, and the marketplace. Entrepreneurial experience of management, presence of a visionary dealmaker, flexibility of the organisation, effective knowledge acquisition and management, and operational efficiency are all important ingredients for successful innovation.

One of the largest differentiators in organisational structures is the size of the organisation, with small firms generally exhibiting a more flexible and opportunistic approach to their decisionmaking. The presence of a "dealmaker" in senior management is far more critical to a small firm's success in commercialising technological innovation due to the financing limitations of many small firms. In larger firms, a key component of an innovative corporate culture in research intensive industries is the resource allocation process. Henderson singles out two models of resource allocation that predominate in successful, innovative pharmaceutical firms. The first revolves around a "single, highly respected and knowledgeable individual" who was able to make cross-boundary connections acting as the key decision maker. The second successful model was that of a "relatively high conflict committee" who made resource allocating decisions through "constructive confrontation across the group."[19]

Henderson's research about organisational competencies in the pharmaceutical industry are relevant to the materials industry as well. She claims that the key competitive advantage for pharmaceutical companies in the 1990s was "the ability to innovate in an information-intensive environment."[20] Henderson's description of the evolution of the pharmaceutical industry from a "regime of random screening" in the 1960s and early 1970s to the current regime of "rational drug design" strongly evokes comparison with the evolution taking place in the materials industry today. In the pharmaceutical industry, Henderson observed that this evolution drove a corresponding increase in importance of accessing new knowledge from outside the firm and integrating knowledge across disciplinary boundaries in the firm.[21] Henderson concluded that "the ability to integrate knowledge both across the boundaries of the firm and across disciplines and product areas within the firm is an important source of strategic advantage" in the current pharmaceutical industry.[22]

| Strategic Tasks | Large Firms | Small Firms |
|---|---|---|
| Integrating technology with production and marketing | • Organisational design<br>• Organisational processes for knowledge flow across boundaries | • Responsibilities of senior managers |
| Monitoring and assimilating new technical knowledge | • Own R&D and external networks | • Trade and technical journals<br>• Training and advisory services<br>• Consultants<br>• Suppliers and customers |
| Judging the learning benefits of investments in technology | • Judgements based on formal criteria and procedures | • Judgements based on qualifications and experience of senior managers and staff |
| Matching strategic style with technological opportunities | • Deliberate organisational design | • Qualifications of managers and staff |

**Table 3.3: How Tasks of Innovation Strategy are Accomplished in Large and Small Firms**[23]

Evaluating the organisational strengths and weaknesses of a firm cannot be entirely generalised. However, it is possible to use the academic literature on organisational structure to form a checklist of attributes to consider. For small firms, that checklist would include: the level of entrepreneurial experience of management, the presence and competence of a visionary dealmaker, level of demonstrated flexibility of the organisation, mechanisms for effective knowledge acquisition and management, and evidence of operational efficiency.

## 3.4 Investment Strategy

The key go / no go questions of investment in the materials innovation or company can be answered by the two main parts of the methodology of figure **3.1**:

(a) Viability. Only if the material is technically and economically viable is an investment justified.

(b) Value Capture. Only if the likelihood of capturing the value created from the introduction of this material innovation is high (after considering potential collaborations), is an investment justified.

This methodology also provides some insight on the type of investing organisation most likely to find investment attractive. Logistics curves (see section 1.3) can help in estimating the length of payback on an initial investment. In the case of long term payback, a public organisation or a very large corporation may be the only interested investors. Conversely, in the case of a staged investment with a 5 year payback, the potential of a buyout, and large "upside" profit, venture capitalists may be quite willing to provide financing for any company.

Given the decision to invest, market approach is the key to managing cash flow. For instance, a new material could first be exploited in small volume high value added applications such as sports equipment to gain credibility, brand name recognition, and to provide initial cash flow. Smaller companies in particular should consider collaborations with suppliers, customers, and distribution channels. Such collaborations can provide financing opportunities, faster penetration of the material, and a more detailed understanding of the market.

In summary, the attractiveness of a materials innovation can be determined by systematically assessing the technical and economic viability, along with the likelihood to capture profits created. This methodology may help match new materials innovations to market opportunities more quickly and may prevent some companies from pursuing investment strategies destined for failure.

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[21] Henderson and Cockburn, 1994. pp.63-84

[22] Henderson and Cockburn, 1994. pp.63-84

[23] Tidd, Bessant, and Pavitt, 1997. p.156

# 4 Viability Assessment of Aluminium Foams

The method of material indices[1] allows a broad screening of applications for which a new material has technical promise. Briefly, the performance of a material in most mechanical and thermal applications is related to a group of materials properties, or "material index". Thus efficient springs require materials with high values of $\sigma_y^2/E$; heat exchangers require materials with high values of $\sigma_y \lambda$; light stiff panels require materials with high values of $E^{1/3}/\rho$; and efficient energy absorbers require materials with high values of $\sigma_y \varepsilon_f$ -- and there are many more. (Here $\sigma_y$ is the yield strength, E is Young's modulus, $\lambda$ is the thermal conductivity, $\rho$ is the density and $\varepsilon_f$ is the ductility). Metal foams, a new class of material with, as yet, no well-developed applications, have poor values of the first pair of these property groups, but have particularly good values of the second pair. On the basis of this sort of screening we identify the application-classes associated with this second pair as worthy of further investigation, seeking specific market sectors in which the value/cost/performance trade-off is favourable.

Accordingly, we first explore the modelling of performance (P) of metal foams in these applications a little more fully, then examine the associated cost (C) and the value (V) in a specific application, and finally review the trade-off between cost and value.

## 4.1 Technical Analysis for Material Choice – Modelling Functional Requirements

To construct a technical model, *performance metrics*, $P_i$, are identified and evaluated. A performance metric is a measure of the performance offered by the material in a particular application. In *minimum weight design* the performance metric is the mass per unit stiffness ($kg/Nm^{-1}$): the lightest material which meets the specifications on stiffness, strength etc. is the one with the greatest performance. In *design for energy-mitigation*, in which it is desired that a protective packaging should crush, absorbing a specified energy, the performance metric is the volume per unit of energy absorbed ($m^3/MJ$), or the mass per unit energy absorbed (kg/ MJ). In *design to minimise heat loss*, the metric might be the heat flux per unit area of structure ($J/m^2$). In *design for the environment*, the metric is a measure of the environmental load associated with the manufacture, use and disposal of the material (such as $CO_2$/kg).

Each performance metric defines an objective: an attribute of the structure that it is desired to maximise or minimise. Models are developed for the performance metrics following the methods detailed by Ashby.[2] The material that maximises the chosen performance metric has the highest technical merit. But for this to be a viable choice, the performance must be balanced against the cost.

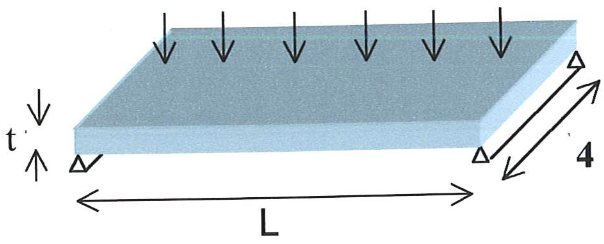


**Figure 4.1: A Panel with Prescribed Stiffness, Requiring Minimum Mass**

We take the light, stiff panel as an example (figure **4.1**). The design requires a panel of width W, length L and stiffness S; the thickness t and the choice of material are free. The performance metric is the mass, m (to be minimised):

$$m = L W t \rho \qquad (4.1)$$

The bending stiffness of the panel S is given by:

$$S = \frac{CEI}{L^3} \qquad (I = \frac{Wt^3}{12})$$

or

$$S = \frac{\beta}{12}\frac{E W t^3}{L^3} \qquad (4.2)$$

where ß is a constant that depends only on the way in which the loads are distributed (C = 48 for the configuration of Figure 4.1). The constraint on S fixes t. Eliminating t between equations (4.1) and (4.2) gives

$$m = \left(\frac{12 S W^2}{\beta}\right)^{1/3} L^2 \left(\frac{\rho}{E^{1/3}}\right) \qquad (4.3)$$

Here everything is prescribed except the material group (or "index") $\rho / E^{1/3}$. The performance metric is thus proportional to this index: ranking materials by the index ranks them also by their performance in the application "light, stiff panel".

Figure **4.2** shows a plot of this quantity for a wide range of materials. For this simple flat panel example, panel cost is just the mass of the panel multiplied by the cost per unit mass of the material. Those in the lower right are the best choices – they have the lowest mass for a given stiffness. Aluminium foams are among these: they are better than light alloys (aluminium and magnesium alloys are marked) and compete with low density woods and rigid polymer foams. If the flammability, creep or degradation of these were a concern, aluminium foams become the best choice.

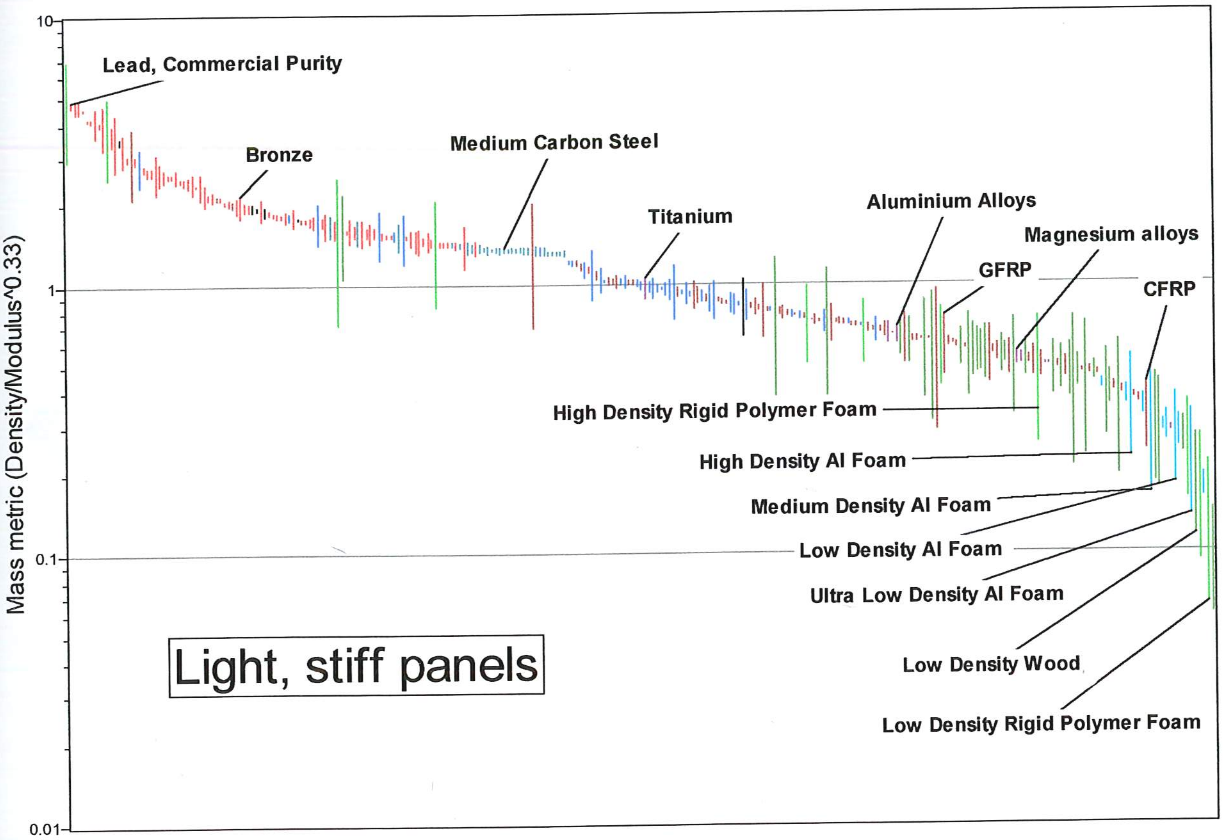


**Figure 4.2: Selection for Maximum Specific Stiffness of a Panel**

This is an example of screening to find applications. As explained above, each application class is characterised by one or more indices; they are catalogued in Ashby (1999). The values of many of these for metal foams are poor – foams do not recommend themselves for these applications. But in at least one other case metal foams emerge as having very attractive values of an index: it is that for controlled energy absorption. This second example is developed fully in Chapter 6.

## 4.2 Comparison and Analysis of Technical Cost Models

The second step of a viability analysis is to establish the manufacturing cost differential between a component made with a novel process or material versus incumbent processes and materials. To enable this, 3 processes for manufacturing aluminium foam are analysed through the construction and comparison of Technical Cost Models.

### 4.2.1 Liquid-state foaming of aluminium

Consider a cost model for the production of panels of a SiC-stabilised aluminium-based metallic foam by the following 4-step liquid state process (figure **4.3**):

a) melting of the pre-mixed alloy
b) holding, providing a reservoir
c) foaming, using compressed gas and a bank of rotating blades
d) delivery of a continuous sheet of foam or of cut panels, via a moving belt

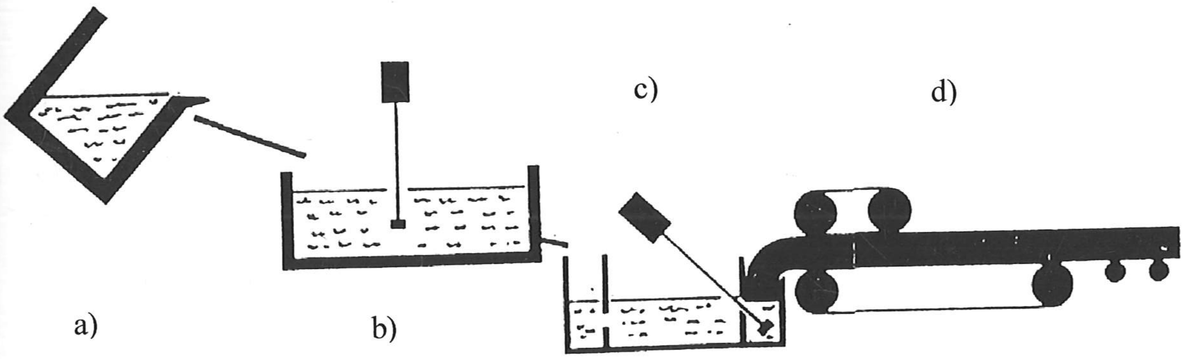


**Figure 4.3: Schematic of Liquid State Aluminium Foaming Process**

The output of one step forms the input to the next, so the steps must match, dictating the size of the equipment or the number of parallel lines in each step. Data characterising the dependence of desired material density and of production rate on the gas flow rate and the stirring rate has been incorporated in the model and links into the intermediate variables of limiting production rate, utilised hours per year, man-hours per year, fraction of capacity utilised, and number of parallel lines of equipment. Through these intermediate variables, the influences of scale-up and of varying product requirements effect the cost line items of equipment, direct labour, and power. Fixed costs are treated in the standard economics fashion, through the use of a cost-of-capital factor and by including the opportunity cost of capital associated with the working capital. A default range of product, process, and business variables can be overridden by the user, providing flexibility and the potential for extensive scenario and sensitivity analysis.

The outputs of the model (Figures **4.5** and **4.6**) show the way in which the cost of the manufactured component depends on production volume and also identify cost drivers. Significantly, the model indicates the production volume which would be necessary to reach the plateau level of cost at which, in the best case shown here, the material cost falls to roughly twice that of the input materials.

### 4.2.2 Titanium-Hydride Expansion of Aluminium via Powder Metallurgical Processing

In comparison, consider a cost model for the production of panels of an aluminium-based metallic foam by either the batch or quasi-continuous processes for the powder metallurgical (PM) processing of aluminium foam. For the batch process, there are six steps (figure **4.4**):

a) Mixing of the Al powder with the powdered foaming agent (< 1% TiH )
b) Cold Isostatic Compression of the powder into an intermediate billet
c) Sintering of the billet (optional)
d) Extrusion of the foamable precursor
e) Placement of Precursor in Mould
f) Batch Foaming of Precursor in Mould

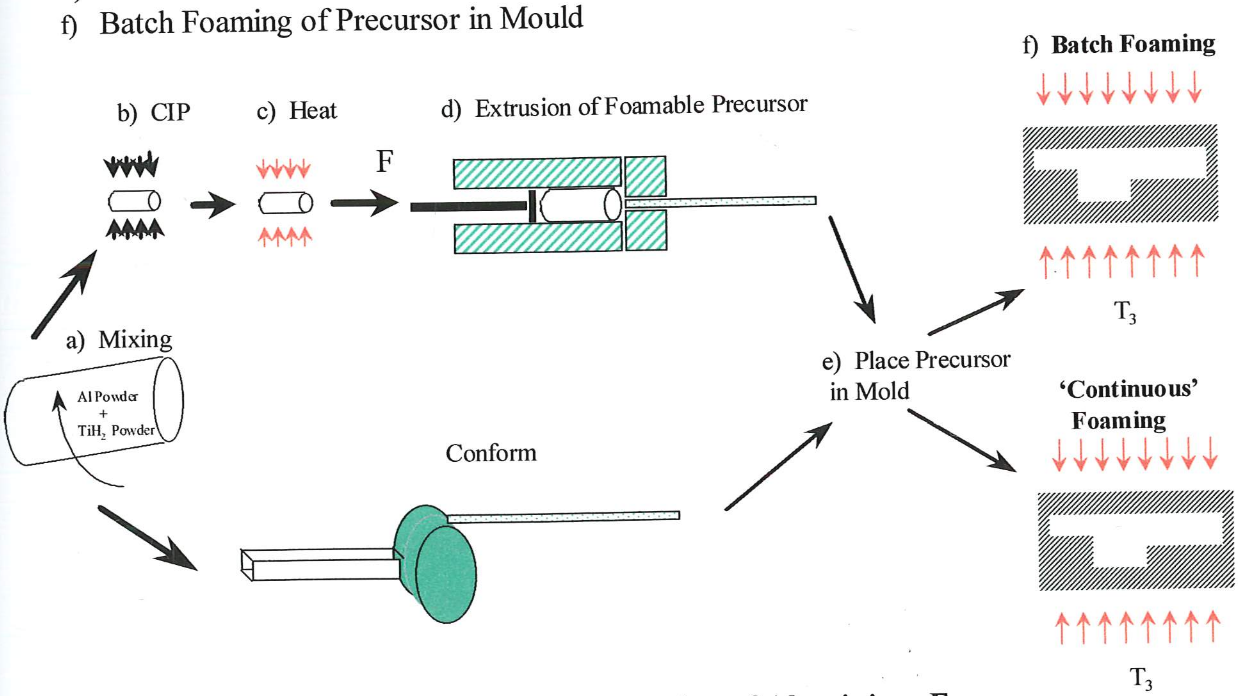


**Figure 4.4: Schematic of PM Processing of Aluminium Foam**

For higher production volumes, automation of steps b, c, and d and of steps e and f have been proposed as follows:

a) Mixing of the Al powder with the powdered foaming agent (< 1% $TiH_2$ )
b) Conversion of powder into precursor strip using the continuous CONFORM process
c) Quasi-continuous foaming of precursor in the mould, meaning that the moulds on a continuous belt are filled robotically, passed through the furnace, opened and emptied.

The rate-limiting step for the current low production volume process is the batch foaming step. The cycle time of this step is heat-transfer limited. The time required to heat the mould then increases with increased part dimensions and the time required to transfer heat into the precursor strips increases both with increasing part dimensions and with part curvature.

An important cost driver in this process is the substantial amount of scrap generated in the foaming stage in order to ensure mould filling, shape definition, and to avoid weak zones along the interfaces of the precursor strips where they meet during foaming. The cost of processing the material lost during the foaming stage is reflected in the material cost line item of the batch foaming and continuous foaming stages. It is assumed that the scrap material can be sold as prompt scrap.

By running comparison scenarios with this model, it was determined that the CONFORM process is not a viable alternative to the manual steps of billet pressing, billet heating, and extrusion of the precursor strips. However, a quasi-continuous foaming process (see Appendix D) to automate the current rate limiting batch process appears viable from this analysis. A comparison was run for a simple flat panel of aluminium foam made by the three options of liquid state processing, batch powder metallurgical processing, and the proposed quasi-continuous powder metallurgical process without the uneconomical CONFORM step. This simple flat panel comparison inherently favours the liquid state process of Section 4.2.1, which is set up for the continuous production of flat panels. Figure **4.5** depicts the relative cost per unit of each of the different options over a range of annual production volumes. For annual production volumes of up to 20,000 parts, the batch powder metallurgical process is the most economical option. From examining Figure **4.6**, which shows a snapshot of the line item costs for each process at

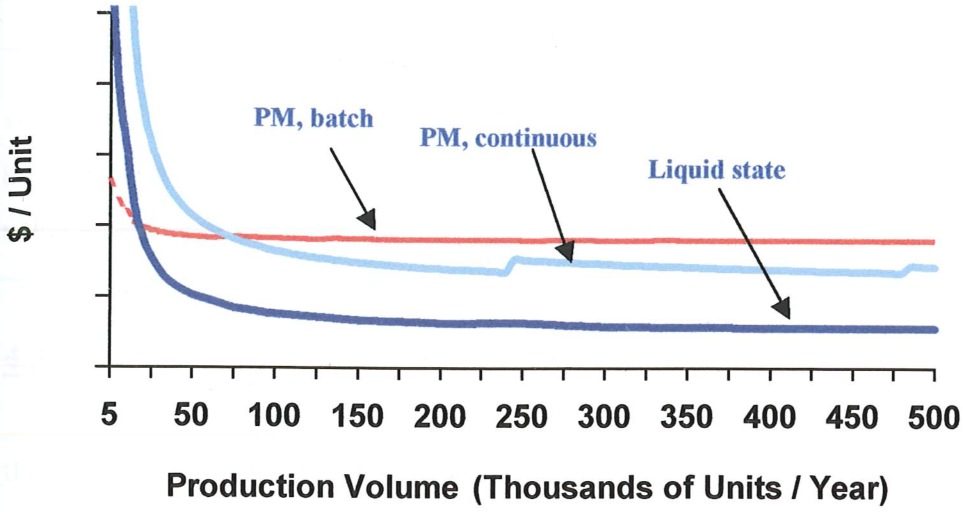


**Figure 4.5: Production Cost for Processing of Aluminium Foam by Three Methods**

20,000 and 300,000 parts per year, we can see that it is fixed costs, in particular equipment costs, that drive the low volume cost of both continuous PM processing and liquid state processing higher than that of batch PM processing. In this way, the TCM can be used to aid the decision about the suitability of converting to a continuous process.

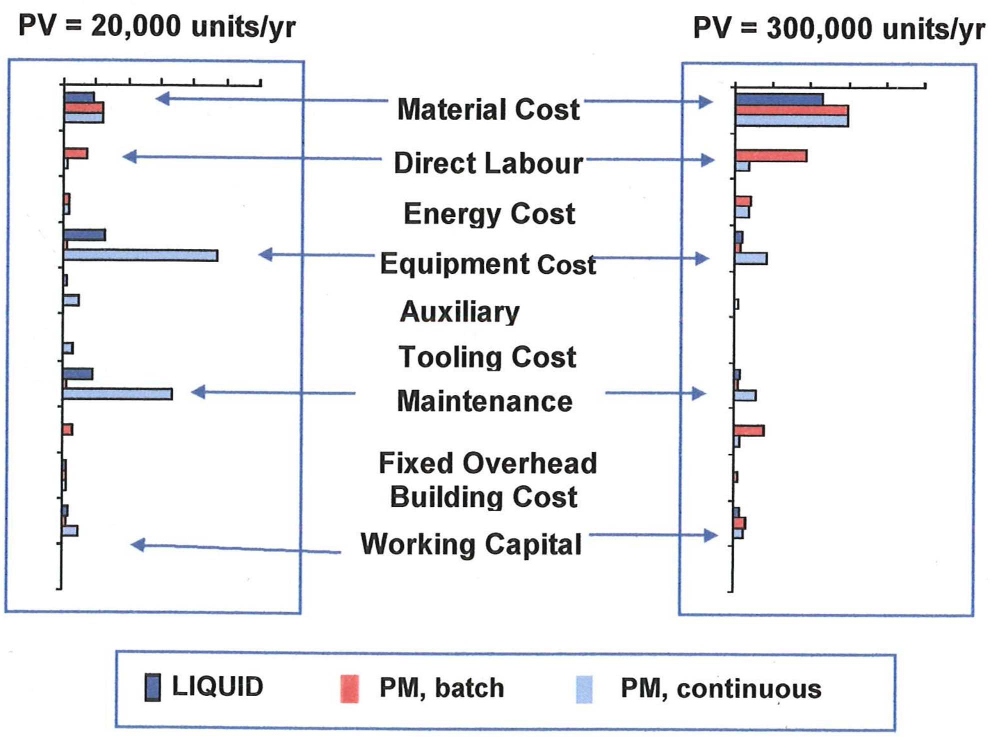


**Figure 4.6: Line Item Cost for Crossover Annual Production Volume of 20,000 and 70,000 units: Processing of Aluminium Foam by Three Methods**

By comparing the cheapest aluminium foam component (at the required production volume) with an incumbent material for any given application, the cost differential between a new and an incumbent material solution can be established. This provides input into the value assessment.

## 4.3 Market Assessment of Potential Applications

Potential markets are identified by scanning all known markets for the utility of those unique technical parameters identified by the technical analysis (Section 4.1). In the case of aluminium foams, the strong technical parameters are energy absorbed per unit volume or weight, bending stiffness per unit weight, and energy absorbed per unit stiffness. For the first two of these, applications with a high utility for energy absorption are sought. From among these, applications in which these functions are combined with others (such as flame resistance, heat dissipation, noise reduction, water resistance, blast amelioration), providing a multifunctional role, are particularly attractive.

There are existing aerospace and automotive applications which require high energy absorption per unit volume. The large scale production of aluminium foams cannot yet meet the tolerances required for aerospace applications (other than the expensive Duocel, which finds a market in defense and space vehicles); thus, automotive applications are prioritised. Annual market size could be as high as $100 million, assuming 1lb of aluminium foam in every passenger car produced worldwide.

| **Transport System** | **U (US $/kg)** | **High End Utility Requirement** |
|---|---|---|
| Family Car<br>(based on fuel saving) | 0.5 - 1.5 | CAFE limit or secondary weight savings |
| Truck<br>(based on payload) | 5 - 10 | value of payload |
| Civil Aircraft<br>(based on payload) | 100 - 500 | power/weight ratio guarantee limit |
| Military Aircraft<br>(performance, payload) | 500 - 2,000 | power/weight ratio guarantee limit |
| Space Vehicle<br>(based on payload) | 1,000 - 10,000 | value of payload |
| Bicycle<br>(based on perceived performance) | 1 - 1,000 | Tour de France standard |

**Table 4.1: Utility of Weight Saving in Transport Systems**

To improve on this gross approximation, we look at available measures of the value of performance in automotive applications, (the "exchange constants" of section 3.2.3). In many engineering applications the exchange constants can be derived approximately from technical models. Thus the value of weight-saving in transport systems is derived from the fuel saving or the increased payload which this allows (see table **4.1**). A more detailed market assessment of potential automotive applications follows in the case study of chapters 5 and 6.

## 4.4 Value Analysis for Metal Foam Applications

### 4.4.1 Multi-Objective Optimisation and Trade-off Surfaces

The viability of a foam in a given application depends on the balance between its performance and its cost. There may be several performance metrics that are important for the substitution decision, and the combination of these metrics and cost can be compared with those of the incumbent through the use of multi-objective optimisation techniques.

Consider the performance-cost tradeoff of aluminium foams versus all other materials for the light, stiff panel of section 4.1. (This example is relevant in many automotive, aerospace, and infrastructure applications). A cost metric – the cost per unit stiffness - is plotted along the vertical axis and a performance metric – the mass per unit stiffness – is plotted on the horizontal axis. The Pareto set (shown by the tradeoff line in figure **4.8**) is the lower envelope of materials on this plot. The three aluminium foams that lie on this tradeoff surface are shown in black. It is clear that the foams are attractive candidates when the value associated with weight savings is high. Dominated solutions (those to the right of the tradeoff surface on figure **4.8**) are never the best solution for an application. Non-dominated solutions are the best solution for an application with a value curve which intersects their position on the tradeoff surface.

Thus, the next step is to plot the value curves for different applications with different exchange constants onto this graph, or evaluate them numerically.* Table **4.2** illustrates the numerical method. Here $P_1$ is the weight-adjusted stiffness metric shown as the horizontal axis of figure 7, and $P_2$ is the cost metric shown as the vertical axis. For an exchange constant of $\alpha 1$=£0.5/kg, cast iron has the lowest value of V and is the best choice; but for a larger exchange constant of $\alpha 1$=£500/kg, the Alporas foam panel is a

* More detailed approaches to utility analysis can be found in "Materials Selection – Maximising Overall Utility", by Field and de Neufville, 1988.

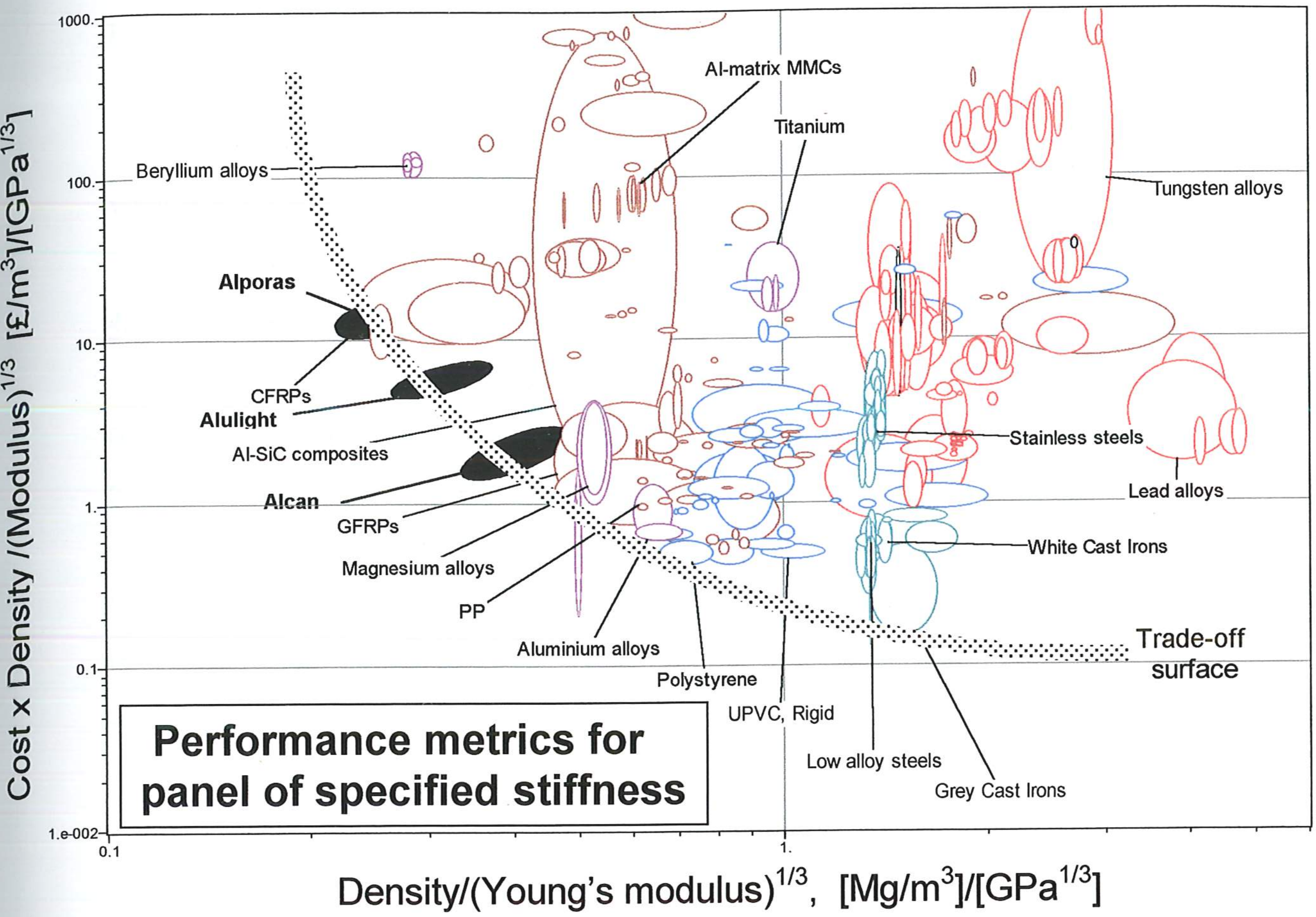


**Figure 4.8: Performance-Cost Tradeoff Example of a Light, Stiff Panel**

| Material | ρ Mg/m$^3$ | E GPa | $C_m$ £/kg | $P_1$ | $P_2$ | V $\alpha_1$=£0.5/kg | V $\alpha_1$=£500/kg |
|---|---|---|---|---|---|---|---|
| Cast iron, nodular | 7.30 | 175 | 0.25 | 1.31 | 0.33 | **0.99** | 655 |
| Low-alloy steel (4340) | 7.85 | 210 | 0.45 | 1.32 | 0.59 | 1.25 | 660 |
| Al 6061-T6 | 2.85 | 70 | 0.95 | 0.69 | 0.66 | 1.01 | 345 |
| Al-6061-20% SiC, PM | 2.77 | 102 | 25 | 0.59 | 14.8 | 15.1 | 309 |
| Ti-6-4 B265 grade 5 | 4.43 | 115 | 20 | 0.91 | 18.2 | 18.7 | 473 |
| Beryllium SR-200 | 1.84 | 305 | 250 | 0.27 | 67.5 | 67.6 | 202 |
| Alporas* | 0.25 | 1.0 | 40 | 0.23 | 10.0 | 10.1 | **125** |
| Alulight* | 0.30 | 0.8 | 16 | 0.3 | 5.2 | 5.4 | 155 |
| Alcan* | 0.25 | 0.4 | 5.8 | 0.34 | 2.0 | 2.2 | 172 |

**Table 4.2. The Selection of Panel Materials: Stiffness Constraint.**

*All three types of metal foam are made in a range of densities, with a corresponding range of properties. These three examples are taken from the middle of the ranges. The costs are estimates only, broadly typical of current prices, but certain to change in the future. It is anticipated that large-scale production could lead to substantially lower costs.

better choice than any other material. However, at these high prices, panels formed of aluminium honeycomb (not shown in this table) will likely become a better solution. Aluminium foam looks far more promising for energy absorbtion applications where volume is a premium. This case study is examined in detail in chapter 6 of this thesis.

## 4.5 Aluminium Foam Viability Assessment

From the analysis in this section and in the case study explored in chapter 5, we can see that aluminium foam is promising for energy absorption applications when space is at a premium. Section 4.4.1 illustrates that Aluminium foam panel are viable in stiffness constrained panel applications only when mass savings is valued at £500/kg or above. The case study in chapter 5 examines automotive energy absorption applications in detail, and concludes that aluminium foams are viable for A-pillar occupant safety applications under certain design constraints.

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[1] Ashby, 1999.

[2] Ashby, 1999.

# 5 Automotive Energy Absorption Applications for Aluminium Foams

In this chapter we explore the technical viability of metal foams in energy-absorbing applications. The chapter starts with a general discussion of energy absorption, and then presents a detailed case study of the substitution of metal extrusion deformation elements by metal foams in an automobile A-pillar.

## 5.1 Principles of Energy Absorption

Ideal energy absorbers have a long, flat stress-strain (or load-deflection) curve, like that of figure **5.1**: the absorber collapses plastically at a constant stress called *plateau stress*. Energy absorbers for packaging and protection are chosen so that the plateau stress is just below that which will cause damage to the packaged object; the best choice is then the one that has the longest plateau and therefore absorbs the most energy. Solid sections do not perform well in this role. Hollow tubes, shells, and metal honeycombs (loaded parallel to the axis of the hexagonal cells) have the right sort of stress-strain curves; so, too, do metal foams[1] (figure **5.2**).

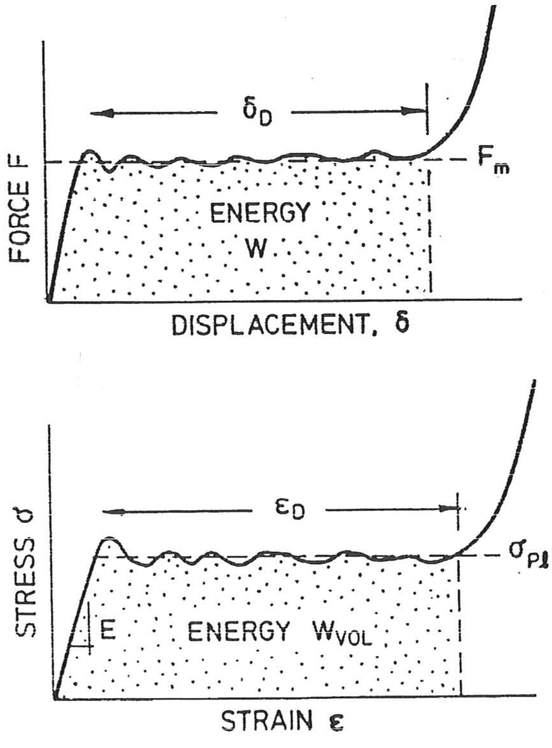


**Figure 5.1 (a)** A load-deflection curve and **(b)** a stress-curve for an energy absorber. The area under the flat part ('plateau') of the curves is the useful energy W, or energy per unit volume $W_V$, which can be absorbed. Here the F is the force, δ the displacement, σ the stress, and ε the strain.[1]

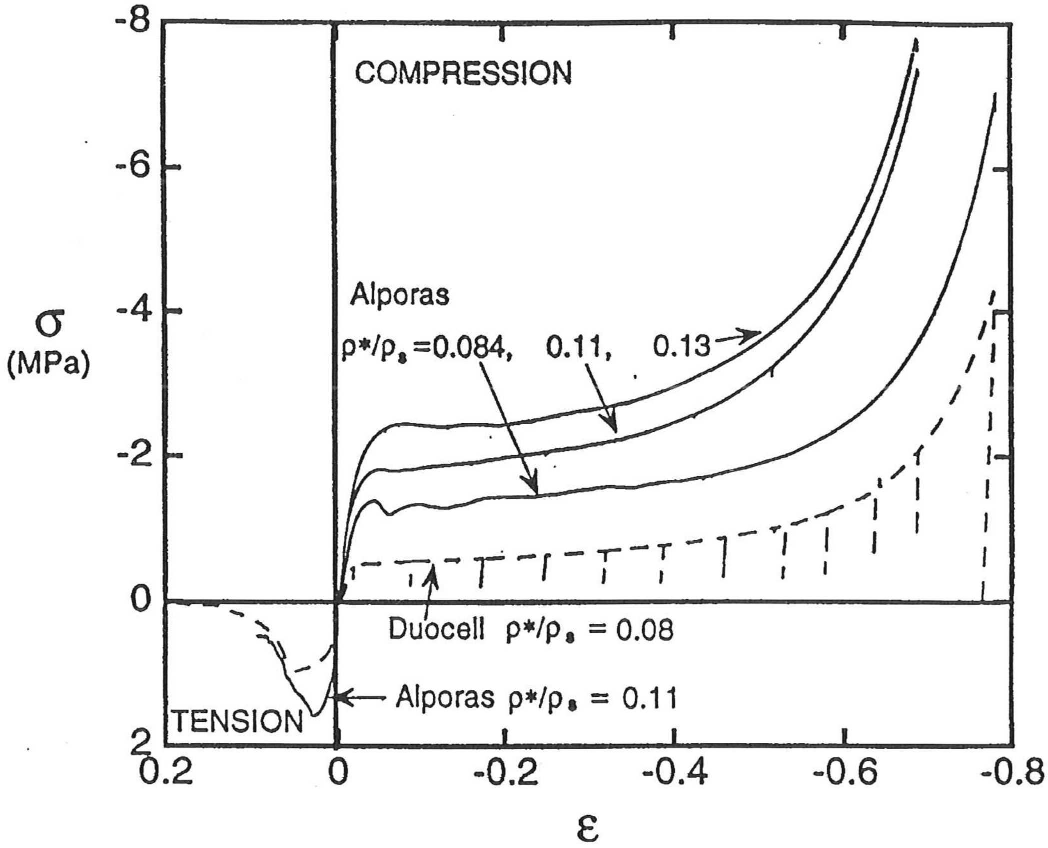


**Figure 5.2: Stress-Strain Curves of Closed-Cell Alporas and Open-Cell ERG Metal Foams.**[1]

### 5.1.1 Packaging and Damage Tolerance

The function of packaging is to protect the packaged object from damaging acceleration or deceleration. The acceleration or deceleration may be accidental (a drop from a fork-lift truck for instance, or a head impact in a car accident) or it may be anticipated (the landing-impact of a parachute drop; the launch of a rocket). The *damage tolerance* of an object is measured by the greatest acceleration or deceleration it can withstand without harm. Acceleration is measured in units of g, the acceleration due to gravity. Table **5.1** lists typical damage tolerances or 'limiting g-factors' for a range of products.

To protect fully, the package must absorb all the kinetic energy of the object in bringing it to rest. The kinetic energy depends on the mass m and the velocity v of the object:

$$KE = \frac{1}{2}mv^2 \qquad (1)$$

Typical velocities for the package design are listed in table **5.2**. They lie in the range 2 to 16 m/s. Package design seeks to bring the product, travelling at this velocity, to rest without exceeding its limiting g-factor.

| **Object** | **Limiting g-factor, a*** |
|---|---|
| Human body, sustained acceleration | 5 - 8 |
| Delicate instruments: gyroscopes | 15 -25 |
| Optical and X-ray equipment | 25 - 40 |
| Computer displays, printers, hard disk drives | 40 – 60 |
| Human head, 36 ms contact time | 55 – 60 |
| Stereos, T.V. receivers, floppy disk drives | 60 – 85 |
| Household appliances, furniture | 85 – 115 |
| Machine tools, engines, truck and car chassis | 115 – 150 |

**Table 5.1: Limiting g-Factors, a*, for a Number of Objects**

| **Condition** | **Velocity, m/s (km/hr)** |
|---|---|
| Freefall from forklift truck, drop height 0.3m | 2.4 (8.5) |
| Freefall from light equipment handler, drop height 0.5m | 3.2 (11.5) |
| Freefall of carried object of from table, drop height 1m | 4.5 (16.2) |
| Thrown package, freefall | 5.5 (19.8) |
| Automobile, head-impact, roll over crash in car* | 6.7 (24.1) |
| High drag parachute, landing velocity | 7 (25.2) |
| Pedestrian Protection (proposed) automotive legislation | 11.1 (40) |
| Low drag parachute, landing velocity | 13 (46.8) |
| Automobile, side impact, USA* | 8.9 (32.0) |
| Europe* | 13.4 (50) |
| Automobile, front impact, USA* | 13.4 (50) |
| Europe* | 15.6 (56) |

* Current Legislation

**Table 5.2: Impact Velocities for a Range of Conditions**

Package design for low-velocity (greatly subsonic) impact differs from that for high velocities (velocities in the sonic range), when elastic and plastic shock waves become important. Here we are concerned with low-velocity impacts.

### 5.1.2 The Basic Equations of Low-velocity Impact Package Design

Ideal energy absorbers have stress-strain curves like those of figure **5.1**. The absorber collapses plastically at the plateau stress, $\sigma_{pl}$, up to a limiting strain $\varepsilon_D$. The area under the flat part of the curve $\sigma_{pl}\ \varepsilon_D$, measures the energy the absorber can absorb per unit volume up to the end of the plateau. Real absorbers approximate the ideal, but are generally a little less good. The efficiency of an absorber (the ratio of actual energy absorbed to $\varepsilon_D$ divided by the ideal case) is given the symbol $B_j$ where $B_j = 1$ describes ideal behaviour. Real energy absorbers have sufficiently large values of B ($0.9 < B < 1$) that we can – at the level we want here – set $B = 1$ and thereafter ignore it.

Consider the package shown in figure **5.3**. It is made from an absorber with a plateau stress $\sigma_{pl}$ and a density strain $\varepsilon_D$. The packaged object, of mass m, can survive deceleration up to critical value $a^*$. From Newton's law the maximum allowable force is

$$F = m\,a^* \qquad (2)$$

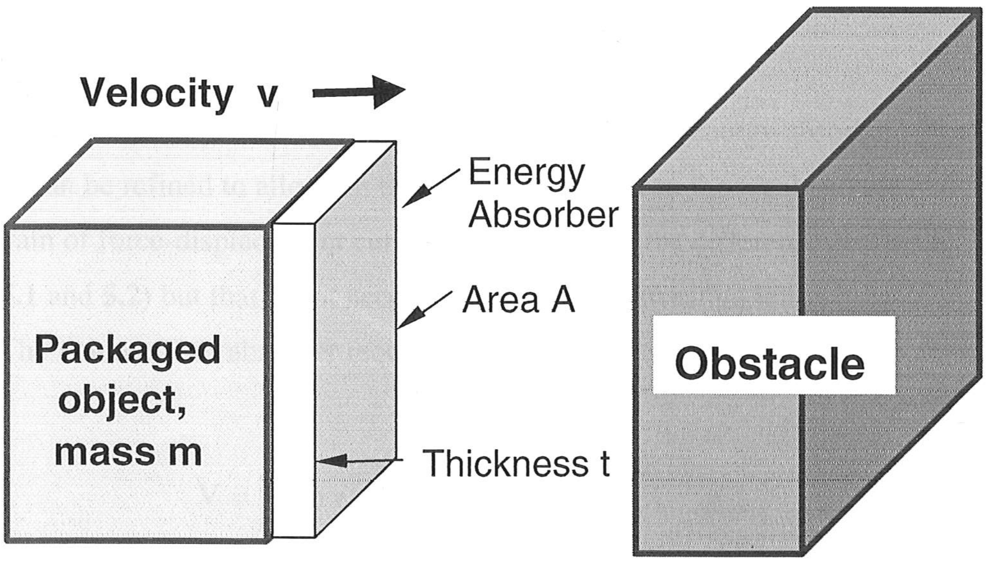


**Figure 5.3: A Packaged Object of Mass m Travelling at Velocity v.**

If the area of contact between the absorber and packaged object is A, the foam absorber will crush when

$$F = \sigma_{pl} A \tag{3}$$

Assembling these, we find the absorber that will just protect the packaged object from a deceleration $a^*$ is that with a plateau stress

$$\boxed{\sigma_{pl} \le \frac{ma^*}{A}} \tag{4}$$

It remains to decide how thick the package must be. The thickness set by the condition that all the kinetic energy of the object is absorbed if the absorber crushes to the end of its plateau. Equating the kinetic energy of equation (1) to the energy absorbed by thickness x of absorber when crushed to its densification strain $\varepsilon_D$ gives

$$\sigma_{pl}\varepsilon_D A x = \frac{1}{2} m v^2 \tag{5}$$

from which

$$\boxed{x = \frac{1}{2}\frac{mv^2}{\sigma_{pl}\varepsilon_D A}} \tag{6}$$

or, using equation (4)

$$\boxed{x = \frac{1}{2}\frac{v^2}{a^* \varepsilon_D}} \tag{7}$$

Equations (4) and (6) are the key to the initial selection of an energy absorber. The treatment can be refined to allow for the differences between the ideal and the real stress-strain of force-displacement curves of an absorber (the differences between figures **5.1** and **5.2**) but that is not necessary in an initial investigation.

The volume V of absorber required to fully protect the packaged object is $xA$; thus:

$$V = \left(\frac{1}{2} m v^2\right)\left(\frac{1}{\sigma_{pl}\varepsilon_D}\right)$$

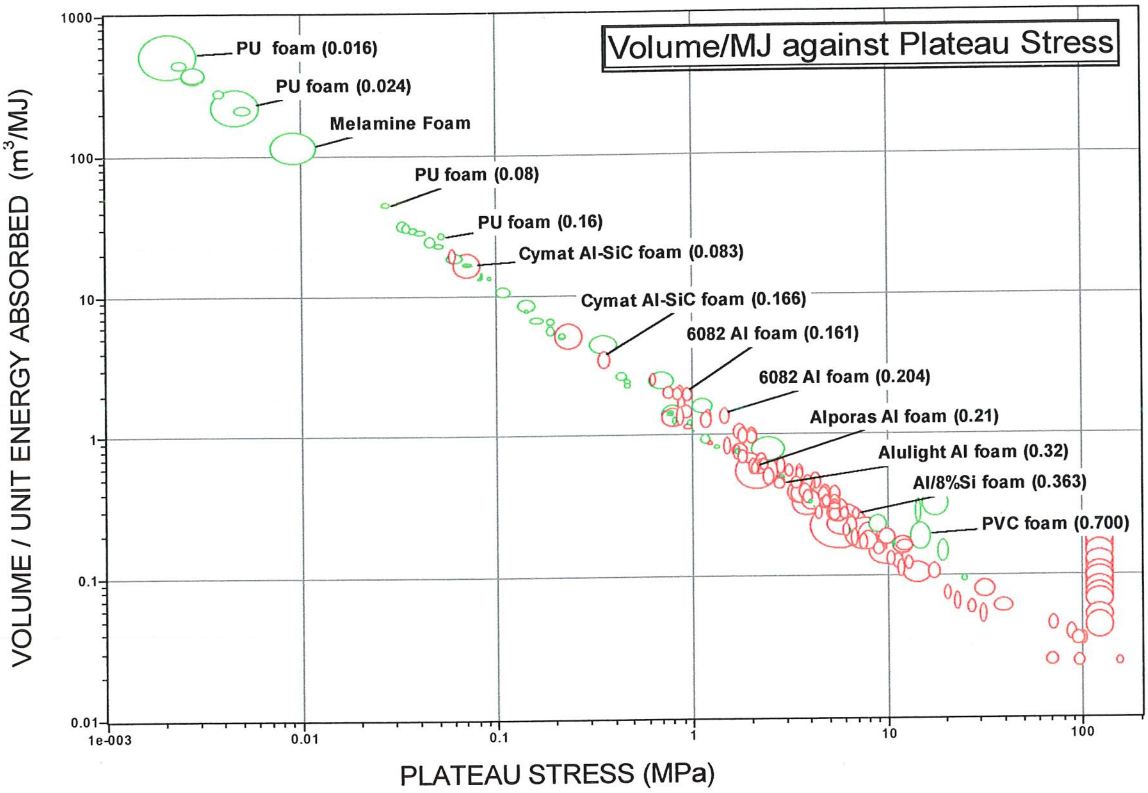


**Figure 5.4(a) Volume per MJ Plotted Against Plateau Stress.**

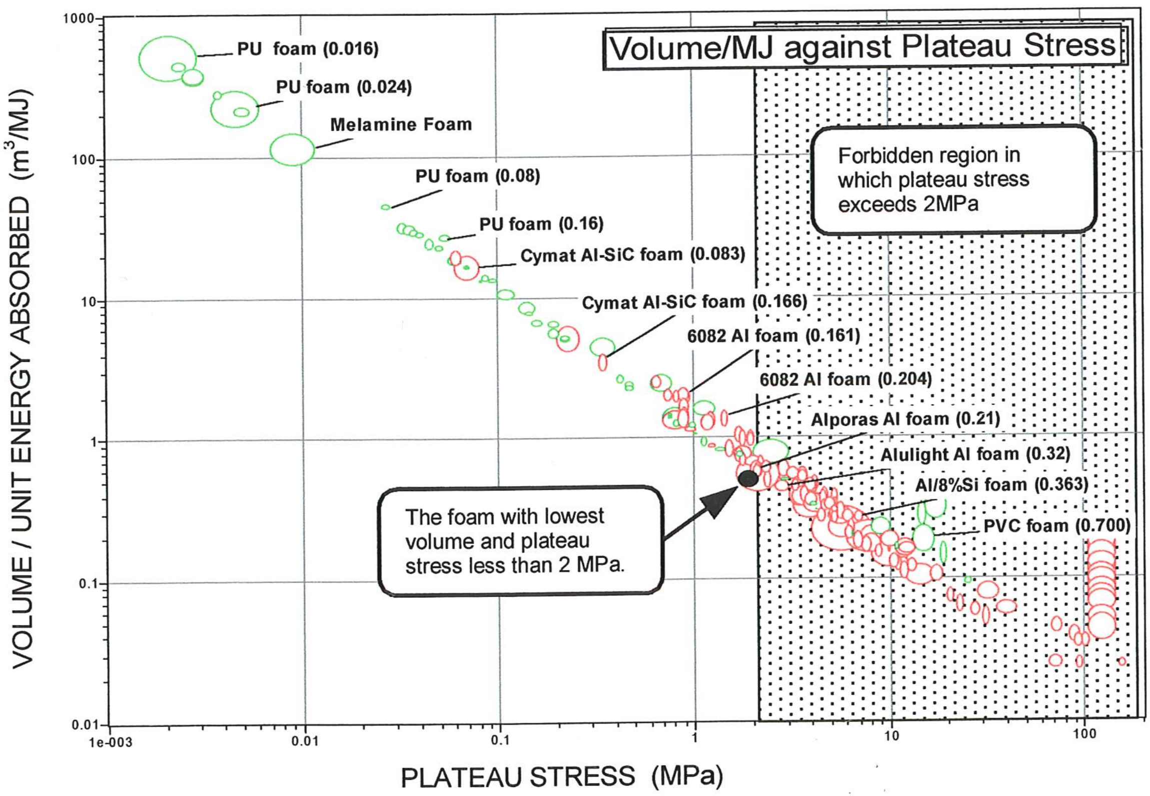


**Figure 5.4(b) The Use of Figure 5.4(a) to Select a Package Material.**

or, if, expressed as a volume per unit energy absorbed, $\tilde{V}$ ; it is

$$\tilde{V} = \frac{V}{\left(\frac{1}{2} m v^2\right)} = \left(\frac{1}{\sigma_{pl}\varepsilon_D}\right)$$

Thus to minimise the volume, we seek absorbers with the lowest values of

$$\tilde{V} = \left(\frac{1}{\sigma_{pl}\varepsilon_D}\right) \quad (8)$$

which at the same time satisfy equation (4).

Figure **5.4(a)** shows how this is done, taking foams as candidates.[1] The vertical axis plots $\tilde{V}$ (equation 8); the horizontal one plots the plateau stress $\sigma_{pl}$. Each bubble is a foam; those in green are polymer foams, and those in red are metal foams. A selection of the materials have been labelled. Polymer foams are labelled with their composition followed, in brackets, by their density in $Mg/m^3$. The metal foams are almost exclusively made of aluminium (alloyed with a foaming agent); they are labelled with their trade name followed, in brackets, by their density.

The first step is to mark the maximum acceptable value of $\sigma_{pl}$ onto the figure; only foams with a plateau stress less than this are acceptable. The second step is to read off the foam with the smallest value of $\tilde{V}$ since this is the one that safely protects at minimum volume. The two steps are illustrated in figure **5.4(b)**.

In some applications it is mass, not volume, that is to be minimised. The mass M of foams that will absorb all the kinetic energy of the packaged object is the volume times the foam density:

$$M = x\,A\,\rho = \left(\frac{1}{2} m\,v^2\right)\left(\frac{\rho}{\sigma_{pl}\,\varepsilon_D}\right)$$

or, if expressed as a mass per unit energy absorbed, it is

$$\tilde{M} = \frac{M}{\left(\frac{1}{2} m\,v^2\right)} = \left(\frac{\rho}{\sigma_{pl}\,\varepsilon_D}\right) \quad (9)$$

[1] The charts of Figure 6.4, 6.5, and 6.6 were constructed using the "Foams" data base of the Cambridge Engineering Selector (CES, 1999)

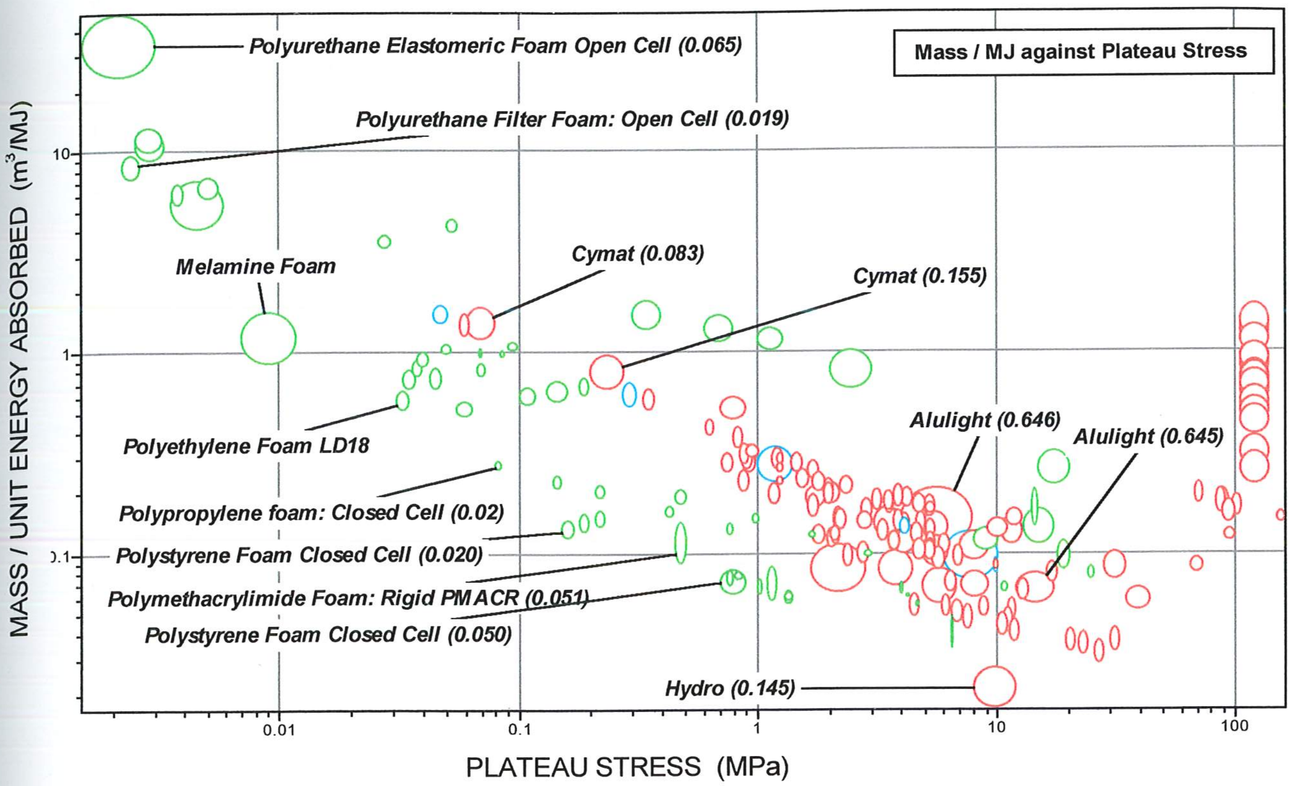


**Figure 5.5(a): Mass per MJ Plotted Against Plateau Stress.**

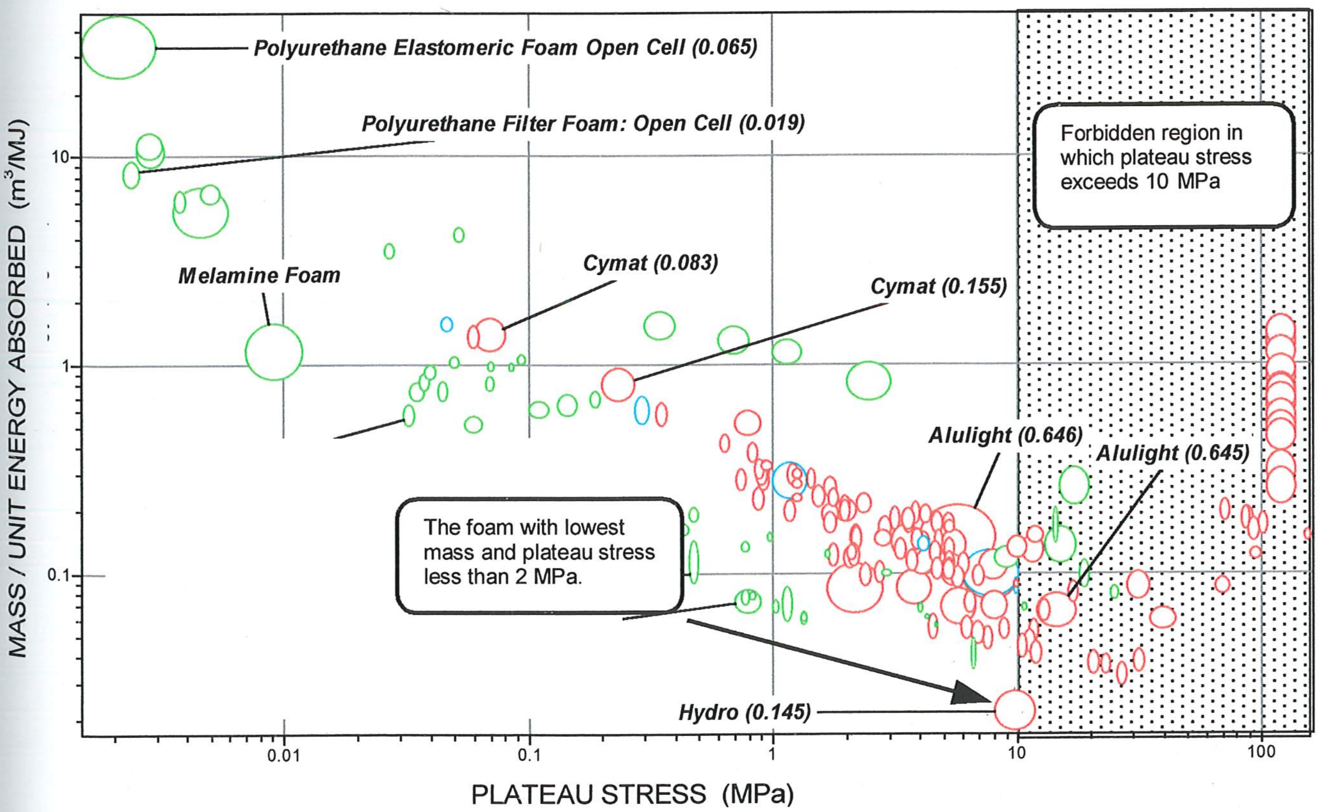


**Figure 5.5(b) The Use of Figure 5.5(a) to Select a Package Material.**

Figure **5.5** shows a plot of $\tilde{M}$ against the plateau stress $\sigma_{pl}$. It is used in the same way as figure **5.4**.

In most applications cost is also a consideration and this raises the issue of co-minimising two objectives – volume and cost (or mass and cost). In an application like that illustrated by figure **5.3**, the foam is used as a slab, more or less in its as-received form except for cutting to size. In such a case, the cost C of the finished block of foam is essential that of the foam itself, $C_m M$, where $C_m$ is the cost per kg of the foam[2] Thus

$$C = C_m M = \left(\frac{1}{2} m v^2\right)\left(\frac{C_m \rho}{\sigma_{pl} \varepsilon_D}\right)$$

or, expressed as a cost per unit energy absorbed, $\tilde{C}$,

$$\tilde{C} = \frac{C}{\left(\frac{1}{2} m v^2\right)} = \left(\frac{C_m \rho}{\sigma_{pl} \varepsilon_D}\right) \qquad (10)$$

Co-minimisation of two objectives was discussed in Chapter 4, which introduced the idea of trade-off plots. Examples of such plots for co-minimising volume and cost in energy-absorbing applications is shown in figure **5.6(a,b,c)**. These require a little explanation. The vertical axis is the same as that of figure **5.4**: it is the normalised volume, $\tilde{V}$. The horizontal axis plots the normalised cost, $\tilde{C}$. Each bubble is a foam, but only foams with a plateau stress below a chosen critical value are shown: for figure **5.6(a)** it is 10 MPa; for figure **5.6(b)** it is 3.5 MPa; and for figure **5.6(c)** it is 1 MPa. Thus *all* the foams on a given figure are candidates provided the critical plateau stress of equation (4) is that to which the figure applies.

The materials found along the tradeoff surface are the best solutions. Figure **5.6(a)** includes all metal and polymer foams with plateau stress of 10 MPa or less, which could be the plateau stress for an application such as the packaging for the air drop of machine tools and engines. Here the best choice, co-minimising volume and cost, is the metal foam labelled Hydro (0.3). Figure **5.6(b)** shows the materials with plateau stresses below 3.5 MPa, which could represent automotive occupant safety

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[2] When, as in the Case Study that follows, the foam must be shaped, the cost of shaping can be significant, and must be included.

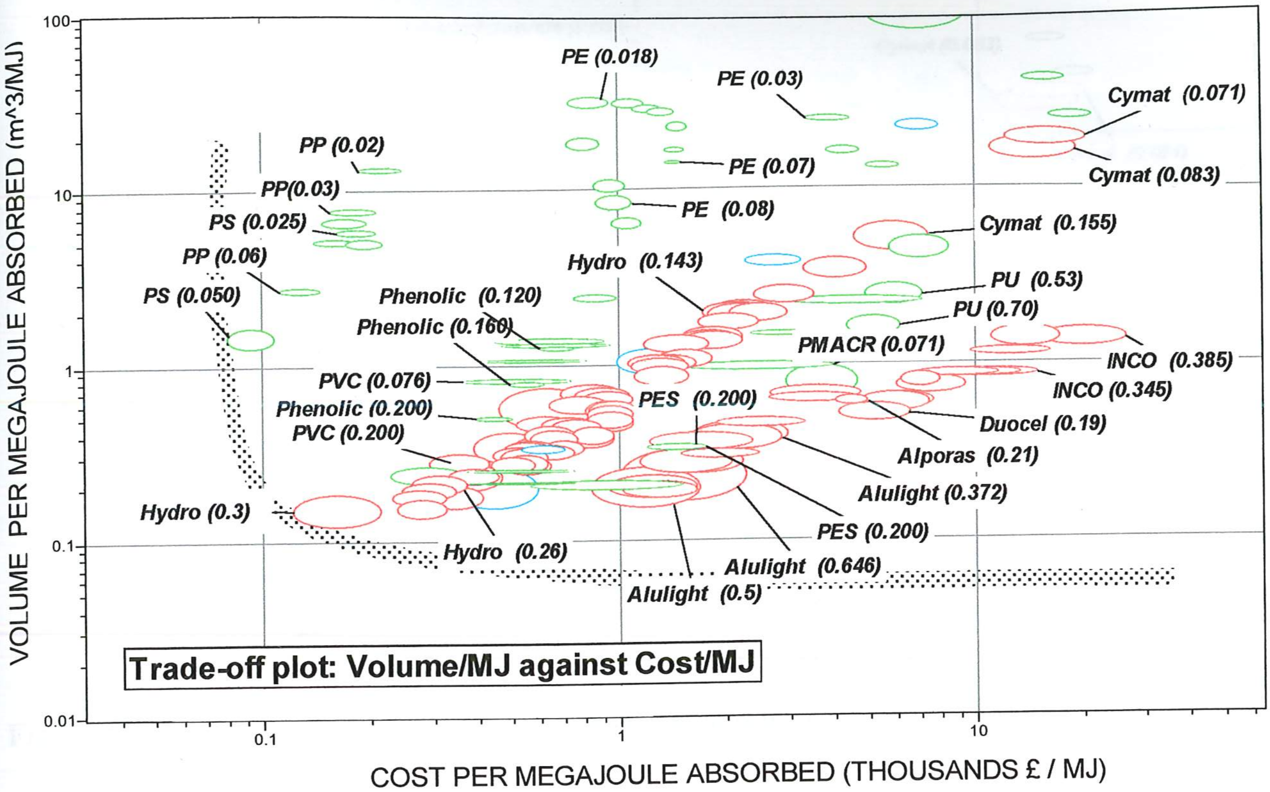


**Figure 5.6a: Selection of Metal Foams and Polymer Foams by Volume and Cost with $\sigma_{pl} \leq 10$ MPa**

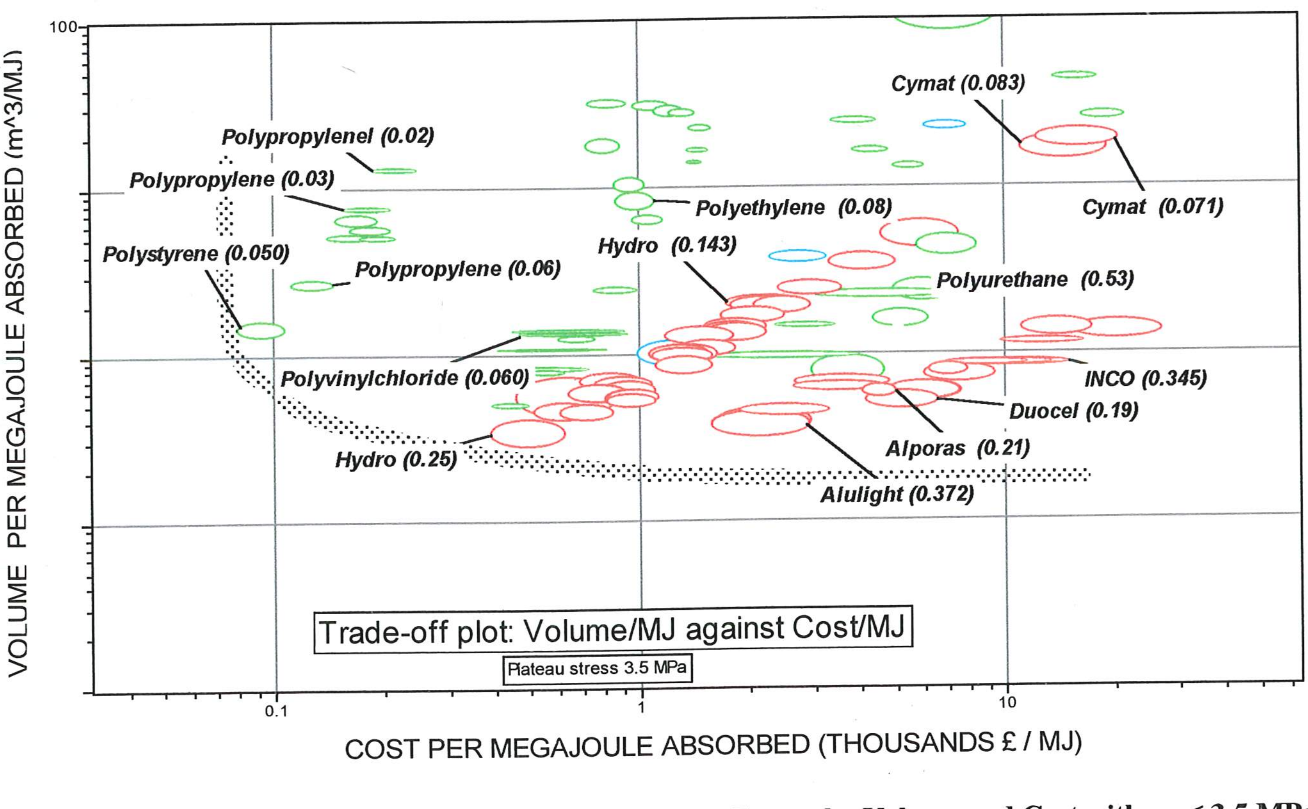


**Figure 5.6b: Selection of Metal Foams and Polymer Foams by Volume and Cost with $\sigma_{pl} \leq 3.5$ MPa**

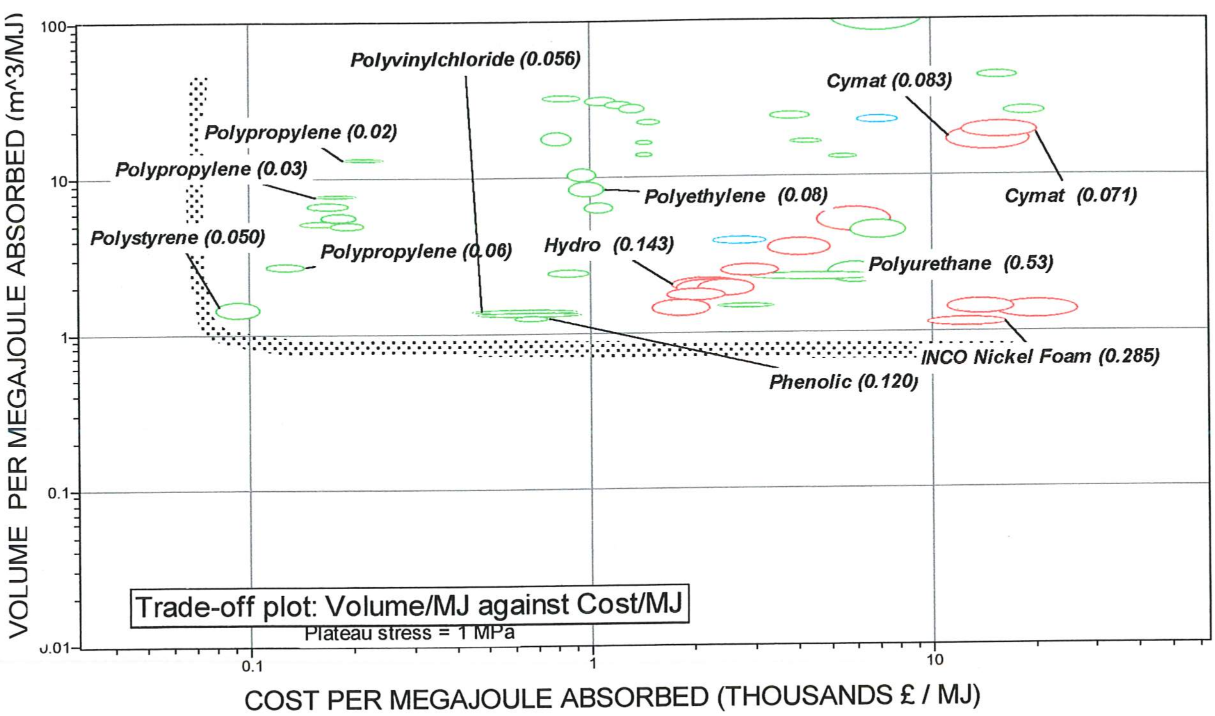


**Figure 5.6c: Selection of Metal Foams and Polymer Foams by Volume and Cost with $\sigma_{pl} \leq 1$ MPa**

applications. Here the aluminium foam labelled Hydro (0.25) has the lowest volume and could be the best solution for automotive occupant and pedestrian head protection applications. Finally, figure **5.6(c)** shows foams with plateau stresses below 1 MPa, desirable for packaging delicate instruments, for example. Now polymer foams are the best choice – polystyrene (0.05), particularly, minimises both volume and cost.

## 5.2 Case Study: The Viability of Metal Foams for Automobile Occupant and Pedestrian Head Protection

### 5.2.1 Introduction

Currently, passenger head protection is regulated in the US market by the Federal Motor Vehicle Safety Standard (FMVSS) 201u. This regulation limits the allowable resultant acceleration for an automobile occupant's head under certain crash and rollover conditions. Hence, potential head impact areas on all upper interior components of the passenger vehicle must pass the Head Impact Criteria (HIC). Proposed legislation to increase passenger head protection to safe levels for higher velocity impacts (HIC d) is currently under consideration. Due to design constraints, it is particularly difficult to meet the new criteria for the A-pillar, which is the vertical structural pillar that borders the windshield on either side of the car. Currently, crush elements (such as hollow hexagonal extruded metal profiles) are attached to the inside face of the A-pillar to absorb energy during head impact. The possibility of meeting the current HIC and/or new HIC(d) legislation with metal foam crush elements is explored in this paper. The criteria states that

$$\mathrm{HIC} = \left\{ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, dt \right\}^{2.5} (t_2 - t_1) \leq 1000 \qquad (11)$$

where a = resultant acceleration magnitude of the headform in g units, and $t_1$ and $t_2$ are any two points in time during the impact event separated by not more than a 36 millisecond time.[2]

$$\mathrm{HIC(d)} = 0.75446\,(\mathrm{HIC}) + 166.4 \ \leq 1000 \qquad (12)$$

For the legislated tests, a dummy head form with mass 4.8kg is crashed against the A-pillar at a speed of 24.1 km/h. The impact zone on the dummy forehead is of dimension 125 mm x 100 mm, as shown in figure **5.7**. Generally, actual contact occurs over an area of 20 mm x 40 mm within this zone.

A second major head impact legislation change is proposed by the European Commission in Brussels. This legislation[3] outlines four tests that all cars would have to meet by 2005 in order to protect pedestrians from serious injury resulting from impact at speeds up to 40 km / hr. Two of the four tests are head

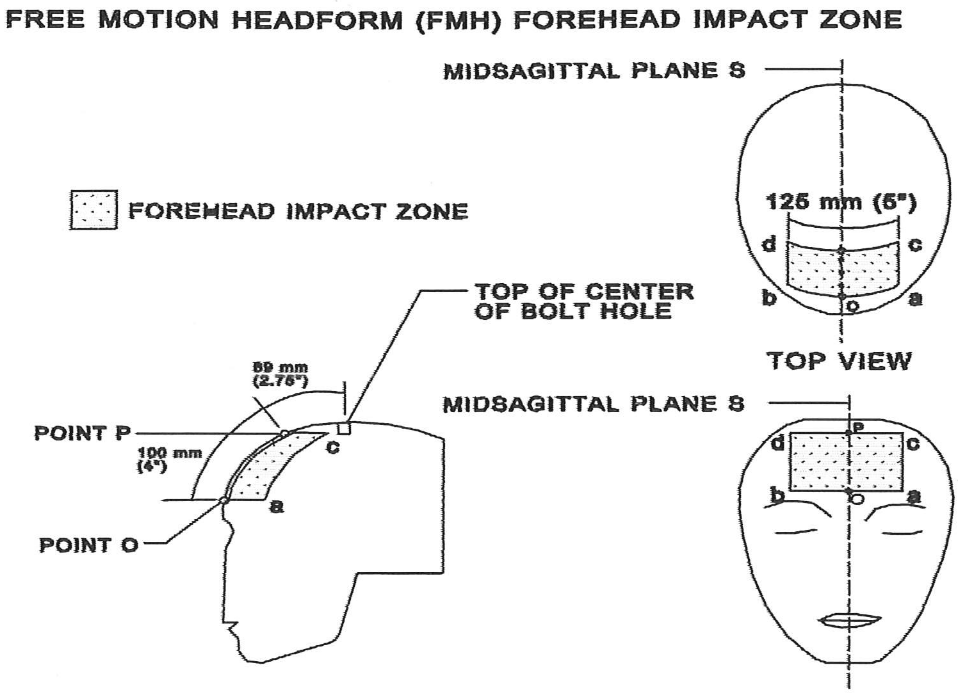


**Figure 5.7: FMVSS201u Head Impact Legislation**

impact tests, including an adult headform (4.8 kg and impacting at 25 degrees from vertical) and a child headform (2.5 kg and impacting at 40 degrees from vertical), as shown in figure **5.8**.

Identical HICd regulations as those governing passenger head impacts would be imposed. The areas of the vehicle that must meet the legislative requirements for energy absorption are the upper portion of the hood for the adult headform and the lower (frontal) portion of the hood for the child headform.[4] Foams are for use under the hood in order to meet the proposed pedestrian protection legislation.

### 5.2.2 Selection of Foams for A-Pillar Head Protection

Reducing head injury in an impact to an acceptable level requires that the deceleration, a, in units of g, must not exceed the value $a^*$ defined by Equation (11).

The quantity in curly brackets is the average deceleration, $\bar{a}$. For an initial exploration of the choice of materials for head protection, we will work with this quantity. Equation (11) then becomes

$$\bar{a}^* = \left(\frac{1000}{\Delta t}\right)^{0.4} \quad \text{(units of g)} \qquad (13)$$

where $\bar{a}^*$ is the critical value of $\bar{a}$ which must not be exceeded and $\Delta t = t_2 - t_1$ is the contact time. If the contact time is 35ms, the value of $\bar{a}^*$ is 60g for the current HIC legislation. In order to meet the more stringent HIC (d) legislation, the value of $\bar{a}^*$ would be 42.5g.

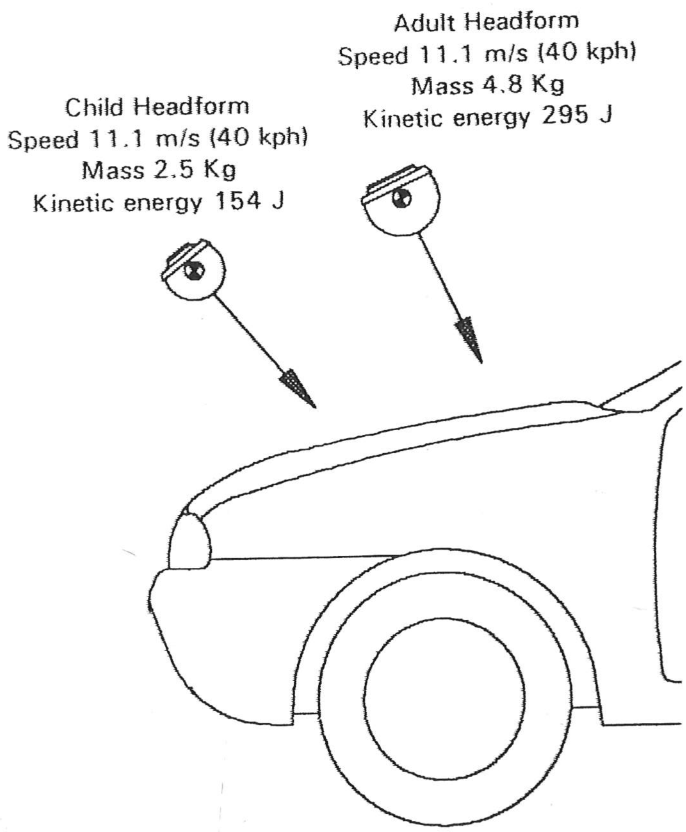


**Figure 5.8: Proposed Pedestrian Protection Head Impact Legislation**[4]

An adult human head weighs approximately 4.5kg. A typical value for the contact area between head and A-pillar is typically $A \approx 40\text{mm} \times 20\text{mm} = 0.0008\ \text{m}^2$. Inserting this value of $A$, together with $\bar{a}^* = 60g*$ and $m = 4.5\text{kg}$ into equation (4) gives:

$$\sigma_{pl} \leq 3.5\ \text{MPa} \qquad (14)$$

Foam-based energy absorbing structures exploit the plateau of their stress-strain curve, which allows energy to be absorbed at a near-constant deceleration. In selecting a foam for passenger protection, the plateau stress is chosen to be equal to the value calculated above. The thickness of foam is then chosen to absorb the kinetic energy of the packaged object (in this case the head) moving at an initial velocity of v. It is given by equation (6). Using the data given above, and with v = 24.1 km/hr and $\varepsilon_D = 0.8$ gives

$$x \geq 45\text{mm} \tag{15}$$

Up until this point, we have been assuming that 100% of the energy absorbed in this test legislation must be dissipated by the crushing of the energy absorbing element (here an aluminium foam part). However, in realistic automotive applications, a substantial portion of the energy is absorbed by the deflection of the BIW structure. For very stiff structures with the A-pillar rigidly attached, approximately 25% of the energy could be absorbed by the BIW structure. For less stiff structures with some elasticity in the A-pillar, 75% of the energy required to meet the HIC legislation can be absorbed by the BIW structure.[5] Thus, the required thickness of the A-pillar energy absorption element is dependent on the stiffness of the structure. In the above example, it could vary from a thickness of 11mm to 34mm.

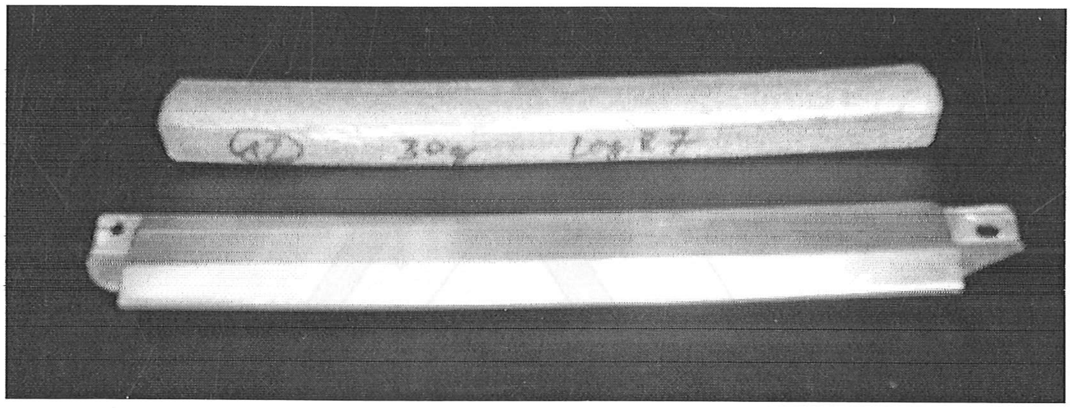

**Figure 5.9: Hexagonal Tube and Aluminium Foam Deformation Elements**

### 5.2.3 The crushing of hexagonal tubes

One current design of an A-pillar energy absorber is based on the crushing of a hexagonal aluminium extrusion. The force-deflection curve for the transverse crushing of a tube has a shape which closely resembles that of figure **5.1**. Consider the crushing of the hexagonal tube of figure **5.10**, caused by a compressive force F. Transverse compression creates plastic hinges at the corners of the hexagon, 4 of which open by an angle $\delta\theta$ and two of which close by an angle $2\,\delta\theta$. The work done in causing one hinge to rotate through $\delta\theta$ is

$$\delta W = M_p \delta\theta$$

Here $M_p$ is the fully-plastic moment of the material of the tube wall:

$$M_p = \frac{b\,w^2}{2}\sigma_y$$

where $w$ is the wall thickness, $b$ the length of the tube and $\sigma_y$ the yield strength of the material of which the tube is made. The work done by the force is F

$$F\delta u = 8M_p\delta\theta$$

where $\delta u$ is the displacement through which F acts during the rotations $\delta\theta$:

$$\delta u = \ell\cos\left(\frac{\theta}{2}\right)\delta\theta$$

Thus

$$F = \frac{8M_p}{\ell\cos\frac{\theta}{2}} = \frac{4\,b\,w^2}{\ell\cos\frac{\theta}{2}}.\sigma_y \qquad (16)$$

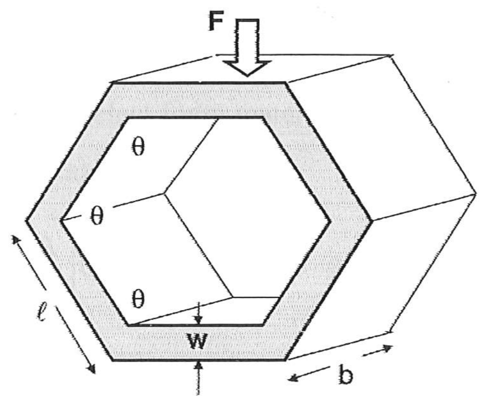


**Figure 5.10: A Hexagonal Tube Energy Absorber**

The projected area of the tube normal to F is $\ell b\left(1+2\cos\frac{\theta}{2}\right)$, so that the plateau stress of the crushing tube is

$$\sigma_{pl} = \frac{F}{b\ell\left(1+2\cos\frac{\theta}{2}\right)} = \frac{4w^2\sigma_y}{\ell^2\cos\left(\frac{\theta}{2}\right)\left(1+2\cos\frac{\theta}{2}\right)} \tag{17}$$

The term involving $\theta$ in this equation is equal to unity for $\theta = 120^0$, so that to an adequate approximation,

$$\sigma_{p\ell} = 4\frac{w^2}{\ell^2}\sigma_y \tag{18}$$

The tube crushes until opposite faces meet when the strain is

$$\varepsilon_D = \frac{2\ell\sin\frac{\theta}{2} - 2w}{2\ell\sin\frac{\theta}{2}} = 1 - \frac{w}{\ell\sin\frac{\theta}{2}} = 1 - \frac{2}{\sqrt{3}}\frac{w}{\ell} \tag{19}$$

Thus a deformation tube can be designed to a specific desired plateau stress and densification strain, limited only by the dimensions of the available space in the A-pillar. However, the manufacturing of a curved hexagonal aluminium extrusion leads to an expensive solution and the dimensional limitations are not always desirable.

### 5.2.4 Selection of Foams Using Cambridge Engineering Selector

Aluminium foams and polymer foams can represent a cheaper solution. Mapping out the most promising foams is a logical method of selecting which materials to test further. Plots to select foam material and thickness are constructed by rearranging equations (4) and (7a) to give

$$a^* = \left[\frac{A}{m}\right]\sigma_{pl} = \alpha_1\,\sigma_{pl}$$

and

$$x = \left[\frac{1}{2}\frac{mv^2}{A}\right]\frac{1}{\sigma_{pl}\varepsilon_D} = \alpha_2\frac{1}{\sigma_{pl}\varepsilon_D}$$

Values for $\alpha_1$ and $\alpha_2$ are given below in table **5.3**, for a number of scenarios. These factors relate the acceleration, velocity, and contact area requirements of the application to the material properties of plateau stress $\sigma_{pl}$ and density strain $\varepsilon_D$.

These factors enable application specific plots to be quickly created (figures **5.11** and **5.12**) and for thickness to be correlated with limiting decelerations. Figure **5.11** depicts the standard test conditions for an A-pillar occupant safety test. In this case of flexible BIW structure, the required A-pillar deformation element thickness is 30 mm and can be made of either aluminium foam or a polymer foam. A thickness of 210 mm is required for the pedestrian protection example (figures **5.8** and **5.12**) which is infeasible regardless of which material chosen.

| Area A, $m^2$ | Mass m, kg | Velocity v m/s (km/hr) | Knock-down factor | Factor $\alpha_1$ | Factor $\alpha_2$ (a* in g) |
|---|---|---|---|---|---|
| 0.0008 | 4.5 (adult head) | 11.2 (40) | 1 | 1.8 x $10^{+1}$ | 3.5 x $10^{-1}$ |
| | | | 0.75 | | 2.6 x $10^{-1}$ |
| | | | 0.25 | | 8.8 x $10^{-2}$ |
| | | 6.7 (24.1) | 1 | | 1.3 x $10^{-1}$ |
| | | | 0.75 | | 9.5 x $10^{-2}$ |
| | | | 0.25 | | 3.2 x $10^{-2}$ |
| 0.0008 | 2.5 (child head) | 11.2 (40) | 1 | 3.3 x $10^{+1}$ | 3.5 x $10^{-1}$ |
| | | | 0.75 | | 2.6 x $10^{-1}$ |
| | | | 0.25 | | 8.8 x $10^{-2}$ |
| | | 6.7 (24.1) | 1 | | 1.3 x $10^{-1}$ |
| | | | 0.75 | | 9.5 x $10^{-2}$ |
| | | | 0.25 | | 3.2 x $10^{-2}$ |

**Table 5.3: Calculating Factors $\alpha_1$ and $\alpha_2$**

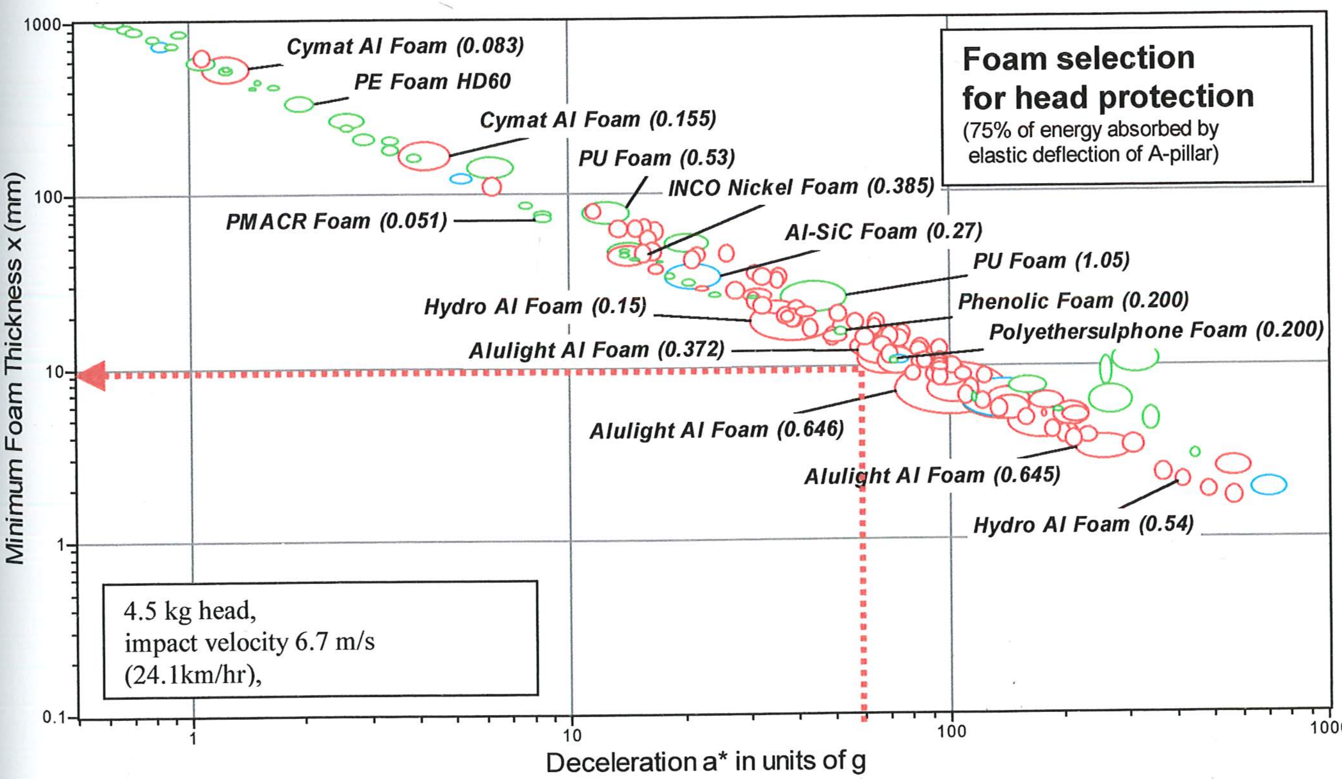


**Figure 5.11: Foam Selection for Automotive A-Pillar Application**

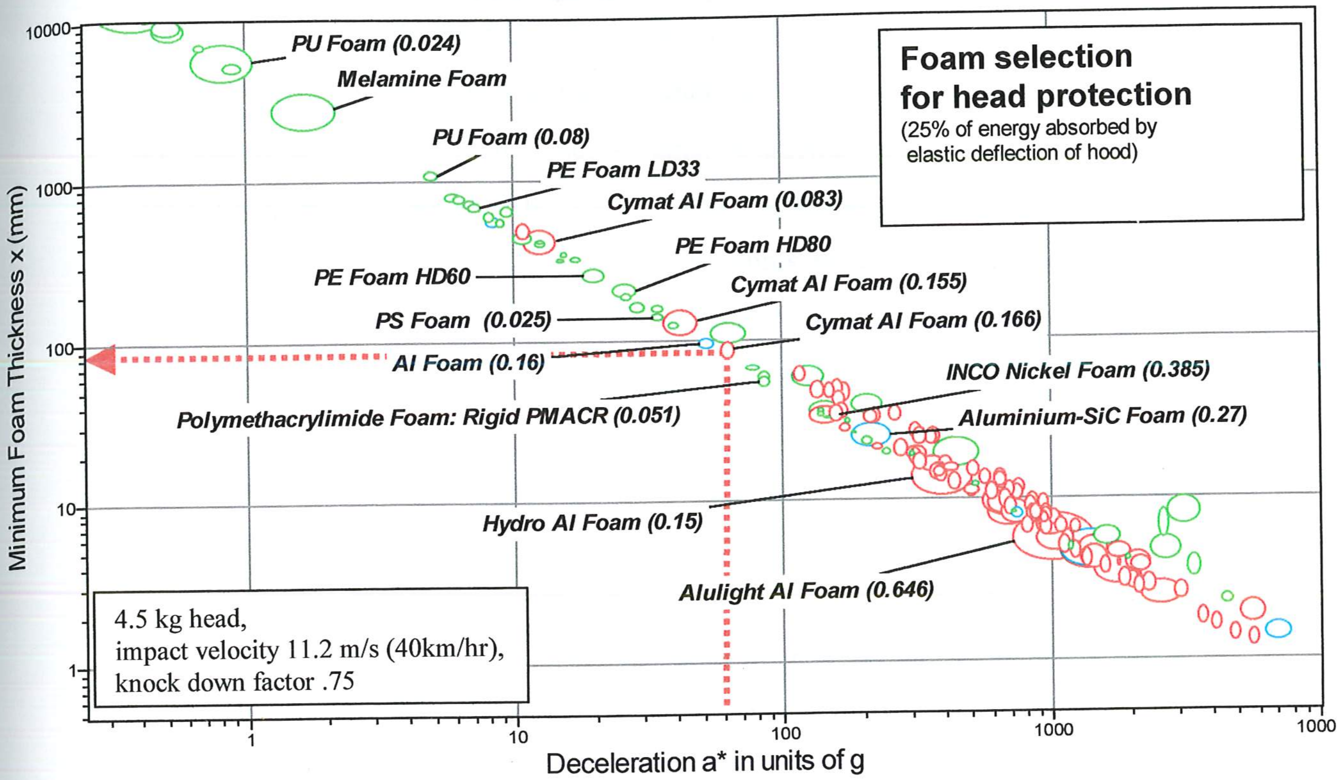


**Figure 5.12: Foam Selection for Automotive Pedestrian Protection Applications**

## 5.3 Conclusions of the Case Study

This case study illustrates the screening of materials for automotive head protection alternatives. The leading candidates for these energy absorbing applications are polymer foams, metal foams, hexagonal tubes, honeycomb structures, and airbags. Airbags are an expensive and heavy solution, so in most cases are reserved as a last alternative. Honeycomb structures are also generally very expensive. Many polymer foams are suitable subject to space restrictions. Aluminium foam of medium to low relative density meet the requirements of high energy absorption per unit volume and sufficiently low plateau stress. Hexagonal tubes, too, can be designed to have the optimal plateau stress. Thus, metal foams and hexagonal absorbers are almost equally efficient as energy absorbers. Metal foams have a cost advantage when the absorber must be shaped to a complex profile or be tailored to fit in to a complex shape, and a performance advantage under circumstances in which the direction of impact may be uncertain.

Aluminium foams appear to be promising solutions for A-pillar, and other interior occupant safety applications. As the velocity requirement is reduced, the foam thickness (which scales as $v^2$ – see equation (7)) falls rapidly. Current A-pillar legislation, which requires protection against an impact of 24.1 km/hr, can be accomplished with a thickness of between 11 mm and 34mm of foam, dependent on the stiffness of the BIW structure. The same energy absorption requires thicknesses of polyurethane foam between 24 mm and 150mm in thickness, again dependent on the stiffness of the BIW structure. Where low cost is of higher priority than low volume, polymer foams are the leading contender for automotive energy absorbing applications, but where minimising volume has the highest priority metal foams can be a better choice.

The pedestrian protection applications appear to be too demanding for aluminium foam – or, indeed, for foams of any type. Absorbing the kinetic energy of the head from a 40km/hr collision requires a thickness of 125mm of foam, when limiting deceleration to 60g. Current automobile design precludes packaging of anything like this thickness. A*ny* absorber, whether crushable foam, aluminium hexagon or hydraulic damper, will require at least this much travel if it is to absorb the kinetic energy of the head whilst limiting the deceleration to a safe level for the human head.

Aluminium foam may still be a candidate for pedestrian protection applications under certain scenarios. If cars are redesigned with more space between the engine bock and the hood, or if the pedestrian protection targets were lowered, aluminium foam would be a well suited for this application. Polymer foams (except perhaps for phenolics) would likely be ruled out because of the effect of temperature on their properties, possible fire hazard and the damaging effect of fuel vapour, oil and antifreeze. But with current automobile design constraints, the proposed pedestrian protection applications are going to be very difficult to achieve. The only solutions that appear viable are air bags on the hood of the vehicle, or some other, similar, deployable structure that can be stowed in a small space and released at the instant of impact.

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[1] Gibson and Ashby, 1997, Ashby et al, 2000

[2] Private communications from Engineering Safety division of Steyr-Daimler-Puch and http://www.nhtsa.dot.gov/cars/rules/standards/safstan2.htm
The complete text of all Federal Motor Vehicle Safety Standards and other NHTSA regulations can be found in Title 49 of the Code of Federal Regulations (CFR), Volume 5.

[3] European Commission, "Draft proposal for a European Parliament and Council Directive relating to the protection of pedestrians and other road users in the event of a collision with a motor vehicle and amending Directive 70/156/EEC" III/5021/96 EN, Brussels, 7 February, 1996.

[4] Brown, 1998.

[5] Private discussions with individuals from the Engineering Safety division of Steyr-Daimler-Puch

# 6 Investment Assessment of Aluminium Foams

## 6.1 Market Assessment of Al foams

The strongest possibilities for short term substitution of aluminium foam lie with substitution into existing markets. Aluminium foam can be used in radically new designs which would take best advantage of the multi-dimensional attributes offered by metal foams, but which will be slowed both by lack of designer awareness or confidence in metal foams and by manufacturing difficulties with achieving high tolerances. Hence, an exploitation of one or two of aluminium foams strongest attributes, by substitution into existing applications, appears to be the best short term strategy to refine production practices and to increase designer awareness and confidence in the material class. In this investment assessment, the positions of two companies will be considered: Company A, which is producing medium quality, medium priced, 3 dimensional, aluminium foam parts by a powder metallurgical process (figure **4.4**), and Company B, which is producing lower quality, lower priced, aluminium foam by a liquid processing method (figure **4.3**).

Following the strategy outlined in section 3.2.4, markets have been identified which exploit aluminium foams' strongest technical parameters of energy absorbed per unit volume and energy absorbed per unit stiffness. Of these markets, the automotive market, estimated at \$100 million annually (assuming 1 lb of aluminium foam for every passenger car produced), is prioritised. Initial applications are interior occupant safety, in particular within the A-pillar, and new pedestrian protection legislation that will affect redesign of the hood and front bumper regions. These applications are examined technically in the case study of chapter 5.

Aluminium foam substituting into A-pillar and pedestrian protection applications will likely follow one of two substitution modes: either lower cost/higher performance, or higher cost/higher performance. The former mode would be followed when the displaced energy absorption element is complex, (as is the case with the hexagonal tube described in chapter 5 and depicted in figure **5.10**), where the design is constrained by minimum volumes and/or by flammability restrictions. In some other A-pillar designs, the Al foam would be replacing a cheaper solution, that will become unsatisfactory with the new occupant safety legislation; leaving the designer options to redesign the A-pillar to provide greater volume, or use aluminium foam as a energy absorption element. Lower cost/higher performance substitution of materials follows a curve depicted in figure **1.2(a)**.

Company B, with their cheaper liquid process for producing aluminium foam, have had greater difficulties achieving the shapes and tolerances required for automotive applications. As such, Company B is initially targeting lower end, continuous mass production applications. Their primary application is aluminium foam pallets for loading of materials that require sensitive weight assessments. Wood pallets are unsatisfactory in this application, due to variable weight associated with absorption of moisture. If weight sensitivity was important in 1% of the annual $6 billion dollar North American wooden pallet market,[1] Company B would be targeting a $60 million dollar market. In this application, Company B is pursuing a higher cost/higher performance application, and is likely to follow an adoption curve such as the one depicted in figure **1.3(c)** which would mean a period of 20 years from first commercialisation to 50% penetration of the market. Company A's and Company B's initial substitution attributes are shown in figure **6.1.**

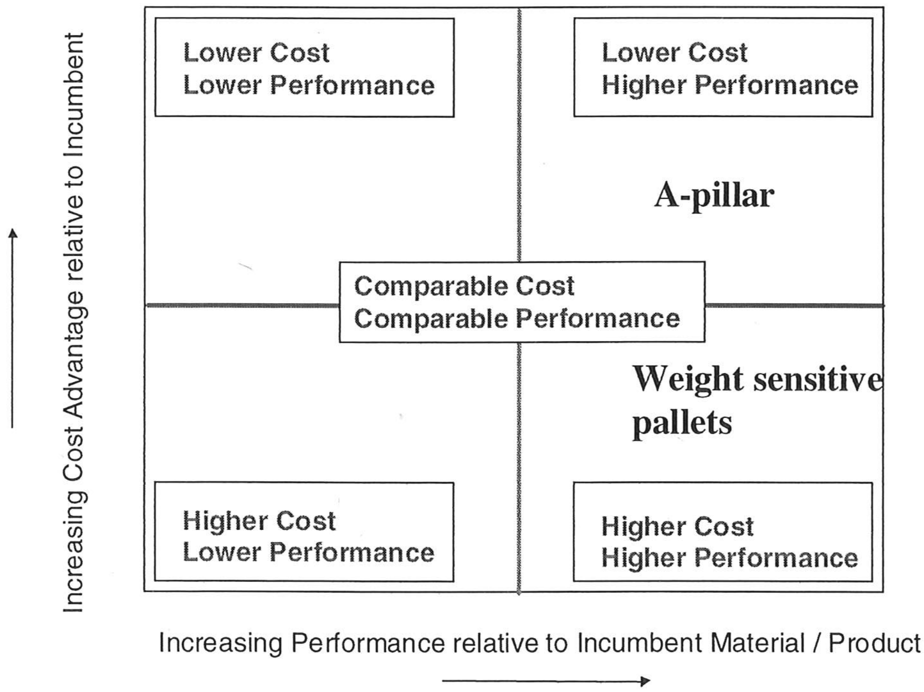


**Figure 6.1: Performance/Cost Categorisation for Selected Al Foam Applications**

A method of comparison with historical substitutions, such as Abernathy and Clark's transilience map[2] (described in section 3.3.2), aids a substitution-timing forecast. Aluminium foam for energy absorbing automotive applications is a revolutionary innovation (figure **6.2**), in that it overturns established technical and production competencies, but does not overturn customer linkages nor require a company to sell into different markets (figure **3.10**). Aluminium foam for pallet applications is also a revolutionary innovation. Figure **6.2** depicts the innovation types of the initial applications for Company A and Company B. Thus, the substitution timing of Aluminium foam for A-pillars can be modelled on the historical substitution of a revolutionary innovation in the automotive industry that was both lower cost and higher performance when compared with the incumbent component. Weight sensitive pallet substitution into the overall pallet market can be modelled on the historical substitution of a revolutionary innovation that was both higher cost and higher performance than the incumbent solution.

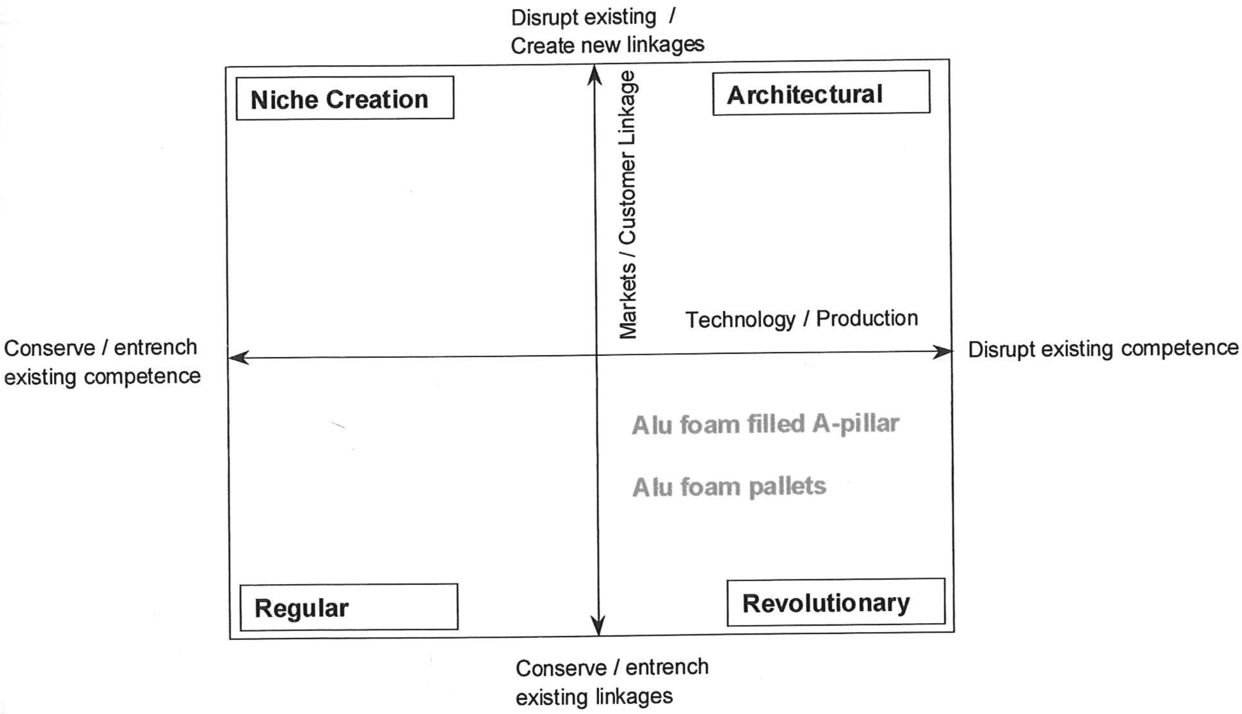


**Figure 6.2: Aluminium Foam Location on Abernathy and Clark's Transilience Map**

Historical examples of lower cost/higher performance, revolutionary innovations in the automotive industry include SMC hoods (bonnets) and polymer composite fenders. With SMC hoods, the performance enhancement is weight saving, and substitution has occurred only for low volume platforms, where designing and manufacturing SMC hoods is cheaper than with steel, and for vehicles that are close to the legislated CAFE limit.[3] For low production volume platforms, substitution can be modelled by the lower cost/higher performance curve shown in figures **1.3(a)** and **6.3**. In the case of polymer composite fenders, the performance enhancements are weight saving and resistance to denting, and the substitution has followed a similar curve (for applications with production volumes at which polymer composite fenders are cheaper to produce than steel ones).[4] If aluminium foams in energy absorption automotive applications are to follow similar substitution patterns, aluminium foams could expect to capture 50 % of the $100 million dollar A-pillar energy absorption market within 12 years.

However, automotive platforms with a flexible BIW structure have looser design constraints on piller size and hence volume of energy absorbers: thus, a significant portion of the automotive energy absorption market targeted by aluminium foams will actually be characterised by a higher cost/higher performance mode of substitution. Historical examples of higher cost/higher performance, revolutionary innovations in the automotive industry include aluminium alloy wheels and air bags. With aluminium wheels, a combination of aesthetic and performance drove substitution in higher end sporty platforms, along a path similar to that depicted in figures **1.3(d)** and **6.3**. In the case of airbags, consumer safety concerns and automotive regulation drove substitution much more quickly (figure **6.3**). If the safety benefits were transparent to the consumer, as in the case of air bags, aluminium foams in energy absorption automotive applications could penetrate along the faster substitution curve for all portions of the A-pillar market. This would lead to a market forecast of $50 million 10 years after first specification into an automotive A-pillar application.

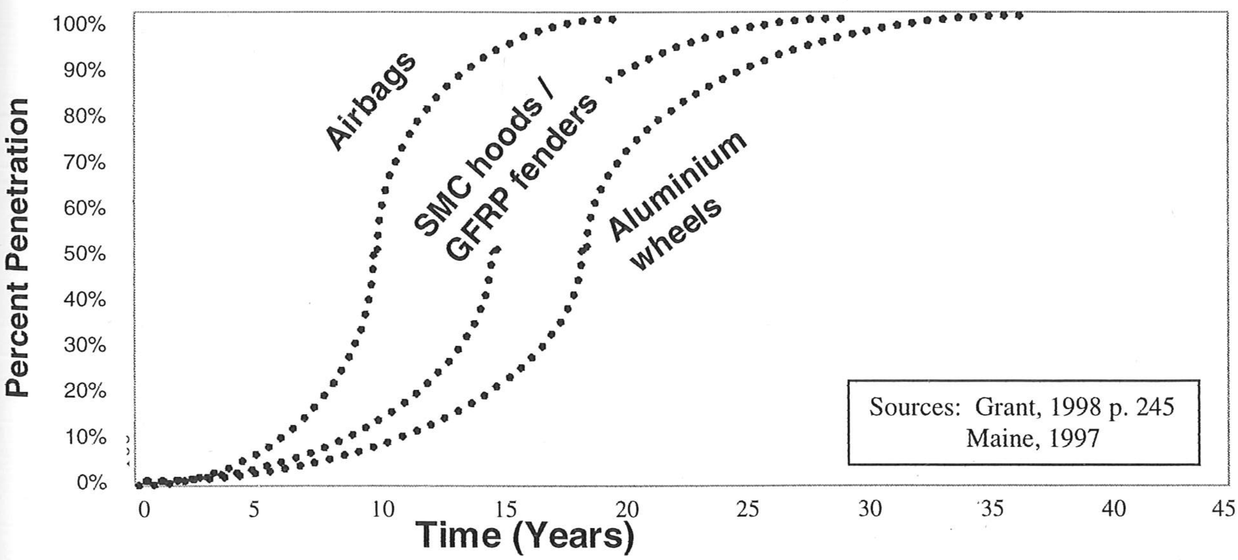


**Figure 6.3: Scenarios for Aluminium Foam Substitution into A-Pillar Market**

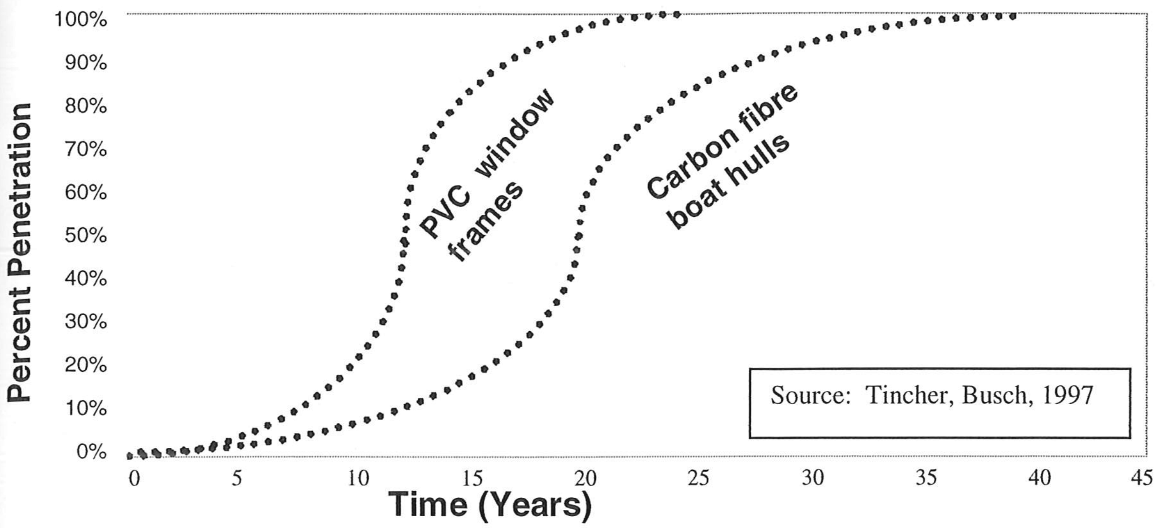


**Figure 6.4: Scenarios for Aluminium Foam Substitution into Pallet Market**

Figures **6.3** and **6.4** depict the envelope of aluminium foam market forecast scenarios for the A-pillar market and weight sensitive pallet markets respectively. For the A-pillar market, $50 million of revenues could be reached in 10 to 18 years. The faster revenue stream will result if a large portion of the market is either lower cost / higher performance or has a strong customer association with enhanced safety. The substitution of aluminium foam pallets into the weight sensitive pallet market can be modelled on the revolutionary, higher cost/higher performance innovation of carbon fibre reinforced boat hulls replacing wooden hulls. For some segments of that market, incumbent solutions may be more expensive than the aluminum foam solution, and then the adoption can be modelled on the lower cost/higher performance historical example of PVC window frames substituting for aluminium frames.[5] Thus, for the weight sensitive pallet market, $30 million of revenues could be reached in 18 to 20 years.

## 6.2 Likelihood of Capturing Created Value by Companies A and B

The viability assessment and market assessment indicate a strong likelihood of a future market for aluminium foams in excess of $100 million per annum, with the medium term possibility of capturing aeronautical energy absorption applications. It remains to be seen, however, whether the small companies who are in the process of commercialising aluminium foam are in a strong position to capture value created by the innovation. In this section, tools to assess industry attractiveness, appropriability, and organisational structures are utilised to predict the likelihood of capturing value.

### 6.2.1 Industry Structure

Porter's methodology for assessing *industry attractiveness*[6] is described in section 3.3.1 of this thesis. When this methodology is applied to companies commercialising aluminium foams, their position in the industry is found to be of only moderate to low attractiveness. For example, Company A's position is weakened by not owning the IP rights to powder metallurgical aluminium foam processing. Their industry is made less attractive because they must fight both against competitors who are commercialising the lower end liquid aluminium foam process and against substitutes for energy absorption in automotive applications, such as, polymeric foams, shaped aluminium sections, and fibre reinforced polymer composites. Additionally, the automotive companies exert very strong buyer power that will be difficult for the small producer to counter. Figure **6.4** summarises these points.

- Few potential entrants but weak IP position
- Substitutes for metal foams: polymeric foams, shaped aluminium sections, fibre reinforced polymer composites, wood
- Strong buyer power in most mass applications (e.g. automotive)
- Overall, medium-low attractiveness

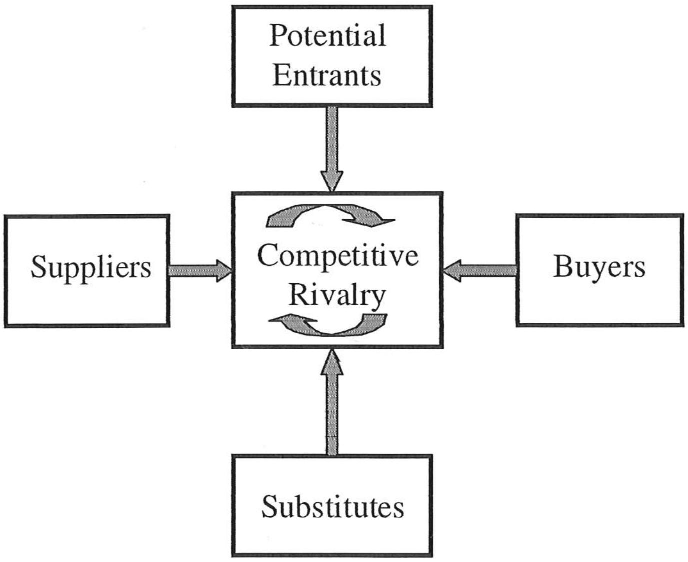


**Figure 6.5: Porter's Five Forces as a Means of Assessing Industry Attractiveness**

### 6.2.2 Appropriability of Profits

Section 3.3.2 describes the concept of appropriability[7] and describes various categories of innovation. Aluminium foam for energy absorbing automotive applications is a revolutionary innovation (figure **6.2**), in that it overturns established technical and production competencies, but does not overturn customer linkages nor require a company to sell into different markets. Tables **6.1** and **6.2** summarise the appropriability regimes of Companies A and B for their respective processes and markets. A tighter appropriability regime will be biased to the left hand side of the table.

| | | | | |
|---|---|---|---|---|
| IP / Trade Secret Protection | High | Medium | **Low** | None |
| Specialised Assets | High | **Medium** | Low | None |
| Co-Specialised Assets | High | Medium | **Low** | None |
| Innovation Type | Architectural | Niche Product | **Revolutionary** | Regular |
| New Product Cycle Time | **Slow** | Medium | Fast | Continuous |
| Protectable Industry? | **Yes** | Medium | Low | No |

**Table 6.1: Assessment of Company A's Appropriability - Moderate**

| | | | | |
|---|---|---|---|---|
| IP / Trade Secret Protection | High | Medium | **Low** | None |
| Specialised Assets | **High** | Medium | Low | None |
| Co-Specialised Assets | High | **Medium** | Low | None |
| Innovation Type | Architectural | Niche Product | **Revolutionary** | Regular |
| New Product Cycle Time | Slow | Medium | Fast | Continuous |
| Protectable Industry? | Yes | Medium | Low | No |

**Table 6.2: Assessment of Company B's Appropriability – Moderate**

Company A has a low ability to protect its intellectual property due to not owning the patents to the process. Specialised assets exist with the process, but most could be assembled by a die casting competitor without excessive difficulty. There is a possibility for co-specialised assets, if certain methods of automotive design propagate. The innovation type is revolutionary, due to the overturning of conventional production and technology competencies. New product cycle time is slow, giving a longer period over which to appropriate value, and the structure of the automotive industry allows for protection of IP. Hence, company A is in a moderate appropriability regime.

Company B has a medium ability to protect its intellectual property and trade secrets as it does not own the initial patents but has customised the process extensively and protected that knowledge to date. Their customised process has incorporated specialised assets and their initial target application includes co-specialised assets. As in the case of Company A, the innovation is revolutionary, the product cycle time is slow, and the industry is protectable. Thus, Company B is also in a moderate appropriability regime.

### 6.2.3 Organisational Structure

Company A has little entrepreneurial experience and suffers from the absence of a visionary dealmaker. On the positive side, they have created a relatively flexible organisation, with effective knowledge acquisition and good operational efficiency.

| Strategic Tasks | Small Firms | Company A |
|---|---|---|
| Integrating technology with production and marketing | • Responsibilities of senior managers | medium |
| Monitoring and assimilating new technical knowledge | • Trade and technical journals<br>• Training and advisory services<br>• Consultants<br>• Suppliers and customers | good |
| Judging the learning benefits of investments in technology | • Judgements based on qualifications and experience of senior managers and staff | medium |
| Matching strategic style with technological opportunities | • Qualifications of managers and staff | medium |

**Table 6.3: Assessment of Organisational Strengths of Company A - Medium**

Company B has good entrepreneurial experience and someone acting in the dealmaker role. The organisation is flexible, with effective knowledge acquisition and relatively good operational efficiency.

| Strategic Tasks | Small Firms | Company B |
|---|---|---|
| Integrating technology with production and marketing | • Responsibilities of senior managers | good |
| Monitoring and assimilating new technical knowledge | • Trade and technical journals<br>• Training and advisory services<br>• Consultants<br>• Suppliers and customers | good |
| Judging the learning benefits of investments in technology | • Judgements based on qualifications and experience of senior managers and staff | medium |
| Matching strategic style with technological opportunities | • Qualifications of managers and staff | good |

**Table 6.4: Assessment of Organisational Strengths of Company B - Good**

## 6.3 Investment Strategy

The key go / no go questions of investment in companies commercialising aluminium foam are:

(a) Viability. ***Yes*** in energy absorption applications in the automotive industry, an $100 million dollar opportunity. ***No*** in pedestrian protection applications currently. (See chapter 5 for analysis of these two applications). Maybe in weight sensitive pallet markets, depending on customer utility.

(b) Value Capture. Medium to low chance.

As the chances of value capture are relatively low and the payback period is relatively long, a small firm would be disadvantaged in commercialising this innovation. A larger company might be interested in pursuing this opportunity if it was in a good position to capture the value created. Alternatively, a government sponsored initiative for pedestrian or occupant safety might invest in assisting the commercialisation of such an innovation. If companies A and B do obtain financing to pursue this commercialisation, they should strongly consider collaboration with either a supplier or a customer. Such collaborations can provide financing opportunities, faster penetration of the material, and a more detailed understanding of the market.

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[1] http://www.palletmanagementsys.com/annual.html

[2] Abernathy, 1985. pp. 3-22

[3] Maine, 1997.

[4] Maine, 1997.

[5] Tincher and Busch, 1997.

[6] Porter, 1985.

[7] Teece, 1987.

# 7 Investment Assessment of LEPs, Oriented Polymers, and Octet Truss

To further illustrate the methodology introduced in chapter 3, it is here used to form a first level analysis of three very diverse, current, materials innovations. It was not possible – in the scope of this thesis – to investigate these innovations in the depth that has been possible with metal foams. But their diversity allows a test of the generality of the methodology. They are case-studies of light emitting polymers (LEPs), oriented polymers (OPs) and octet truss material (OT). Each is explored through an initial market assessment and value-capture analysis. The information on which they are based derives both from publicly available sources and from my personal interviews.

## 7.1 Market Assessment of LEPs

The capability of making light emitting diodes (LEDs) from light emitting polymers (LEPs) such as polyphenylene vinylene (PPV) was discovered at the Cavendish laboratory at the University of Cambridge in 1989. Subsequent experimentation and analysis revealed that polymer LEDs were suitable for the creation of high quality, thin, flat panel displays, due to their high efficiency of light emission to power outlay (luminous efficiency >10%), low operating voltage, 180 degree view angle, and competitive cost prospects.[1,2] The major competitive technologies are cathode ray tube (CRT) televisions and monitors, active matrix liquid crystal displays (AMLCDs), photoluminescent liquid crystal displays (PLLCDs), plasma display panels (PDPs), and field emission displays (FEDs). LEP technology is aimed at producing televisions, computer monitors, mobile phone displays, and personal assistant displays with the following features: they are much lighter and thinner than CRTs; cheaper, lighter, more efficient, and with better viewing angles than LCDs; and cheaper and more efficient than plasma displays.[3]

LEPs are aimed at six major flat panel display market applications, all with different technical and cost requirements. These applications are flat panel televisions, desktop computer monitors, portable computers, mobile phones, wireless communication devices ("WAP"s), and advertisement display screens. In each application, the performance and manufacturing cost predictions for LEP technology must be compared with the incumbent and with other potential substitutes. Given our viability assumptions[4], LEPs, when compared with the CRT, raise the industry demand curves for televisions, computer monitors, and portable computers through good quality, lightweight, portable, and fashionable flat panel display product offerings. LEPs, compared with LCDs, both lower the industry cost curve and raise the industry demand curve for portable computers, mobile phone displays, and wireless application protocols (WAPs) where portability is important. LEPs, when compared with PDPs, lower the industry cost curve for flat panel televisions and computers (for small to medium diameter screens) but may also lower the demand curve due to inferior quality. Figure **7.1** depicts the performance/cost attributes of LEP versus the competitive technologies for the major applications.

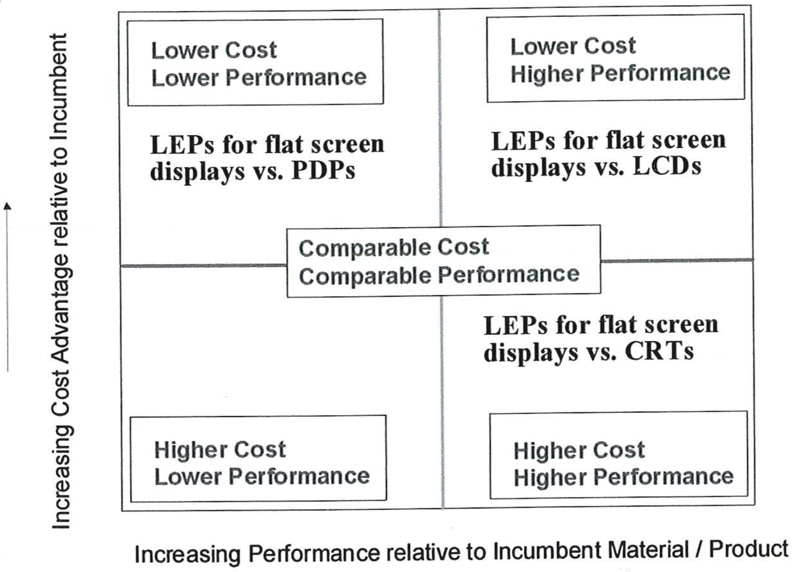



**Figure 7.1: Performance/Cost Categorisation for Selected LEP Applications**

By categorising LEPs performance/cost attributes relative to competitive technology offerings and the transilience (see section 3.2.4), it is possible to model the forecast of LEPs penetration into key markets on relevant historical precedents. Figure **7.2** shows LEPs aimed

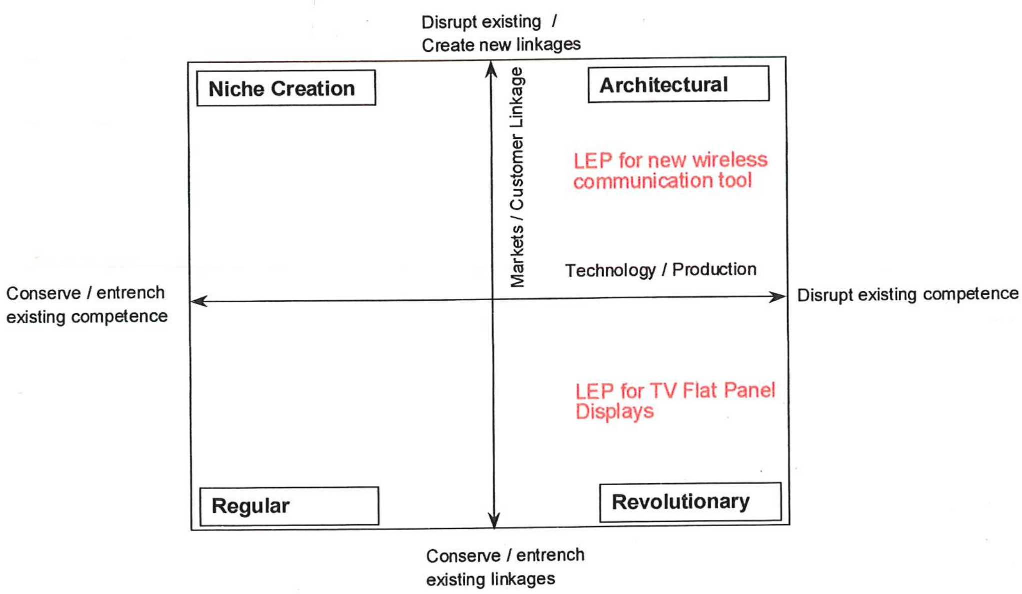
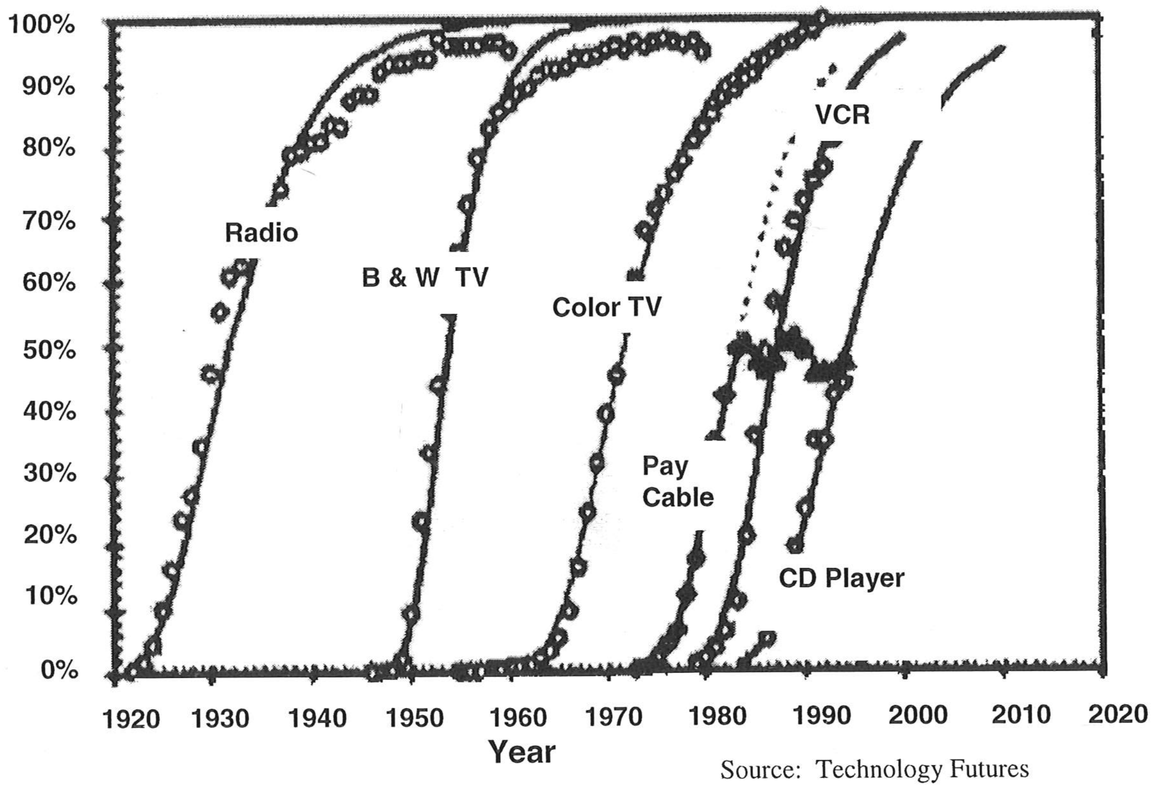



**Figure 7.2: LEP location on Abernathy and Clark's Transilience Map**

at television and computer flat panel displays to be a revolutionary innovation, while LEPs aimed at the emerging WAP products are an architectural innovation.

Some historical examples of adoption of innovations in the consumer electronics industry are shown in figure **7.3**. Black and white television adoption is a good example of an architectural innovation, breaking new ground in both technology and market space, with a rapid rate of adoption. The subsequent substitution of colour television for black and white television is an example of a higher cost / higher performance, revolutionary innovation, and substitution rate decreases accordingly (figure **7.3**). VCRs can be viewed as a lower cost / higher performance, revolutionary innovation substituting into the movie market space. And digital LCD watches substituting for analogue watches is an example of lower cost[5] / lower performance[6], revolutionary innovation. If LEPs in the major flat panel display applications are to follow similar substitution patterns as the historical precedents identified in table **7.1**, LEPS could expect to capture an approximately $ 50 billion market within 10 to 15 years.




Source: Technology Futures

**Figure 7.3: Historical Adoption Rates of Innovations in the Consumer Electronics Industry**

| Application | Size of Target Market ($M) Favourable for LEPs | Cost / Performance | Innovation Type | Historical Precedent | Expected Year of First Commercialisation |
|---|---|---|---|---|---|
| Flat Panel TVs | $15,000[7] | Higher / Higher[*] vs. CRT<br>Lower / Higher[♦] vs. LCDs | Revolutionary | Colour TV<br>VCRs | 2003 |
| Desktop Computer Monitor | $5,000[8] | Higher / Higher vs. CRT<br>Lower / Higher vs. LCDs | Revolutionary | Colour TV<br>VCRs | 2003 |
| Portable Computer Monitor | $7,500[9] | Lower / Higher vs. LCDs<br>Lower / Lower vs. Plasma | Revolutionary | VCRs<br>Digital watches | 2003 |
| Mobile Phones | $20,000[9] | Lower / Higher vs. LCDs | Revolutionary | VCRs | 2000 |
| WAPs | $60,000[10] | No Incumbent | Architectural | B&W TV | 2001 |
| Advertising Displays | $500[10] | LED<br>Plasma | Revolutionary | Colour TV<br>Digital Watches | 2003 |

**Table 7.1: Target Applications for LEP Flat Panel Displays**

## 7.2 Market Assessment of Oriented Polymers

The remarkable strength and energy-absorption attributes of Kevlar$_{TM}$, Dyneema$_{TM}$ fibre and Spectra$_{TM}$ fibre demonstrated in the 1970s and early 80s that the straightening of polymers on a molecular level could increase mechanical properties 100 fold.[11,12] But these properties were only attainable in fibres or thin films due to processing limitations. In the late 80s and early 90s, methods were discovered to enable the bulk orientation of commodity polymers resulting in a 5 to 20 fold increase in stiffness and strength depending on product dimensions and processing method.[13,14] Company D licensed the technology, adapted it for a

[*] Higher performance in the sense of lighter weight, lower volume, and lower power consumption
[♦] Higher performance in the sense of better viewing angle and lower power consumption

pilot plant, and began manufacturing in Canada in 1995, with EMMite$_{TM}$ drumsticks as their first product. Currently they sell a broad range of rock, jazz, and band drumsticks in various aesthetics, including transparency, glow-in-the-dark, wood-grained, and solid colours. In 1999, Company D expanded to develop and manufacture synthetic hardwood flooring, an oriented polypropylene product with 30% wood fibre filler. This product is targeted at the OEM homebuilder market for new residential construction in North America.

The oriented polymer drumsticks are a higher cost (but lower life-cycle cost when considering replacements) / higher performance, revolutionary innovation (figures **7.4**, **7.5**) substituting for the incumbent wooden sticks, which are predominantly of hickory, maple or oak. The distinguishing performance attributes are 500% longer life, protection against Carpal Tunnel Syndrome (CTS)[15], and aesthetic options such as glow-in-the-dark. Although the medium term cost of the EMMite$_{TM}$ sticks is lower (5 pair of hickory sticks per month costs approximately \$70 vs. 1 pair of EMMite$_{TM}$ sticks per month at \$20)[16], the purchasing decision is often based on immediate cost, and thus the longer life is treated as a performance attribute rather than a cost attribute. The North American drumstick market of 12 million pairs per year translates into a target market size of \$50 million, after accounting for longer lifespan of the EMMite$_{TM}$ sticks. As an initial estimate, we could assume 50% of this market would be favourable for EMMite$_{TM}$ sticks over wooden sticks.

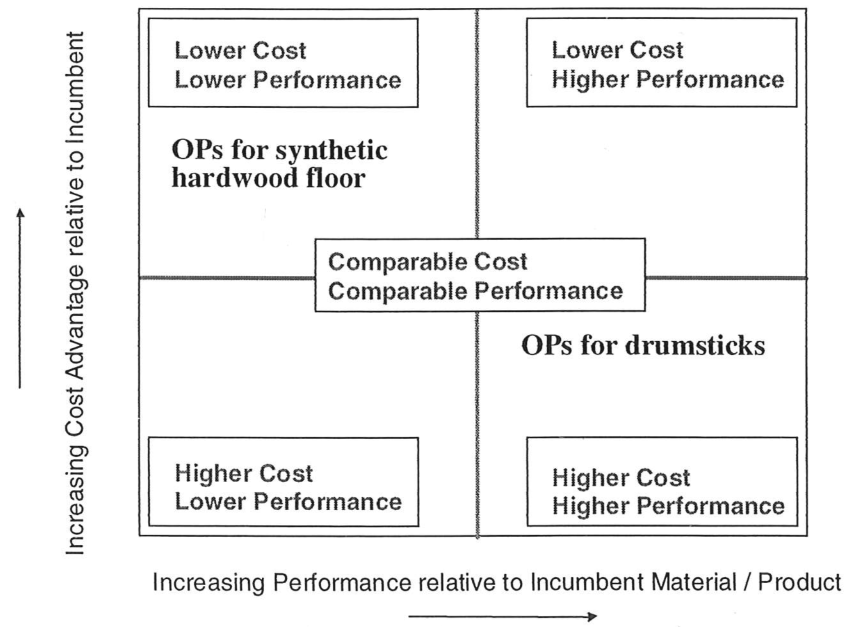



**Figure 7.4: Performance/Cost Categorisation for Selected OP Applications**

Oriented polymer synthetic hardwood flooring can be viewed conservatively as a lower cost / lower performance, revolutionary innovation (figures **7.4**, **7.5**). The selling price of the OP flooring is approximately 25% lower[17] than the incumbent natural hardwood flooring, which is generally oak or maple. The average value to manufacturers of a square foot[18] of oak flooring is US $2[19]. Additionally, installation costs appear to be significantly lower than the $4/sq ft typical for hardwood floor, due to a snap-lock fit and no requirement for any adhesive under or between planks (known as floating floor construction). Attributes of the OP flooring are viewed as advantageous, such as resistance to water, rot and termites, making the flooring particularly functional for basements, kitchens, bathrooms, and for full house flooring in tropical regions. Although in appearance it is difficult to distinguish from hardwood[20], many segments of the market are expected to continue to accord a price premium to authentic hardwood flooring, hence the lower performance assumption. In the United States, annual revenues from hardwood floor sales are $1.2 billion of the $15 billion US floor coverings market.[21] As an initial estimate, we could assume that 25% of the US hardwood floor market was favourable for oriented polymer synthetic hardwood flooring.

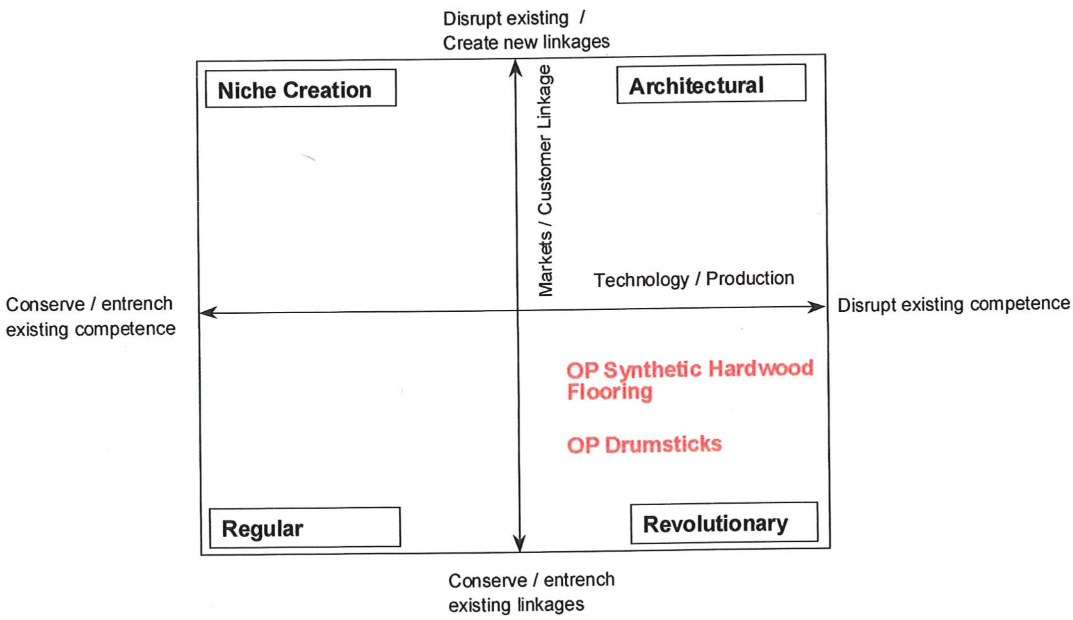



**Figure 7.5: OP Application Locations on Abernathy and Clark's Transilience Map**

The market penetration rate of these two products might be likened to the historical precedents depicted in figure **7.6**. Thus, company D might anticipate a $12.5 million annual market for EMMite$_{TM}$ drumsticks within 20 years and a $250 million annual market for oriented polymer synthetic hardwood flooring within 25 years.

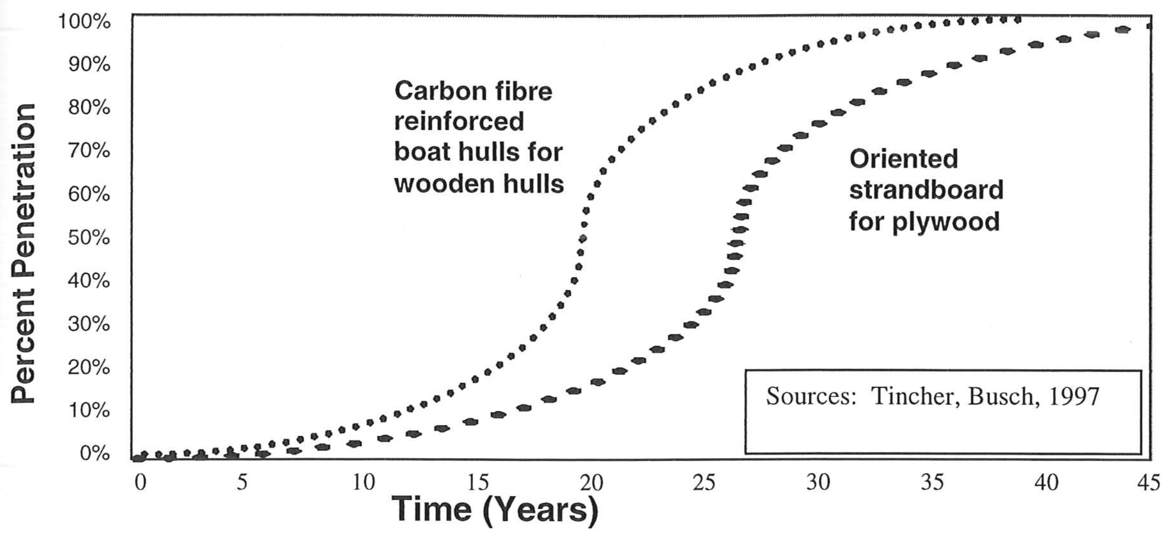



**Figure 7.6: Scenarios for OP Substitution into Drumstick and Hardwood Floor Markets**

## 7.3 Market Assessment of Octet Truss Material

Company E was founded in 1996 to develop and commercialise innovations in the field of Biomimetics, an emerging field which mimics biological structures in the design of new materials, devices, and manufacturing processes. Through their proprietary databases for matching macrostructural market needs to microstructural optimisation of novel materials, biomimetic principles, and customised manufacturing strategies, Company E developed a process to produce biomimetic scaffolding material referred to as "octet truss" material in 1997.

Metallic and polymeric octet truss materials have functional advantages for high tolerance, lightweight, stiff structures and for thermal exchange and would compete with modules of metal parts, aluminium honeycomb, metal foam, and polymeric and mettalic sandwich structures on the basis of these attributes. Industrial applications for octet truss materials include space mirror backings, airplane fuel storage (eliminates fuel temperature gradients and slosh)[22], and parts integration (integration of structural functions with electronics or thermal systems) in aerospace and automotive applications. Stiff panels that allow for integration of electronics and thermal exchange functions in aerospace or automotive applications would be viable if they offered a lower cost / higher performance module (when considering a total cost comparison that includes assembly costs). Thus, as a revolutionary, lower cost / higher performance innovation, octet truss materials could follow the substitution path of glass fibre reinforced polymer fenders in automotive applications (figure **6.3**). Lightweight, stiff support structures for space mirrors would be a viable application if aluminium octet truss materials could be manufactured more cheaply than the incumbent open cell aluminium foam, since the current product adequately fills its function.

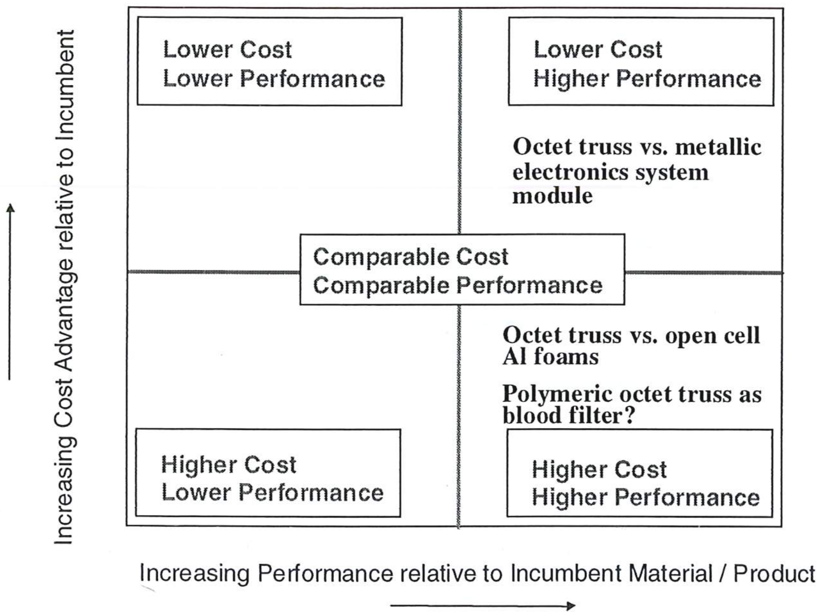



**Figure 7.7: Performance/Cost Categorisation for Selected OT Applications**

Polymeric octet truss micromaterials have biomedical applications, such as blood cell filters and possibly as drug delivery devices. The market size of semi-permeable membranes for non-separating applications in drug delivery was $3.7 billion in the United States in 1999.[23] How much of this market, if any, octet truss material could target is unknown. The market size of semi-permeable membranes for separating applications in microfiltration (0.1 to 10 microns) in the U.S. medical devices industry is $20 million.[24] A further $130 million.[25] dollar US market for ultrafiltration (1.5 nanometres to 0.1 microns)[26] is unlikely to be accessible to octet truss technology due to the complications of manufacturing structures at the nanometre scale. The polymeric octet truss applied to biomedical blood filters is a revolutionary innovation. If it is also a higher cost / higher performance substitution into microfiltration applications, it could take 20 years for octet truss material to attain $10 million of revenues in this sector.

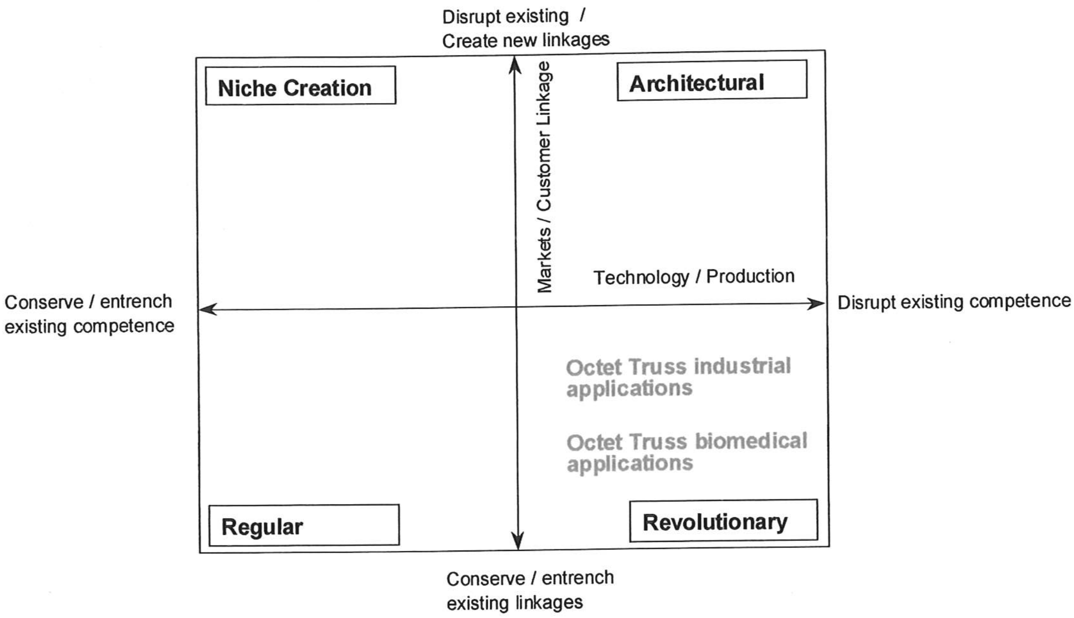



**Figure 7.8: Octet Truss Application Locations on Transilience Map**

## 7.4 Likelihood of Capturing Created Value by Companies C, D, and E

A thorough viability assessment has not been conducted on these three applications - - that alone could take a single person two years. Taking the market estimates of sections 7.1, 7.2, and 7.3 as reasonable approximations, this section aims to determine the likelihood of capturing value through the use of tools to assess industry attractiveness, appropriability, and organisational structures.

### 7.4.1 Industry Structure

Porter's methodology for assessing *industry attractiveness* is described in section 3.3.1 of this thesis. This methodology, applied to company C, within the flat panel display industry, is analysed in figure **7.9**. The high barriers to entry in the flat panel display manufacturing industry (overcome by Company C by joint venture partnerships), an extremely strong patent position, an industry with strong growth forecasts, secure negotiating power with both suppliers and buyers, and a technology with enormous potential make this a highly attractive industry.

- Few/no potential entrants on LEP technology due to very strong IP position.
- Little/no competitive rivalry within LEP technology but rivalry with incumbents
- Substitutes of cathode ray tube, LCD, FED, PDP, LED
- Strong power of suppliers and buyers mitigated by joint venture arrangements
- Overall, highly attractive unless substitutes are technically or economically superior

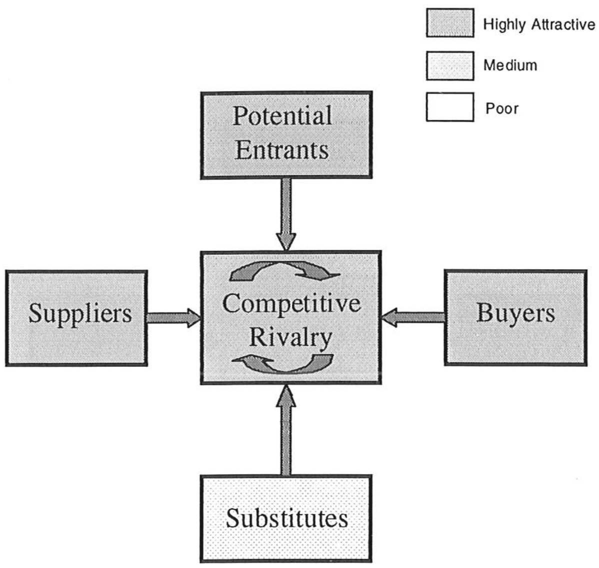



**Figure 7.9: Porter's Five Forces as a means of Assessing Industry Attractiveness for the Licensing of LEP Technology and the Manufacturing of LEP Flat Panel Displays**

A similar analysis of the synthetic hardwood flooring manufacturing industry is shown in figure **7.10**. Barriers to entry are relatively high, as hardwood flooring manufacturers do not have plastic manufacturing equipment, plastics workers, or the trade secrets of oriented polymer processing. Plastics companies, who do have many of the required specialised assets, will likely be blocked from entry by the composition of matter patent filed by Company D. (The drumstick market is an entry market for Company D. It is both too small for most plastic companies to consider and protected by patents). These positive factors are tempered by the anticipated strong rivalry with substitutes, to result in an industry of medium attractiveness.

The manufacturing of octet truss materials for integrated automotive components is the subject of figure **7.11**. Biomimetic materials of some sort are likely to have a major influence on structural industrial design of the future. Company E's appears to have a good strategy in providing contract design services utilising their proprietaty software to custom create biomimetic materials for a client's application needs. However, industrial applications for the octet truss material are insufficiently explored at this moment and a broad strategy of developing light, stiff structural modules that allow for the integration of electronics and/or thermal exchange is not attractive

- Limited potential entrants on bulk state orientation due to strong IP position.
- Little/no competitive rivalry within OP technology but rivalry with incumbent woods and other synthetic flooring.
- Substitutes of oak, maple, hickory, engineering laminates, ceramic tiling, vinyl sheet, carpet, GFRP, CFRP, aluminium
- Medium power of suppliers and low- medium power of buyers
- Overall, medium attractiveness

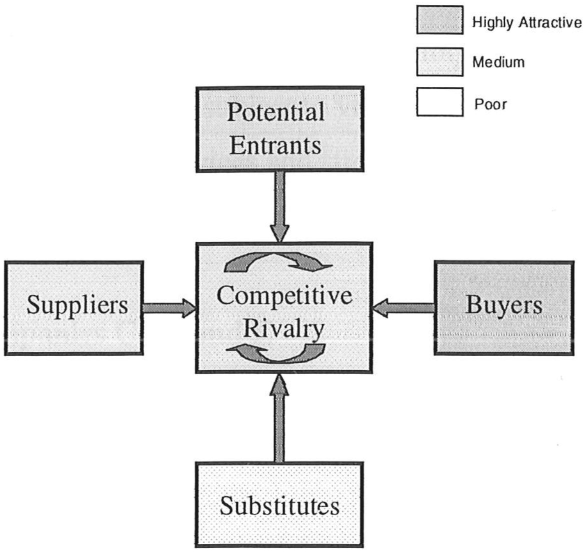



**Figure 7.10: Porter's Five Forces as a Means of Assessing Industry Attractiveness for the Manufacturing of OP Synthetic Hardwood Flooring**

in the automotive or aerospace industries without guarenteed development funding. (figure **7.11**) This low level of attractiveness is due to strong buyer negotiating power, expensive and longterm development costs, a contestable IP position, and strong competition from incumbents.

- Some potential entrants on octet truss technology and similar processing methods
- Medium - high competitive rivalry
- Substitutes of engineered metal structures, GFRP, open cell metal foams, separate components
- Strong power of suppliers and buyers
- Overall, medium - low attractiveness in mechanical engineering applications

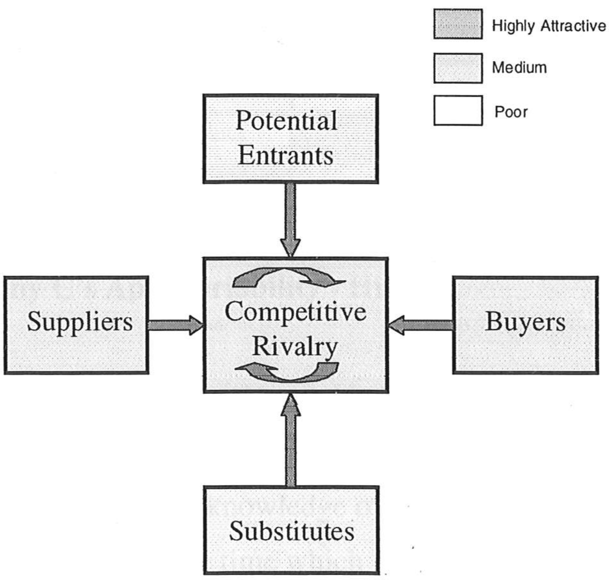



**Figure 7.11: Porter's Five Forces as a Means of Assessing Industry Attractiveness for the Manufacturing of OT in Automotive Parts Integration Applications**

Biomedical applications for polymeric octet truss materials and possibly catalyst delivery in the chemical industry could be more attractive, subject to viability analysis. The growth markets of biomedical filters and drug delevery devices and strong price negotiating position of the biomedical device manufacturer merit a closer look at these applications.

### 7.4.2 Appropriability of Profits for Companies C, D, and E

Section 3.3.2 described the concept of appropriability and describes various categories of innovation. Tables **7.2**, **7.3**, and **7.4** summarise the appropriability regimes of Companies C, D, and E for their respective processes and markets. A tight (high) appropriability regime lies to the left hand side of the table, poor appropriability to the right.

Company C has tight appropriability of its potential product range, greatly increasing the likelihood of capturing profits generated (table **7.1**). This assessment is based on company C's very strong patent position, specialised assets such as manufacturing facilities for LEP and for flat panel displays, and co-specialised assets, such as the interdependence of the WAP on power-efficient, easily packaged technology such as LEPs. Applications are both architectural and revolutionary, with architectural innovations of particular benefit to companies holding strong IP. Patents are enforceable in the consumer electronics industry and the cycle time for new products is of medium length.

| | | | | |
|---|---|---|---|---|
| IP / Trade Secret Protection | **High** | Medium | Low | None |
| Specialised Assets | **High** | Medium | Low | None |
| Co-Specialised Assets | **High** | Medium | Low | None |
| Innovation Type | **Architectural** | Niche Product | **Revolutionary** | Regular |
| New Product Cycle Time | Slow | **Medium** | Fast | Continuous |
| Protectable Target Industry? | **Yes** | Medium | Low | No |

**Table 7.2: Assessment of Company C's Appropriability - High**

Company D has a medium to high appropriability regime (table **7.2**). This assessment is based on company D's strong patent position[27], specialised assets such as manufacturing facilities for bulk orientation of polymers and the specific knowledge of employees, an industry where patents are enforceable and a product cycle time which allows for some payback time for R&D investment.

| | | | | |
|---|---|---|---|---|
| IP / Trade Secret Protection | **High** | **Medium** | **Low** | None |
| Specialised Assets | **High** | Medium | Low | None |
| Co-Specialised Assets | High | Medium | **Low** | None |
| Innovation Type | Architectural | Niche Product | **Revolutionary** | Regular |
| New Product Cycle Time | Slow | **Medium** | Fast | Continuous |
| Protectable Target Industry? | **Yes** | Medium | Low | No |

**Table 7.3: Assessment of Company D's Appropriability – Medium to High**

Company E has a medium to low strength appropriability regime (table **7.3**). Whereas their proprietary software for biomimetic design may be classified as an architectural innovation, the octet truss material has thus far been proposed for revolutionary innovations that are substituting into existing applications. Specialised assets are limited to know how in the industrial applications although other specialised assets may exist in biomedical applications. Patents are enforceable in these manufacturing industries but Company E does not have a strong enough IP position to greatly benefit.

| | | | | |
|---|---|---|---|---|
| IP / Trade Secret Protection | High | **Medium** | **Low** | None |
| Specialised Assets | High | Medium | **Low** | None |
| Co-Specialised Assets | High | Medium | **Low** | None |
| Innovation Type | **Architectural** | Niche Product | **Revolutionary** | Regular |
| New Product Cycle Time | Slow | **Medium** | Fast | Continuous |
| Protectable Industry? | Yes | **Medium** | Low | No |

**Table 7.4: Assessment of Company E's Appropriability – Medium to Low**

### 7.4.3 Organisational Structure

In table **7.4** we evaluate companies C, D, and E by the four aspects of organisational structure that Pavitt et al suggest are relevant for technological innovation. From these criteria (see section 3.3.3) company C is assessed to have a medium-good organisational structure. Additionally, as a small company negotiating licenses and joint ventures with large polymer suppliers and large consumer electronics manufacturers, Company C has benefited from a visionary deal-maker leading their contract negotiations. Human resources issues such as employee morale, individual workload and incentives were not investigated for this assessment.

| Strategic Tasks | Company C | Company D | Company E |
|---|---|---|---|
| Integrating technology with production and marketing | medium - good | medium - good | medium - good |
| Monitoring and assimilating new technical knowledge | good | good | good |
| Judging the learning benefits of investments in technology | medium | medium | good |
| Matching strategic style with technological opportunities | good | good | good |

**Table 7.5: Organisational Structure of Companies C, D, and E**

Company D was also assessed to have a medium-good organisational structure. As a start-up company entering a large competitive market such as flooring for new residential construction, Company D will require a strategic deal-maker for securing early stage hardwood floor contracts from homebuilders. As the contracts are currently being negotiated, Company D's strengths in this area are yet to be determined.

Despite having undergone restructuring recently to focus on biomedical markets, Company E was assessed as having good organisational structure, based on the criteria shown in table **7.4**. The restructuring appears to have been an example of "matching strategic styles with technological opportunities" as well as following funding sources.

## <u>7.5 Investment Strategy</u>

The likelihood of value capture has been assessed for these three case studies but not the technical or economic viability of the applications. A viability assessment, such as the one proposed in the methodology in chapter 3, would be required before an informed investment recommendation could be made. However, a value capture assessment alone can be enough to determine that an investment is not warranted, due to such factors as a small market size, low potential margins, or strategic misfit. The caveat here is that, without a viability assessment, additional potential applications may be overlooked altogether.

The value capture assessment in this chapter has indicated that light emitting polymers (LEPs) are an attractive investment, subject to careful viability examination of LEPs relative to LCDs in flat panel display applications. Such a viability assessment would refine the market forecast of $50 billion within 15 years. If this market does materialise, company C is well positioned to appropriate substantial value in terms of license and manufacturing royalties and contract services. Their organisational structure is a help rather than a hindrance.

Oriented polymers represent a good investment, subject to a positive outcome from detailed market research on customer response to Company D's synthetic hardwood flooring product. The market forecast of $260 million in revenue by 2020 (dependant on market perception of quality) represents a medium sized market opportunity from which Company D is well positioned to capture value. Organisational structure is appropriate for the current growth stage of the company. Opportunities for future growth exist both in the global hardwood flooring market and in growing market share in the remainder of the US hardwood market and the total floor coverings market.

Value capture analysis does not recommend octet truss materials for investment at this time. This is due to a weak appropriability regime, low attractiveness for industrial applications, and insufficient knowledge of the potential applications. Viability analysis on developing biomedical applications and subsequent value capture analysis could change this recommendation.

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[4] For this market assessment and value capture analysis, we assume that LEP technology will result in small and medium sized flat panel displays that are more expensive than CRTs but less expensive to manufacture than LCDs. PDPs, and FEDs. We also assume that the performance attributes of LEPs will include: better power efficiency than LCDs and PDPs, lighter weight than LCDs and better viewing angle than LCDs. A thorough viability analysis is recommended here.

[5] http://home.att.net/vintageelectronics/ads/sinblack.jpg,
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[7] analysis incorporates data from the following sources: The Display Search Monitor (http://www.displaysearch.com/japanese/j_monitor.html), Electronic Buyers News "Covering New Ground" 2000, IDC (http://www.idc.com/AP/Press/PR/APHW060600PR.stm), Mentley, David E. (Stanford Resources Inc.) "The Market Potential for Organic Light-Emitting Diode Displays" (www.stanfordresources.com), Website of Cambridge Display Technologies (www.cdtltd.co.uk), Website of Candescent Technologies (www.candescent.com),

[8] analysis incorporates data from the following sources: The Display Search Monitor (http://www.displaysearch.com/japanese/j_monitor.html), Electronic Buyers News "Covering New Ground" 2000, IDC (http://www.idc.com/AP/Press/PR/APHW060600PR.stm), Mentley, David E. (Stanford Resources Inc.) "The Market Potential for Organic Light-Emitting Diode Displays" (www.stanfordresources.com), Website of Cambridge Display Technologies (www.cdtltd.co.uk), Chen, H.K., "Taiwan's Flat Panel Display Industry Has Come a Long Way" (http://channelmag.supersites.net/channeln2/981112/taiwan1.htm)

[9] analysis incorporates data from the following sources: "Plastic LCDs cash in on portable-phone sales" http://library.northernlight.com, Mentley, David E. (Stanford Resources Inc.) "The Market Potential for Organic Light-Emitting Diode Displays" (www.stanfordresources.com), Website of Cambridge Display Technologies (www.cdtltd.co.uk)

[10] analysis incorporates data from the following sources: The Display Search Monitor (http://www.displaysearch.com/japanese/j_monitor.html), Electronic Buyers News "Covering New Ground" 2000, IDC (http://www.idc.com/AP/Press/PR/APHW060600PR.stm), Mentley, David E. (Stanford Resources Inc.) "The Market Potential for Organic Light-Emitting Diode Displays" (www.stanfordresources.com), Website of Cambridge Display Technologies (www.cdtltd.co.uk)

[11] Peijs, Jacobs, and Lemstra, 2000.

[12] http://www.dsm-basf.com/elastomers/elasto_engels/p_m.html

[13] Newson, Osborne, and Maine, 2000.

[14] Richardson, Parsons, and Ward, 1986.

[15] Zaza, Fleiszer, Maine, and Mechefske, 2000.

[16] http://www.emmitedrumsticks.com

[17] private communications with Dr. Frank Maine of SHW Technologies Inc. Guelph, Canada

[18] a square foot is equal to a board foot one inch thick; 144 cubic inches

[19] SBI Market Profile: Wood Flooring. Published by Kalorama Information, LLC New York, NY 1999
US Department of Commerce information, compiled by Specialists in Business Information

[20] http://www.synthetichardwood.com/testimonials.shtml

[21] "SBI Market Profile: Wood Flooring". Published by Kalorama Information, LLC New York, NY 1999

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[23] Medical Devicelink.com "New Applications Drive Semipermeable Membrane Market." http://devicelink.com/news/market6.html

[24] Srikanth, G. "Membrane Separation Processes – Technology and Business Opportunities". Technology Information, Forecasting & Assessment Council (TIFAC), Department of Science and Technology, Government of India. http://www.tifac.org.in/news/memb.htm

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[26] "Membrane Technology". Weir Envig Ltd. http://www.weirenvig.co.za/membrane.htm

[27] Company D owns one OP bulk orientation patent, have exclusive NA license for another bulk orientation patent, and are filing both composition of matter patent on the OP flooring and additional processing patents

# 8 Discussion and Conclusions

This chapter pulls together the main themes of the thesis, questions, proposed methodology and conclusions.

## 8.1 New Materials Industry Structure

The characteristically long gestation period between the technical understanding of new materials and the commercial take-up (see figure **1.3**) may be a thing of the past. The long gestation period has been due, in part, to a mismatch between designers' and entrepreneurs' understanding of market needs and the development of new materials for various applications, exacerbated by the many layers of separation between material and end consumer. Small and medium sized enterprises (SMEs), often started by the inventor of a new material, have had particular difficulty in commercialising the new material – either due to the upfront and risky expense involved in displacing an incumbent material in a mature industry or due to the need for complementary innovations to enable a radical (or "architectural") innovation. It was hypothesised that several current trends and information technology developments could be harnessed to shorten the gestation period of new materials, and that, as a result, SMEs would be in a better position to drive new materials innovations. These factors were further investigated through interviews with senior management at five SMEs formed on a new materials innovation. A methodology to facilitate the matching of technical possibilities with the market, through the systematic use of predictive software tools and forecasting techniques, was developed with the intention of shortening the gestation period of materials innovation and substitution. Any method of reducing the time period between invention, first commercial introduction, and significant marketplace adoption of a new material, would give the company driving the commercialisation of the new material many more financing options due to the shorter payback time.[1]

Organisational level forces have changed significantly in the past decade with the advancement of the capabilities and utilisation of information technology (see table **1.1**). These forces could be changing the structure of the materials industry such that SMEs can drive a major materials innovation today, where they have not been able to do so for the past 50 years. The views of senior management of SMEs formed around new material innovations were gathered to test this hypothesis in a preliminary way. The same individuals were asked which aspects of the innovation commercialisation process were effected by the changes and what barriers to materials innovation remained (Appendix A).

The results are shown in figures **2.2** to **2.4**. The average results indicate that small, materials innovating companies perceive connectivity and collaborative work as the factors which have most positively influenced the chances for successful commercialisation of a materials innovation. They perceive access to venture capital to have been highly positively impacted by these factors. They also believe that the manufacturing interface, the market interface, and the design process have been moderately to highly influenced by these factors. Materials industry structure was perceived to have been slightly to moderately influenced in the past decade by these factors. The largest reductions in barriers to materials innovations were perceived to be in reputational clout for partnering, access to venture capital, ability to scan the marketplace. These results support the hypothesis that the environment for commercialising materials innovation is changing positively due to factors to do with the dissemination of information technology tools (such as tools for connectivity) and trends towards collaborative work. The methodology developed and demonstrated in this thesis is aimed at assisting materials SMEs in harnessing these new tools to guide their strategy and prepare their business plans.

## 8.2 Methodology for Assessing Attractiveness of Materials Innovation

In order to judge investments by a new material innovation's credible positioning on a matrix such as that of figure **3.2,** forecasting techniques must be employed. In the past, a large R&D department integrated with a large advanced marketing department would be required to attempt to position an early stage material's innovation on such a matrix. Additionally, given the long gestation period of a new materials' innovation, only a company with secure long term financing would attempt to commercialise a new material. However, with changing organisational level forces in the materials industry, the opportunity exists for small companies to reasonably assess the potential of a new materials' innovation and to drive the commercialisation process. The methodology introduced and developed in this thesis has been designed to help identify promising materials innovations at an early stage. A team of three people could use this methodology to thoroughly assess the promise of a new materials innovation within one month's time.

The three aspects of this methodology are a viability assessment, a market forecast, and a value capture assessment (figure **8.1**). The viability assessment is the most technical of the three, but is nearly worthless if not tightly woven into the market forecast. The viability assessment consists of two predictive models and a value trade-off. The models forecast technical performance attributes of a future product and production economics, and the value trade-off predicts whether customers will buy the product.

The market forecast iterates with the viability assessment to identify promising market segments, obtain information about customer preferences, and forecast the size of the market which is likely to adopt the materials innovation. Historically relevant innovations are utilised to as a basis for the forecast. Market forecasts are typically done very poorly by technology based SMEs and often not at all by technology research groups at universities. This methodology aims to simplify the steps of scenario planning through market and technology forecasts.

The value capture assessment utilises three strategy tools which are not unique to this thesis: those of industry analysis, appropriability, and organisational assessment. What is unique is the incorporation of this essential component of business analysis into the early stage viability assessment of a new material's innovation.

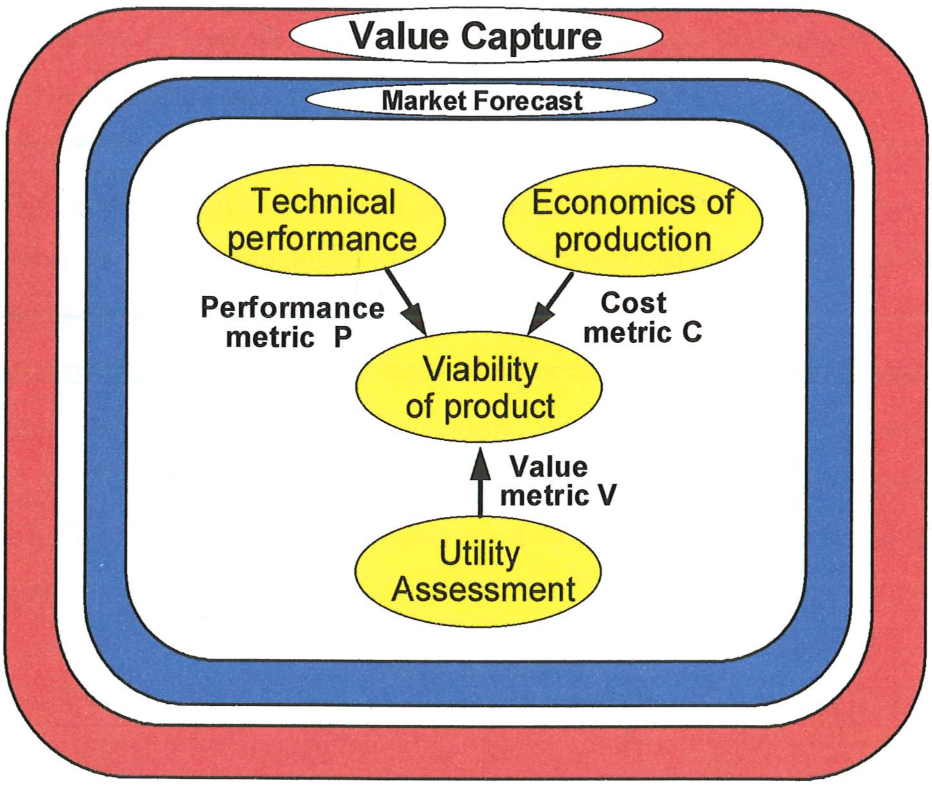



**Figure 8.1: Methodology for Materials Investment Assessment**

This methodology was demonstrated through a case study of the competition between several processes for one new materials innovation: that of aluminium foams. In addition, the market forecast and value capture portions of the methodology were used on the new materials innovations of Light Emitting Polymers, Oriented Polymers, and Octet Truss material. The following is a summary of results from the analysis of the latter three.

LEPs are aimed at six major flat panel display market applications, all with different technical and cost requirements. These applications are flat panel televisions, desktop computer monitors, portable computers, mobile phones, wireless communication devices ("WAP"s), and advertisement display screens. If LEPs in the major flat panel display applications are to follow similar substitution patterns as the historical precedents identified in table **7.1**, LEPS could expect to capture an approximately $50 billion market within 10 to 15 years. When industry analysis is applied to company C, the flat panel display industry is found to be highly attractive, subject to meeting technological and economic projections (figure **7.8**). Company C has a tight (high) appropriability regime, greatly increasing the likelihood of capturing profits generated (table **7.1**), and is not hindered by its organisational structure.

Oriented polymers represent a good investment, subject to a positive outcome from detailed market research on customer response to Company D's synthetic hardwood flooring product. The market forecast of $260 million in revenue by 2020 represents a medium sized market opportunity from which Company D is well positioned to capture value. Organisational structure is appropriate for the current growth stage of the company. Opportunities for future growth exist both in the global hardwood flooring market and in growing market share in the remainder of the US hardwood market and the total floor coverings market.

Value capture analysis does not recommend octet truss materials for investment at this time. This is due to a weak appropriability regime, low attractiveness for industrial applications, and insufficient knowledge of the potential applications. Viability analysis on developing biomedical applications and subsequent value capture analysis could change this recommendation.

## 8.3 Market Forecast, Viability Assessment, and Value Capture of Metal Foams

The strongest possibilities for short term substitution of aluminium foam lie with substitution into existing markets. Aluminium foam can be used in radically new designs which would take best advantage of the multi-dimensional attributes offered by metal foams, but which will be slowed both by lack of designer awareness or confidence in metal foams and by manufacturing difficulties with achieving high tolerances. Hence, an exploitation of one or two of aluminium foams strongest attributes, by substitution into existing applications, appears to be the best short term strategy to refine production practices and to increase designer awareness and confidence in the material class. In this investment assessment, the positions of two companies were considered: Company A, which is producing medium quality, medium priced, 3 dimensional, aluminium foam parts by a powder metallurgical process (figure **4.4**), and Company B, which is producing lower quality, lower priced, aluminium foam by a liquid processing method (figure **4.3**). The market forecast, viability, and value capture potential are summarised below.

Following the strategy outlined in section 3.2.4, markets were identified which exploit aluminium foams' strongest technical parameters of energy absorbed per unit volume and energy absorbed per unit stiffness. Of these markets, the automotive energy absorbtion market, estimated at $100 million annually (assuming 1 lb of aluminium foam for every passenger car produced), was prioritised through technical modeling of the non-dominated properties of aluminium foams. The initial applications of interior occupant safety, in particular within the A-pillar, and new pedestrian protection legislation that will affect redesign of the hood and front bumper regions were examined technically in the case study of chapter 5.

With input from the market analysis, the viability of aluminium foam in automotive applications and pallet applications was examined. Aluminium foams were found to be viable in energy absorption applications in the automotive industry, an $100 million dollar opportunity, but do not offer much likelihood of attractive value capture for the companies assessed. Aluminium foams are not currently viable in pedestrian protection applications. Aluminium foams might be viable in weight sensitive pallet markets, depending on customer utility.

Aluminium foams are promising for energy absorption applications when space is at a premium. Section 4.4.1 illustrates that Aluminium foam panel are viable in stiffness constrained panel applications only when mass savings is valued at £500/kg or above. For volume constrained energy absorption applications, aluminium foam energy absorption elements are viable when volume savings are valued at £1/cm thickness or above. The case study in chapters 5 and 6 examines automotive energy absorption applications in detail, and concludes that aluminium foams are viable for A-pillar occupant safety applications under certain design constraints.

Current A-pillar legislation, which requires protection against an impact of 24.1 km/hr, can be accomplished with a thickness of between 11 mm and 34mm of foam, dependent on the stiffness of the Body-In-White (BIW) structure. The same energy absorption requires a thickness of polyurethane foam between 24 mm and 150mm, again dependent on the stiffness of the BIW structure. Where low cost is of higher priority than low volume, polymer foams are the leading contender for automotive energy absorbing applications, but where minimising volume has the highest priority metal foams can be a better choice (figure **5.6b**).

The pedestrian protection applications appear to be too demanding for aluminium foam – or, indeed, for foams of any type. Absorbing the kinetic energy of the head from a 40km/hr collision requires a thickness of 125mm of foam, when limiting deceleration to 60g. Current automobile design precludes packaging of anything like this thickness. Any absorber, whether crushable foam, aluminium hexagon or hydraulic damper, will require at least this much travel if it is to absorb the kinetic energy of the head whilst limiting the deceleration to a safe level for the human head.

Aluminium foam may still be a candidate for pedestrian protection applications under certain scenarios. If cars are redesigned with more space between the engine block and the hood, or if the pedestrian protection targets were lowered, aluminium foam would be a well suited for this application. Polymer foams (except perhaps for phenolics) would likely be ruled out because of the effect of temperature on their properties, possible fire hazard and the damaging effect of fuel vapour, oil and antifreeze. But with current automobile design constraints, the proposed pedestrian protection applications are going to be very difficult to achieve. The only solutions that appear viable are air bags on the hood of the vehicle, or some other, similar, deployable structure that can be stowed in a small space and released at the instant of impact.

Figures **6.3** and **6.4** depict the envelope of aluminium foam market forecast scenarios for the A-pillar market and weight sensitive pallet markets respectively. For the A-pillar market, $50 million of revenues could be reached in 10 to 18 years. The faster revenue stream will result if a large portion of the market is either lower cost / higher performance or has a strong customer association with enhanced safety. The substitution of aluminium foam pallets into the weight sensitive pallet market can be modelled on the revolutionary, higher cost/higher performance innovation of carbon fibre reinforced boat hulls replacing wooden hulls. Thus, for the weight sensitive pallet market, $30 million of revenues could be reached in 18 to 20 years.

However, value capture is not as promising as the viability analysis. Industry analysis shows the positions of both companies A and B to be of only moderate to low attractiveness. This means that the chances of creating profit margins in the A-pillar energy component and the pallet markets are poor. Company A and B are both in a moderate appropriability regime, which means that they have a moderate chance of appropriating a low profit margin. And while the organisational structure of Company B is good, that of Company A is of medium strength.

As the chances of value capture are relatively low for companies A and B and the payback period is relatively long, a small firm would be disadvantaged in commercialising this innovation. A larger company might be interested in pursuing this opportunity if it was in a good position to capture the value created. Alternatively, a government sponsored initiative for pedestrian or occupant safety might invest in assisting the commercialisation of such an innovation. If companies A and B do obtain financing to pursue this commercialisation, they should strongly consider collaboration with either a supplier or a customer. Such collaborations can provide financing opportunities, faster penetration of the material and a more detailed understanding of the market.

## 8.4 Conclusions

Many risks stand in the way of introducing a new material into the market place, some technical, some production related, and some market oriented. If the risks can be quantified at an early stage and the expected financial payback is large enough to justify the risks, then the gestation time of a new materials innovation is likely to be shortened. Tools exist for investigating aspects of these risks, but they were not originally developed with materials innovations in mind, nor have they been integrated into a coherent and accessible methodology. Adapting them to materials innovations and linking them to give a practical, comprehensive procedure, has been the aim of the work described in this thesis. Its viability has been demonstrated both by testing some of its parts through exploration of innovation with LEPs, oriented polymers, and cast octet-truss structures, and – demonstrating the whole procedure – through a major case study of the introduction of metal foams into automobiles.

This – the result of a 3-year study – clearly demonstrates that the approach has merit; indeed two major automotive OEMs have expressed interest in it and used parts of it in company presentations. All of the materials SMEs who participated in this thesis have expressed interest in using the methodology. It would clearly be valuable to work closely with them, and with other companies, to follow through the entire design cycle, providing information to refine the methodology. That requires a longer-term research program. It is one that I hope to pursue as part of the next phase of my career.

## References

[1] Private discussions with representatives from Arthur D. Little, Cambridge Research and Innovation Ltd., and 3i

# Appendix A:

## Questionnaire on Changes in Materials Innovation

# Questionnaire on Innovation and Adoption of New Materials

1. Company Name ______________________________

2. Number of Employees ______________________________

3. Date of incorporation ______________________________

4. What country are you based in? ______________________________

5. Industry Sector(s)

| Sales into Sector (tick where appropriate) | |
|---|---|
| Aerospace | |
| Automotive | |
| Electronics and Communications | |
| Construction | |
| Biomedical | |
| Sporting Equipment | |
| Transportation (other than automotive) | |
| Other | |

6. Main Product Type ______________________________

7. What is your company's materials innovation? ______________________________

______________________________

8. Percentage of Company (by revenue) involved with this materials innovation (0% to 100%) __________ %

9. Recent Revenue History

| Year | Total Company Revenues |
|---|---|
| 1995 | |
| 1996 | |
| 1997 | |
| 1998 | |
| 1999 | |

10. Do you believe that your company is better placed to successfully commercialise your materials innovation today than you would have been a decade ago? (Yes / No) ______________________________

11. If so, which factors have been the most critical in this change?
*(0 = no importance, 1 = slight importance, 2 = moderate importance, 3 = high importance)*

| Factors effecting successful commercialisation | Ranking (0-3) |
|---|---|
| Information technology (information scanning software) | |
| Connectivity (internet, email, networking) | |
| Globalisation (internationalisation of companies) | |
| Collaborative work (R&D alliances, distribution alliances) | |
| Predictive tools (predictive software for material development, product design and cost forecasting) | |
| Outsourcing | |
| Other | |

12. From the factors you identified, on which areas of the innovation commercialisation process was their greatest impact?
*(0 = no importance, 1 = slight importance, 2 = moderate importance, 3 = high importance)*

| Areas of factor impact | Ranking (0-3) |
|---|---|
| Market interface (market scanning, feedback) | |
| Design process (development of material and of product) | |
| Venture capital access (money for company growth) | |
| Industry structure (barriers to entry, buyer or supplier power, competitive rivalry, threat of substitutes) | |
| Appropriability (ability to retain profits from innovation) | |
| Manufacturing interface (cost and production forecasting) | |
| Other | |

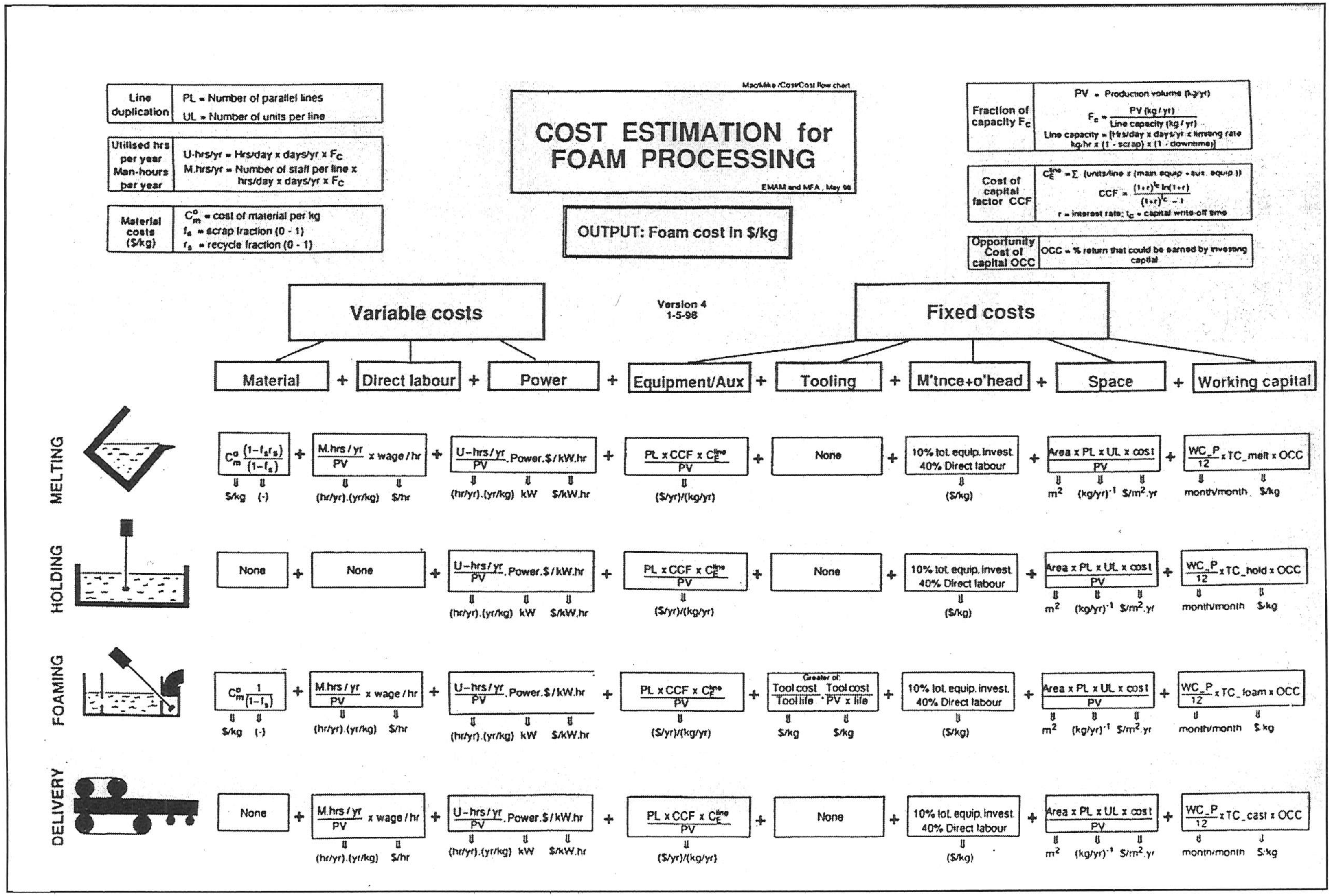
13. Which barriers to commercialising materials innovation do you think have been changed by the factors in question 11?
*(0 = no change, 1 = slight change, 2 = change, 3 = large change)*

| Barriers to Materials Innovation | Ranking (0-3) |
|---|---|
| Inability to access capital for large, capital intensive innovations | |
| No reputational clout for partnering | |
| Inability to scan the market and technical opportunities with broad R&D and marketing departments | |
| Limited experience in industry sector | |
| No existing distribution system or customer base | |
| Long gestation time of materials innovations | |
| Other | |

14. Do you believe that SMEs (Small and Medium sized enterprises) are better placed to successfully commercialise materials innovation today than they would have been a decade ago? (Yes / No) ______________________

# Appendix B:

## Schematic of Technical Cost Model for Liquid Processing of Aluminium Foam



Line duplication
PL = Number of parallel lines
UL = Number of units per line
Utilised hrs per year
Man-hours per year
U-hrs/yr = Hrs/day x days/yr x Fc
M.hrs/yr = Number of staff per line x hrs/day x days/yr x Fc
Material costs ($/kg)
C°m = cost of material per kg
fs = scrap fraction (0 - 1)
rs = recycle fraction (0 - 1)
Mac/Mike /Cost/Cost flow chart
COST ESTIMATION for FOAM PROCESSING
EMAM and MFA , May 98
OUTPUT: Foam cost in $/kg
Fraction of capacity Fc
PV = Production volume (kg/yr)
Fc = PV (kg/yr) / Line capacity (kg/yr)
Line capacity = [Hrs/day x days/yr x limiting rate kg/hr x (1 - scrap) x (1 - downtime)]
Cost of capital factor CCF
r = interest rate; tc = capital write-off time
Opportunity Cost of capital OCC
OCC = % return that could be earned by investing capital
Variable costs
Version 4
1-5-98
Fixed costs
Material
Direct labour
Power
Equipment/Aux
Tooling
M'tnce+o'head
Space
Working capital
MELTING
HOLDING
FOAMING
DELIVERY
None
M.hrs / yr / PV x wage / hr
U-hrs / yr / PV . Power.$ / kW.hr
PL x CCF x C line E / PV
10% tot. equip. invest.
40% Direct labour
Area x PL x UL x cost / PV
WC_P / 12 x TC_melt x OCC
WC_P / 12 x TC_hold x OCC
WC_P / 12 x TC_foam x OCC
WC_P / 12 x TC_cast x OCC
Greater of:
Tool cost / Tool life
Tool cost / PV x life
$/kg
(-)
(hr/yr).(yr/kg)
$/hr
kW
$/kW.hr
($/yr)/(kg/yr)
($/kg)
m²
(kg/yr)⁻¹
$/m².yr
month/month

# Appendix C:

## Process Stages of Powder Metallurgical Processing of Aluminium Foam

Figure C1: PM Processing of Al Foam

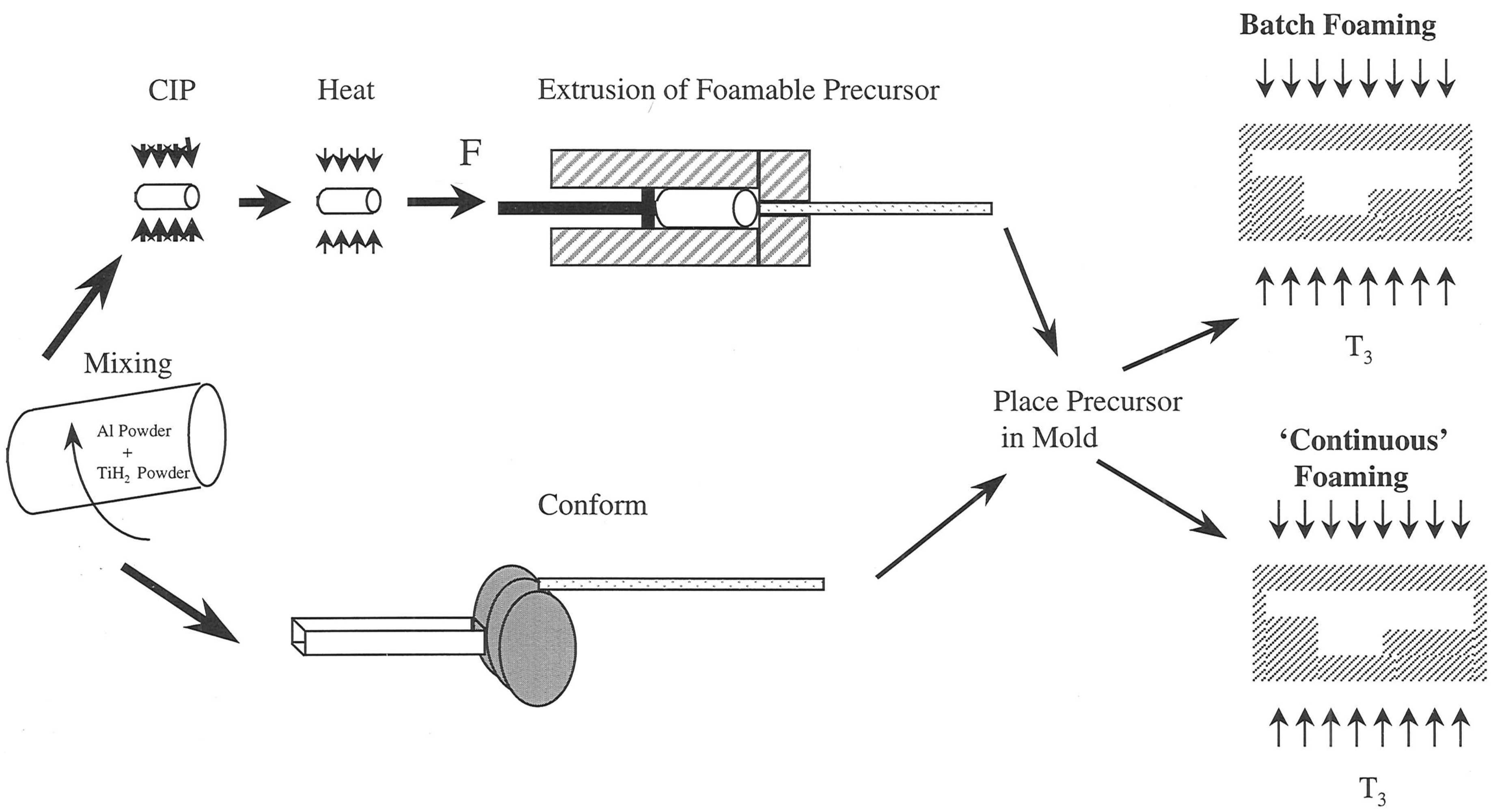
Figure C2: Conform Process vs. Compression, Heating, and Extrusion

Figure C3: Current Batch Foaming Process

Figure C4: Concept for 'Continuous' Foaming

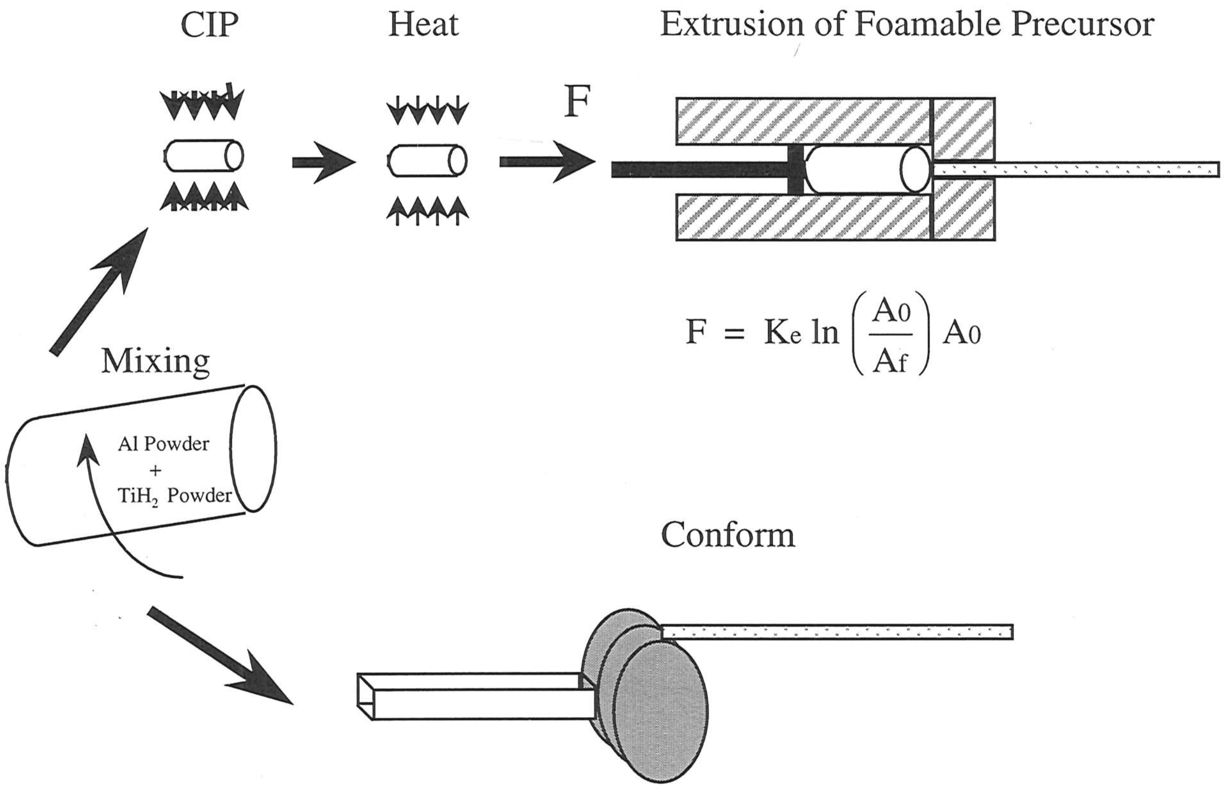
Figure C5: Cost Estimation for Foam Processing: Typical Cells

# Figure C1: PM Processing of Al Foam




EMAM and MFA, University of Cambridge, August 98

# Figure C2: Conform Process vs.Compression, Heating, and Extrusion




$$F = K_e \ln\left(\frac{A_0}{A_f}\right) A_0$$

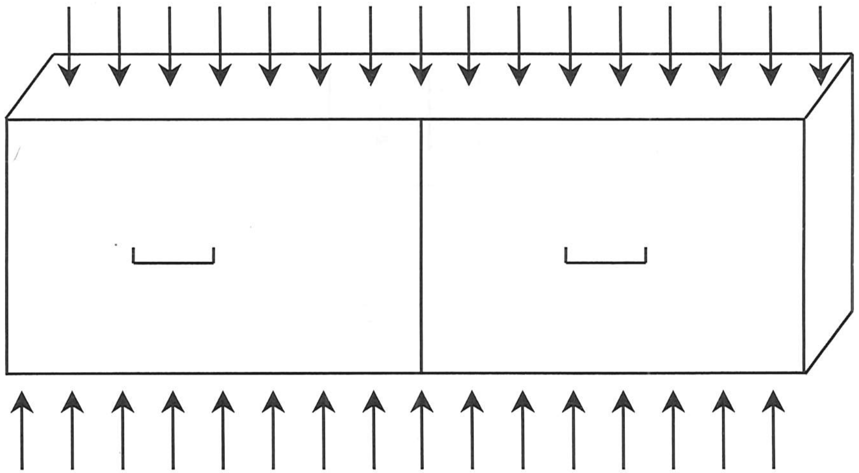
- Higher labour
- Parallel lines of CIP and billet heating for high volume

- Lower labour requirements
- Higher capital cost

900 C

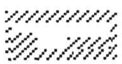
# Figure C3: Current Batch Foaming Process

Foaming Furnace at $T_3$
Initial Mould Temperature $T_1$
Desired Foaming Temperature $T_2$



Place precursor into mold.
Mass of precursor required is:

$$m = \frac{\text{Desired Relative Density} * \text{Volume of Part}}{(1 - \text{Percentage Overflow of Foaming Process})}$$



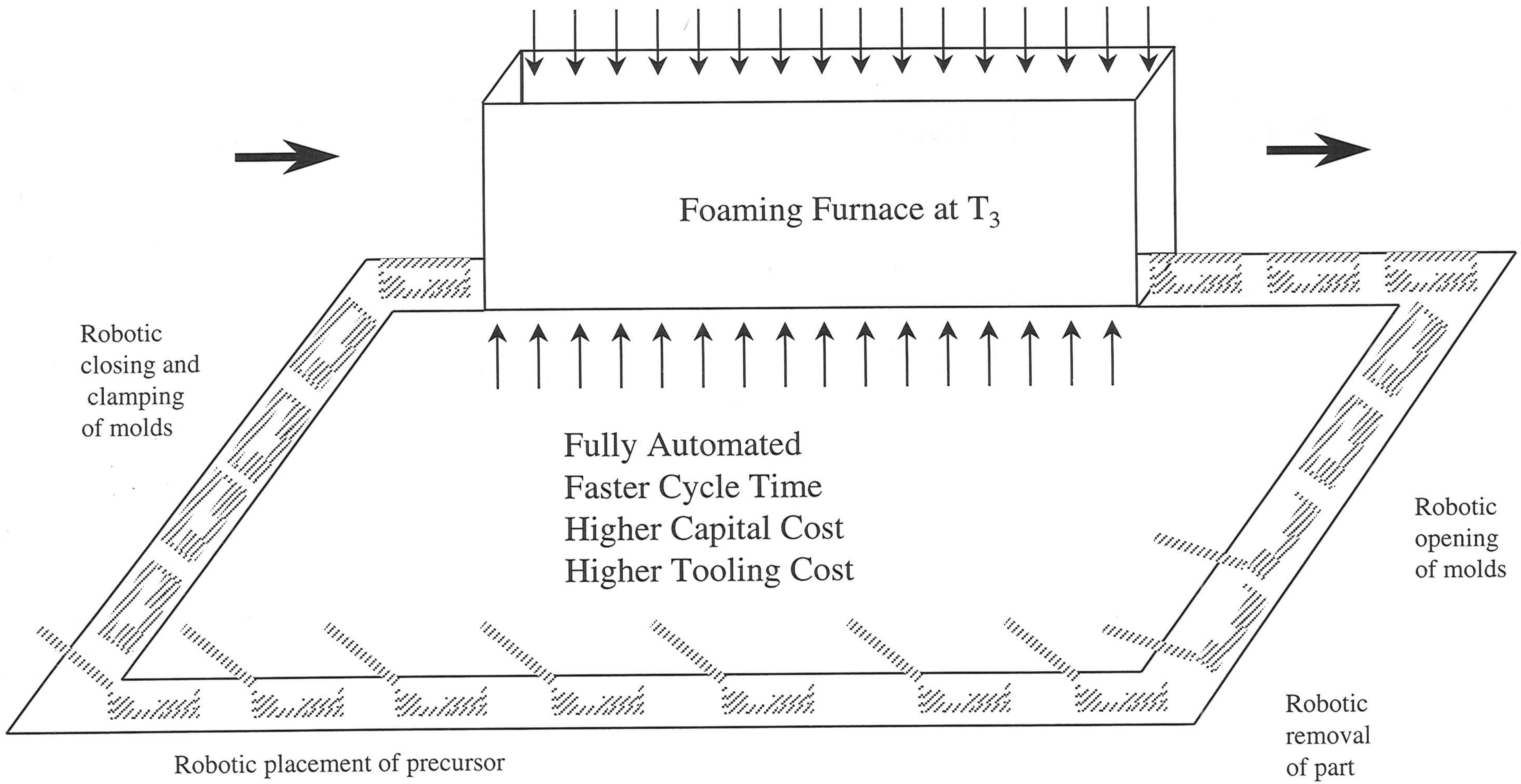
Foaming Cycle Time of Part is:
( heat transfer limited )

$$t = \frac{\dfrac{C_p\ \rho\ x}{h}\ \ln\left(\dfrac{T_3 - T_1}{T_3 - T_2}\right) + \text{Removal and Reload Time}}{\text{Number of Parts in Furnace}}$$

where, $C_p$ is the Specific Heat of the material, $\rho$ is the density of the material

$h$ is the heat transfer coefficient of the material, and $x$ is the characteristic dimension

# Figure C4: Concept for 'Continuous' Foaming



# Figure C5: Cost Estimation for Foam Processing: Typical Cells

- Batch Foaming Cycle Time (seconds / unit) =

$$\frac{\dfrac{\text{Characteristic Thickness} * \rho * C_p * ln\left(\dfrac{T_3 - T_1}{T_3 - T_2}\right)}{\text{Empirically Calculated Effective Heat Transfer}} + \text{Removal and Reload Time}}{\text{Number Of Parts In Furnace}}$$

- Fraction of Capacity Utilisation:

$$F_c = \frac{\text{Required Production Volume (kg/yr)}}{\text{Hrs/day x days/yr x limiting rate (kg/hr) x (1- scrap) x (1 - downtime)}}$$

# Appendix D:

## Cost Estimation and the Viability of Metal Foams

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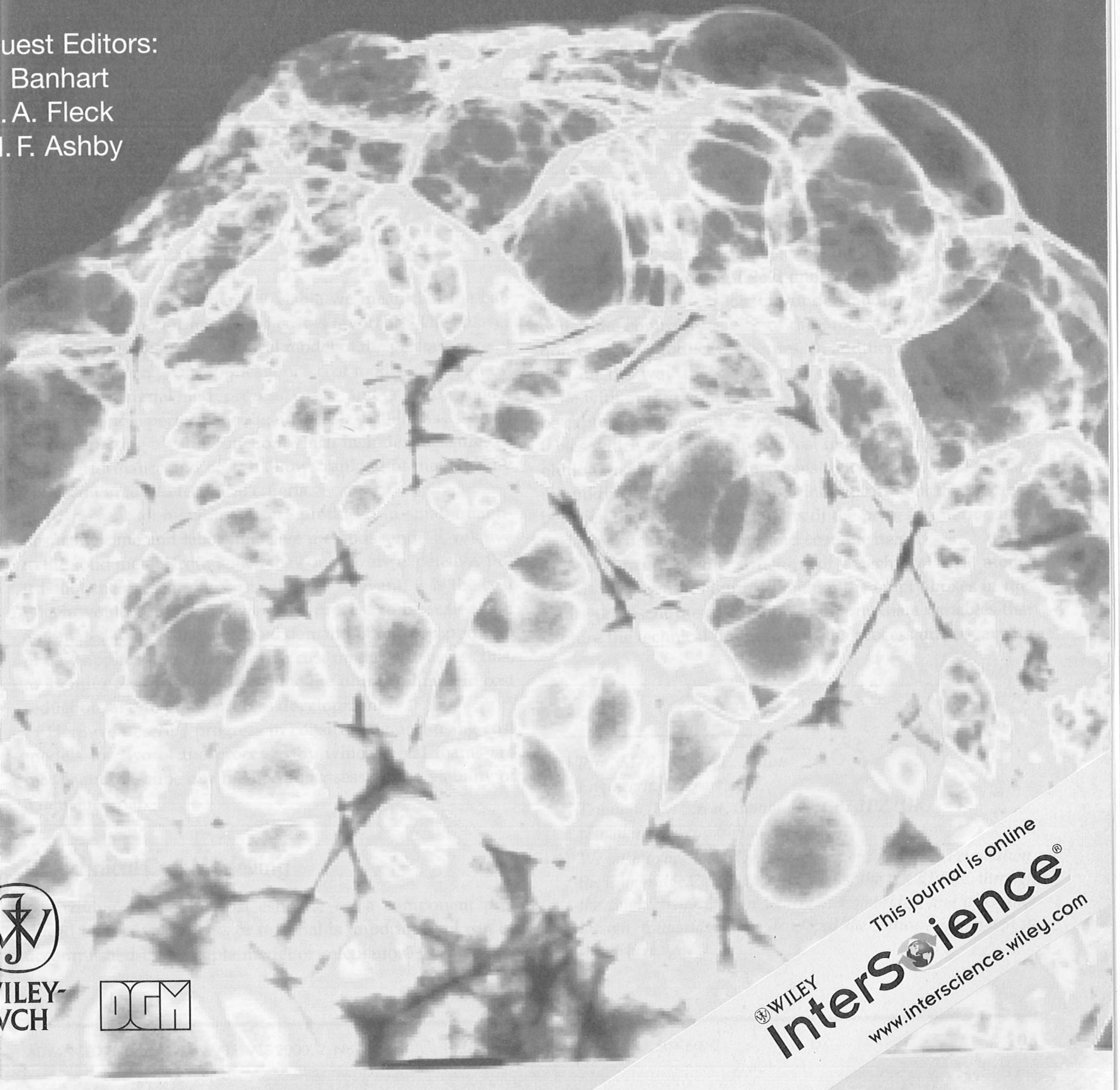
# ADVANCED ENGINEERING MATERIALS

## Special Issue
## Metal Foams

uest Editors:
Banhart
.A. Fleck
I. F. Ashby



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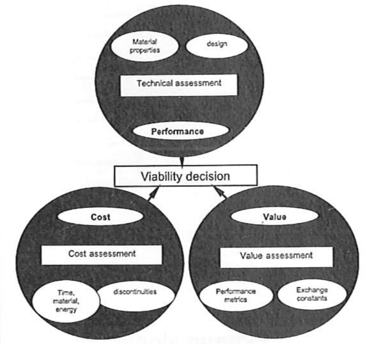
# Cost Estimation and the Viability of Metal Foams**

By *Elicia Maine* and *Michael F. Ashby**

*At present all metal foams are produced in small quantities using time and labor-intensive methods, and all, relative to the solid metals from which they derive, are expensive. Thus, one may ask if metal foams are viable. By viable a favorable balance between performance and cost is meant. Viability is assessed by constructing a value function which includes measures of both performance and cost. It allows ranking of materials by both economic and technical criteria. The authors describe progress in constructing and using cost models for two of the processes by which metal foams are made, and describe their method for assessing the viability of a new material.*




## 1. Introduction

Are metal foams viable? By viable we mean that the balance between performance and cost is favorable. The answer has three ingredients: a technical model of the performance of the material in a given application, a cost model giving an estimate of material and process costs, and a value model which balances performance against cost. Viability is assessed by constructing a value function which includes measures of both performance and cost. It allows ranking of materials by both economic and technical criteria.

At present all metal foams are produced in small quantities using time and labor-intensive methods, and all, relative to the solid metals from which they derive, are expensive. But it is not the present-day cost which is relevant; it is the cost which would be obtained were the process to be scaled and automated to meet the increased demand of one or a portfolio of new applications. The role of a cost model is to assess this, to identify cost drivers, to examine the ultimate limits to cost reduction, and to guide process development.

Here we describe progress in constructing and using cost models for two of the processes by which metal foams are made, and describe our method for assessing the viability of a new material.

## 2. Technical Cost Modelling

Arriving at a point cost estimate for a component produced by a novel process or material is important but can be accomplished by a simple model or calculation. Greater predictive power can be obtained by introducing elements of technical cost modeling (Field and de Neufville, 1988; Clark et al. 1997) which exploit the understanding of the way in which the control-variables of the process influence production-rate and product properties. In addition it uses information on the way the capital cost of equipment and tooling scale with output volume. These and other dependencies can be captured in theoretical and empirical formulae or look-up tables which are built into the cost model, giving greater resolution. In addition, informed sensitivity-analysis and scenario-building are enabled through the capturing of the linkages between the technical limitations of the process, intermediate variables such as cycle time, and cost line items.

A schematic of the structure of a technical cost model (TCM) is shown in Figure 1. Each of the empty boxes in this figure represent the calculation of intermediate variables that capture the technical limitations of the process under varying

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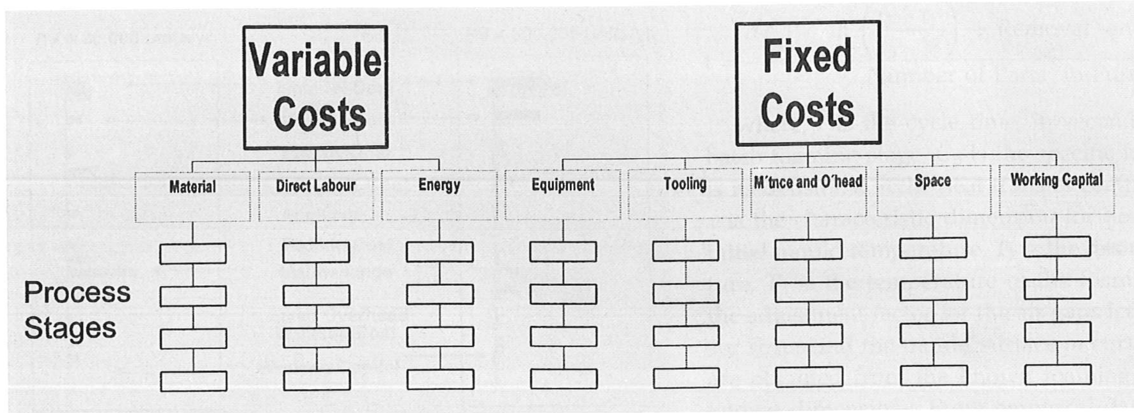


*Fig. 1. Schematic of a technical cost model (TCM).*

input product specifications, process choices, and selected production volumes. The final output consists of both a range of unit cost numbers and the identification of cost drivers. We have constructed technical cost models for two established processes for making metal foams. They are described briefly in the next sections.

### 2.1. Liquid-State Foaming of Aluminum

Consider a cost model for the production of panels of a SiC-stabilized aluminum-based metallic foam by the following 4-step process:

a) melting of the pre-mixed alloy,

b) holding, providing a reservoir,

c) foaming, using compressed gas and a bank of rotating blades,

d) delivery of a continuous sheet of foam or of cut panels, via a moving belt.

The output of one step forms the input to the next, so the steps must match, dictating the size of the equipment or the number of parallel lines in each step. Data characterizing the dependence of desired material density and of production rate on the gas flow rate and the stirring rate has been incorporated in the model and links into the intermediate variables of limiting production rate (LPR, in kg/h), utilized hours per year (U.h/yr), man-hours per year (M.h/yr), fraction of capacity utilised ($F_c$), and number of parallel lines of equipment (PL), which are calculated in the model as shown below:

$$\text{U.h/yr} = \text{h/day} \times \text{days/yr} \times F_c \quad (1)$$

$$\text{M.h/yr} = \text{Number of staff per line} \times \text{h/day} \times \text{days/yr} \times F_c \quad (2)$$

$$F_c = \text{Production Volume (PV) / Line Capacity (kg/yr)} \quad (3)$$

where Line Capacity = h/day × days/yr × limiting rate (kg/h) × (1 – scrap) × (1 – downtime) and, Production Volume = required annual output in kg.

$$\text{PL} = \text{number of parallel lines} = F_c \text{ rounded up to the nearest whole number} \quad (4)$$

Through these intermediate variables, the influences of scale-up and of varying product requirements effect the cost line items of equipment, direct labor, and power. Fixed costs are treated in the standard economics fashion, through the use of a cost of capital factor (CCF) and by including the opportunity cost of capital (OCC) associated with the working capital. These factors are defined as:

$$\text{CCF} = \frac{(1+r)^{t_c}\ln(1+r)}{(1+r)^{t_c}-1} \quad \text{where, } r = \text{interest rate}, \; t_c = \text{capital write-off time} \quad (5)$$

$$\text{OCC} = \text{the percentage return that could be earned by investing the capital} \quad (6)$$

A range of product, process, and business variables can be overridden by the user, providing flexibility and the potential for extensive scenario and sensitivity analysis.

The outputs of the model (Figs. 2 and 3) show the way in which the cost of the material depends on production volume and also identifies cost drivers. Significantly, the model indicates the production volume which would be necessary to

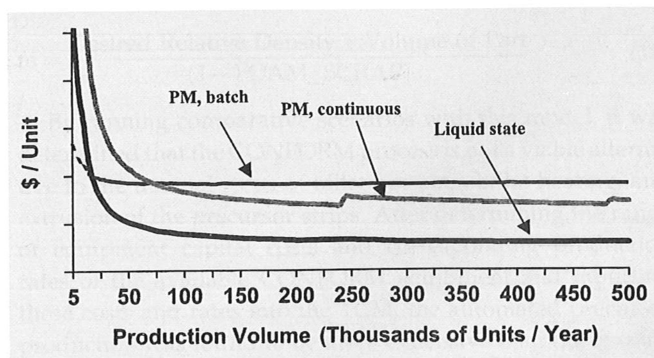


*Fig. 2. Manufacturing cost for varying production volumes: processing of aluminum foam by three methods.*

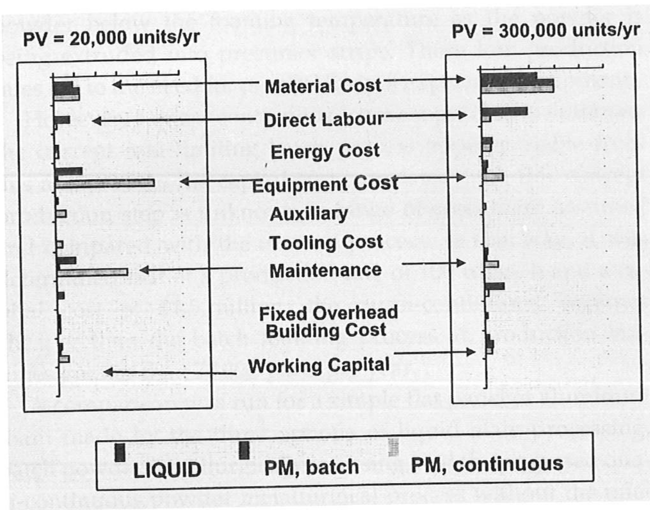


*Fig. 3. Line item cost for crossover annual production volume of 20 000 and 300 000 units: processing of aluminum foam by three methods.*

reach the plateau level of cost in which, in the best case shown here, the material cost falls to roughly twice that of the input materials.

### 2.2. Titanium-Hydride Expansion of Aluminum via Powder Metallurgical Processing

In comparison, consider a cost model for the production of panels of an aluminum-based metallic foam by either the batch or quasi-continuous processes for the powder metallurgical (PM) processing of aluminum foam. For the batch process, there are six steps:

a) Mixing of the Al powder with the powdered foaming agent (<1 % $TiH_2$ ).

b) Cold isostatic compression of the powder into an intermediate billet.

c) Sintering of the billet (optional).

d) Extrusion of the foamable precursor.

e) Placement of precursor in mould.

f) Batch foaming of precursor in mould.

For higher production volumes, automation of steps b, c, and d and of steps e and f have been proposed as follows:

a) Mixing of the Al powder with the powdered foaming agent (<1 % $TiH_2$).

b) Conversion of powder into precursor strip using the CONFORM process.

c) Quasi-continuous foaming of precursor in the mould, meaning that the moulds on a continuous belt are filled robotically, passed through the furnace, opened and emptied.

The rate-limiting step for the current low production volume process is the batch foaming step. The cycle time of this step is heat-transfer limited. The time required to heat the mould then increases with increased part dimensions and the time required to transfer heat into the precursor strips increases both with increasing part dimensions and with part curvature, according to the equation below:

$$t = \frac{\beta \frac{C_p \rho x}{h} \ln\left(\frac{T_3 - T_1}{T_3 - T_2}\right) + \text{Removal and Reload Time}}{\text{Number of Parts in Furnace}} \quad (7)$$

where, $t$ is the cycle time, in seconds, of one unit in the batch foaming stage, $C_p$ is the specific heat of the material, $\rho$ is its density, $h$ is the heat transfer coefficient of the material, $x$ is the characteristic dimension for heat diffusion, $T_1$ is the initial mould temperature, $T_2$ is the desired foaming temperature, $T_3$ is the temperature of the foaming furnace, and $\beta$ is the adjustment factor for the air gaps left between the precursor strips and the mould surface in curved parts. Values of $\beta$ are obtained from the known foaming times for moulds of known dimensions. From empirical data, curved parts have an approximately 50 % longer foaming time than flat parts because of poor contact and heat transfer between the bars of precursor and the mould surface. The adjustment factor, $\beta$, corrects for this. To ensure the validity of assuming heat-transfer, rather than conduction, is limiting, a check of the Biot number is performed, as follows:

$$\text{Biot Number} = \frac{\lambda}{h\,x} \quad (8)$$

If the Biot Number is greater than 1, the heat transfer condition is met.

An important cost driver in this process is the substantial amount of scrap generated in the foaming stage in order to ensure mould filling, shape definition, and to avoid weak zones along the interfaces of the precursor strips where they meet during foaming. Throughout the model, the percentage of material that is lost during the foaming stage is referred to as FOAM_SCRAP and the cost of processing this waste material is reflected in the material cost line item of the batch foaming and continuous foaming stages. As the material can be sold as prompt scrap, the additional material cost in the foaming stage can be expressed as:

(powder cost – price of prompt scrap +
cost of processing powder) × FOAM_SCRAP (9)

Accounting for this scrap and the desired relative density of the final part, the amount of precursor material required per part in the foaming stage is:

$$m = \frac{\text{Desired Relative Density} * \text{Volume of Part}}{(1 - \text{FOAM\_SCRAP})} \quad (10)$$

By running comparative scenarios with this model, it was determined that the CONFORM process is not a viable alternative to the manual steps of billet pressing, billet heating, and extrusion of the precursor strips. After determining the range of equipment capital costs and corresponding production rates of the available CONFORM equipment and inputting these costs and rates into the TCM, the automated precursor production was found to be more expensive than the manual process. This result was unexpected, but arose because the feasible production rates of the CONFORM equipment were limited by adiabatic heating: it is necessary to keep the aluminum powder below the foaming temperature as the powder is being extruded into precursor strips. These low production rates led to the need for parallel lines of expensive equipment.

However, a quasi-continuous foaming process to automate the current rate limiting batch process appears viable from this analysis. As the capital cost associated with this concept production step is unknown, a range of costs were assumed and compared with the manual process. In this way, it was determined that at a production rate of 100 units/h and a capital cost of $1.5 million, the quasi-continuous becomes cheaper than the batch foaming process at production volumes greater than 70 000 parts per year.

A comparison was run for a simple flat panel of aluminum foam made by the three options of liquid state processing, batch powder metallurgical processing, and the proposed quasi-continuous powder metallurgical process without the uneconomical CONFORM step. This simple flat panel comparison inherently favors the liquid state process of Section 2.1, which is set up for the continuous production of flat panels. Figure 2 depicts the relative cost per unit of each of the different options over a range of annual production volumes. For annual production volumes of up to 20 000 parts, the batch powder metallurgical process is the most economical option. From examining Figure 3, which shows a snapshot of the line item costs for each process at 20 000 parts per year, we can see that it is fixed costs, in particular equipment costs, that drive the low volume cost of both continuous PM processing and liquid state processing higher than that of batch PM processing.

In comparison, Figure 3 also shows the cost drivers for all processes at a production volume of 300 000 parts per year, where the continuous PM process is more economical than the batch PM process. The continuous process reduces the variable costs of direct labor, and avoids the need for multiple parallel lines of batch furnaces at higher annual production volumes. The equipment cost is still large for the quasi-continuous PM process, even after amortization over significant production volume; however, the direct labor savings now compensate for the higher equipment costs, making quasi-continuous PM processing more economical that batch PM processing. From this analysis and from using the TCM on other proposed products, maximum viable levels of capital equipment expenditure and expected cycle time for a continuous process can be set. The required cycle time, the part size, and the foaming time feed into the calculation of the length of furnace required which, in turn, feeds into the capital expenditure estimate. In this way, the TCM can be used to aid the decision about the suitability of converting to a continuous process.

## 3. Viability

### 3.1. Value Functions

The viability of a foam in a given application depends on the balance between its performance and its cost. There are three steps in evaluating it (Fig. 4).

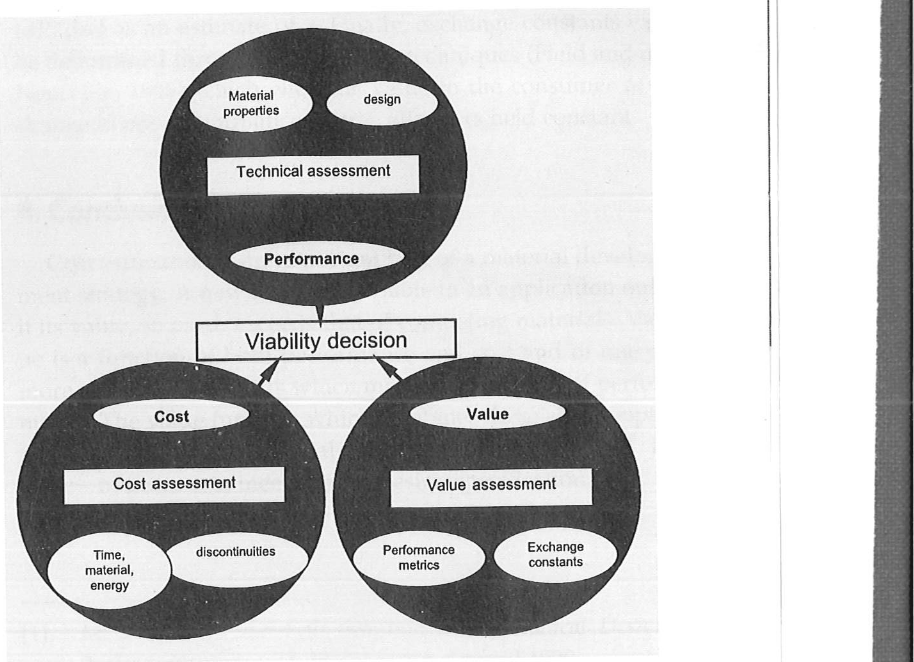


*Fig. 4. The three parts of a viability study.*

The first is the technical assessment (Fig. 4, upper circle). Performance metrics, $P_i$, are identified and evaluated for the foam and for competing materials or systems. A performance metric is a measure of the performance offered by the material in a particular application. In minimum weight design the performance metric is the mass: the lightest material which meets the specifications on stiffness, strength, etc. is the one with the greatest performance. In design for energy-mitigation, in which it is desired that a protective packaging should crush, absorbing a specified energy, and occupy as little volume as possible, the performance metric is the volume. In design to minimize heat loss, the metric could be the heat flux per unit area of structure. In design for the environment, the metric is a measure of the environmental load associated with the manufacture, use and disposal of the material.

The second step is the analysis of cost (Fig. 4, lower-left circle): how much does it cost to achieve a part/component with a given performance metric? The quantity of foam required to meet constraints on stiffness, on strength, on energy absorption etc. is calculated from straightforward technical models. The cost C of producing this quantity of material in the desired shape is the output of the cost model, as described in Section 2.

The final step is that of assessing value (Fig. 4, lower-right circle). To do this we form a value function

$$V = \alpha_1 P_1 + \alpha_2 P_2 + \ldots - C \quad (11)$$

where the $\alpha$'s are exchange constants: they relate the performance metrics $P_1$, $P_2$ ... to value, $V$, measured in $.

For substitution to occur, the difference in value $\Delta V$ needs to be large enough to justify the investment in new technology, and there must be sufficient financial or strategic incentive for one or more companies to invest in the new technology, and also, if necessary, in the manufacturing facilities.

### 32. The Exchange Constants, $\alpha$

An exchange constant is a measure of the value of performance. Its magnitude and sign depend on the application. Thus the value of weight-saving in a family car is small, though significant: in aerospace it is much larger. The utility of heat transfer in a heat exchanger is positive; in applications requiring thermal insulation it is negative. The value of performance can be cost-based, meaning that it measures an actual saving of cost, energy, materials, time or information. But value can, sometimes, be perceived, meaning that the consumer, influenced by forces such as scarcity, or advertising, or fashion, or aesthetics, or convenience, etc. will pay more than the cost-based value of these metrics.

In many engineering applications the exchange constants can be derived approximately from technical models. Thus the value of weight-saving in transport systems is derived from the fuel saving or the increased payload which this allows. The value of heat transfer can be derived from the price of the energy transmitted or conserved by unit change in this metric. Approximate exchange constants can sometimes be derived from historical pricing-data; thus the value of weight-saving in a bicycle can be approximated by plotting the price $P$ of bikes against their mass m, using the slope ($dP/dm$) as an estimate of $\alpha$. Finally, exchange constants can be determined through interviewing techniques (Field and de Neufville, 1988) which elicit the value to the consumer of a change in one performance metric, all others held constant.

## 4. Conclusions

Cost estimation is an important part of a material development strategy. A new material is viable in an application only if its value, so used, exceeds that of competing materials. Value is a function of both performance and cost and of one or more exchange constants which measure the utility of performance. The value function which combines these allows optimized selection of material and—with a cost model in place—of process to meet a given design specification.

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