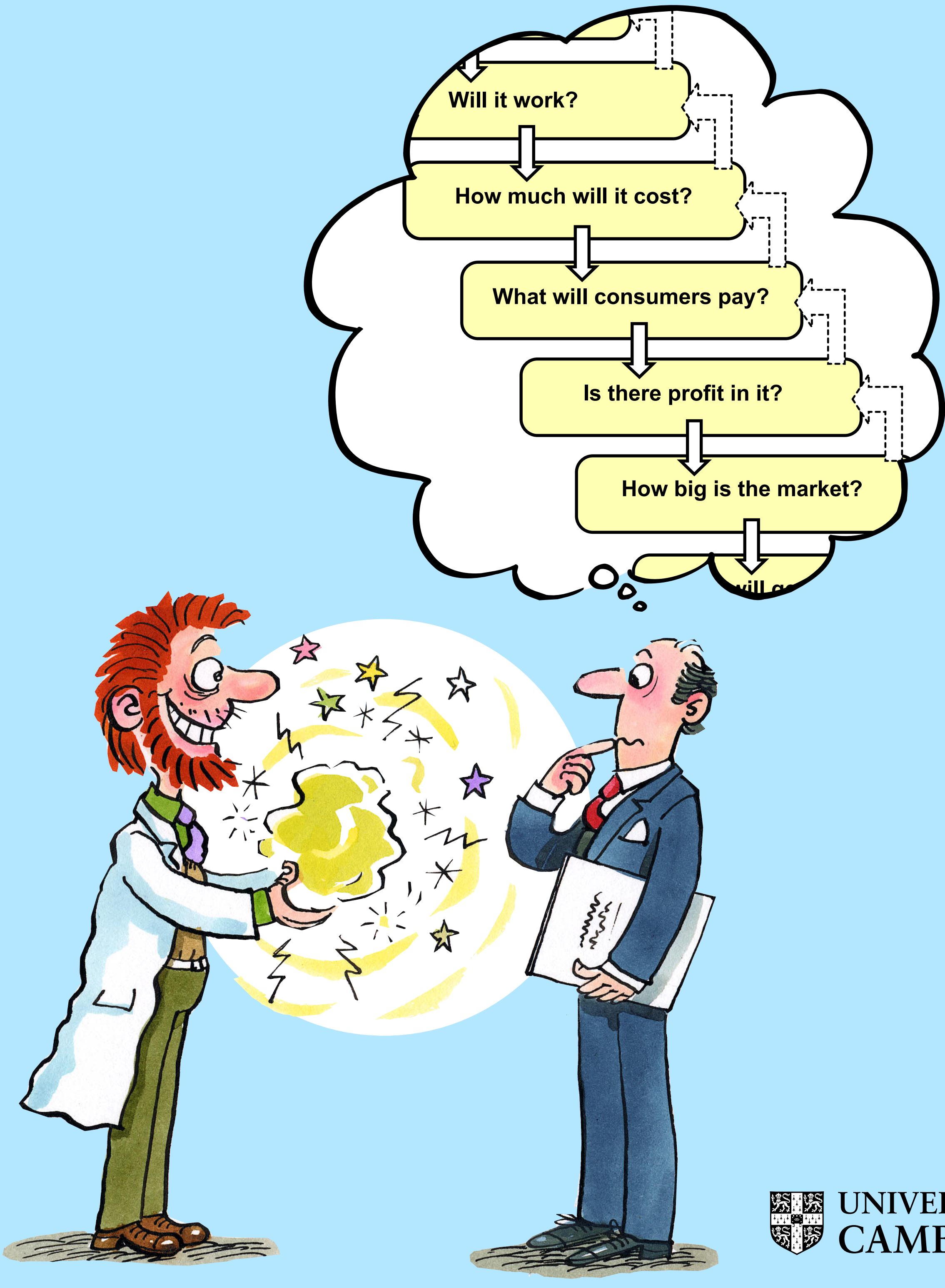
Succeeding with New Materials

A comprehensive guide for assessing market potential



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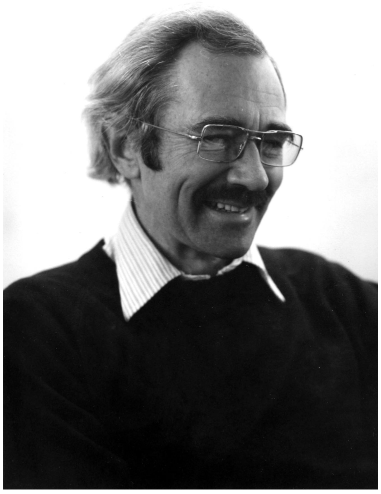

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Introduction

What's the problem?

New materials and new ways of processing them can offer potential for innovation in product design. But with upwards of 50,000 materials and many hundreds of processes already out there to choose from, how do we establish that a new one is **viable**[*]**,** in other words, that it can be used to make products that are sufficiently profitable to justify investment? Commercialising a new material can take 15 years and an investment of many millions of dollars. Its failure in the market place is then a major disaster. Assessing risk and establishing viability are of paramount importance.

What are the benefits of using this workbook?

This workbook outlines a strategy for increasing the knowledge-base on which investment decisions are taken, and for guiding the research, the development and the commercialisation required for successful materials innovation. The flow-chart on the facing page shows the eight stages of the strategy.

Who is it for?

This workbook can be used in a number of ways, addressing the needs of:

- Vice President or Director of Research and Development (R&D), Vice President or Director for Strategy, Product Managers, and R&D Managers of a large or small firm facing decisions on product development in aerospace, automotive, consumer electronic, and other industries
- Material developers
- Seed Venture Capitalists
- Government R&D Managers

How can it be used?

There are three suggested levels of use for this workbook:

- As a ***check-list*** to be used as a pre-requisite for seed venture capital investment.
- As a set of ***guidelines*** for in-house monitoring of new materials / product development – to set stage-gates and ensure balanced distribution of in-house resources in a development program.
- To structure an ***in-depth analysis*** guiding investment decisions in the commercialisation of a new material.

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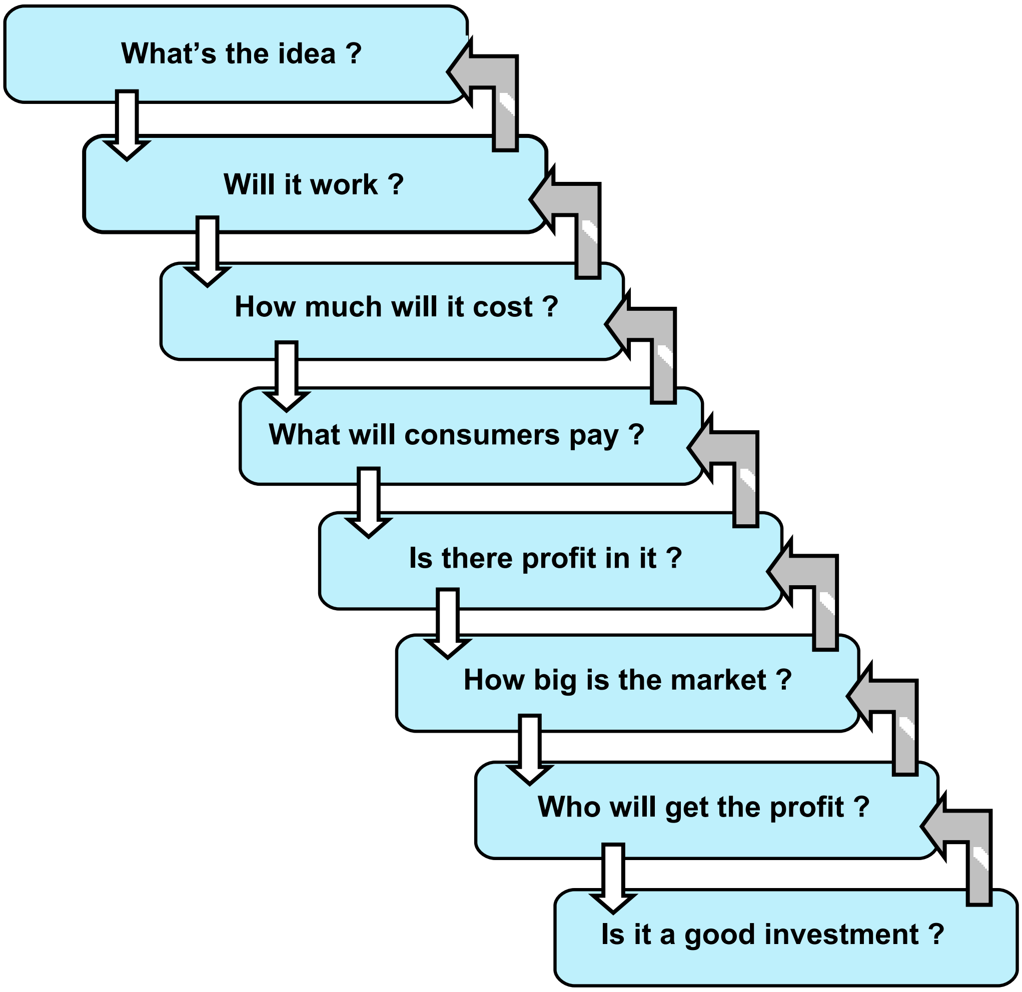
[*] Terms printed in **bold** in the text are defined in the Glossary at the end of this workbook.



The eight stages of the methodology

The flow diagram above shows the eight key activities involved in the application of the Investment Methodology for Materials (IMM). It forms the basis of this workbook, which is designed to support decision making. A double page of this guide describes each of the eight stages. Additional information for each is provided in a set of ***Appendices.***

A ***Bibliography*** lists key sources and identifies the references that appear in the text of the Appendix.

The ***Glossary*** defines technical terms, printed in bold in the text.

Stage 1
What's the idea?

A **material innovation** is a development in material or process technology leading to a new material with properties or features that differ, in one or more ways, from existing materials. The differences may be in material properties, or in processability, or in cost, or in its aesthetic potential. The fact that one or more of these are different opens up the possibility of using the material to make products that are, in some way, innovative. The first step is to investigate these opportunities, and compare the strengths and weaknesses of the new material with those of existing materials.

Inputs:

- The properties of the new material (mechanical, thermal, electronic, and optical properties, approximate cost, process-methods, environmental compatibility, as far as these are known)
- Similar information for existing materials, with their established applications.

Key steps:

- List the properties of the new material.
- Compare these with the properties of existing, commercial materials.
- Identify existing materials with **property-profiles** like those of the new material.
- Identify applications filled by these materials.
- Identify the properties of the new material that are exceptional – both better and worse – when compared with these materials.

Outputs:

- List of existing commercial materials with properties like those of the new material.
- List of applications for these existing material – these applications are potential applications for the new one.
- List of any properties, or combination of properties of the new material that are "exceptional" – unusually good or bad, or just different.

Tools/techniques

- Data sources for existing materials – see facing page and *Appendix for Stage 1* for details.

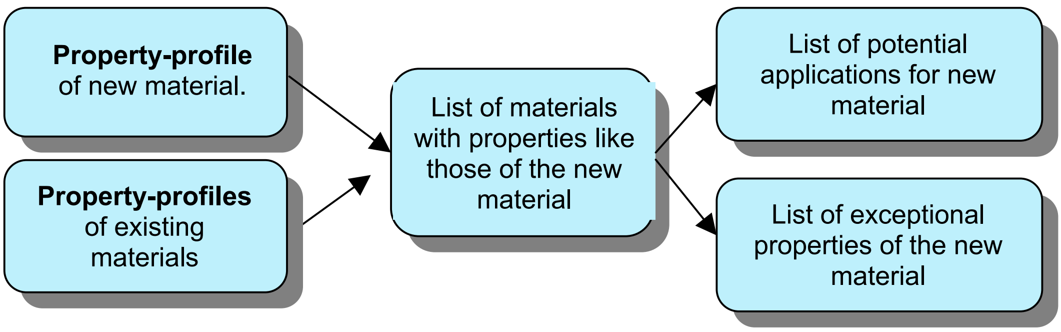
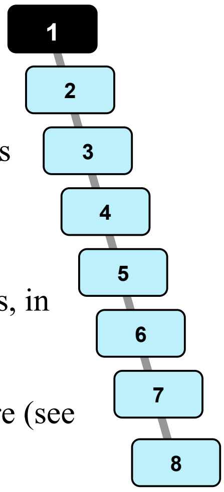


Figure 1.1. The steps in implementing Stage 1 of the method.

Guidelines for key steps ***(Appendix for stage 1 gives details)***



List the properties of the new material

- List the mechanical, thermal, optical, electrical and environmental properties of the new material, and the methods of shaping, joining and finishing it.

Compare these with the properties of existing, commercial materials

- Data for properties of standard engineering materials are listed in handbooks, in proprietary software and on the web.
- An efficient way to compare materials is to plot their attributes on **material property charts**; these are available both in hard-copy form and as software (see *Appendix for Stage 1*).

Identify existing materials with property-profiles like those of the new material

- The **material property chart** approach identifies materials that have **property-profiles** like that of the new material.
- Software systems such as CES 4 (2002) enable the comparison to be done automatically.

Identify applications filled by these materials

- Existing materials with **property-profiles** like that of the new one have established applications.
- These applications become the initial targets for gaining a toe-hold in the market.

Identify the properties of the new material that are exceptional

- Is it stiffer, stronger, tougher or lighter than the other materials that it resembles? Are its thermal, electrical, optical or aesthetic properties unusual? Can it be processed in new ways? Is it cheaper than any of the existing materials with which it might compete? List these.

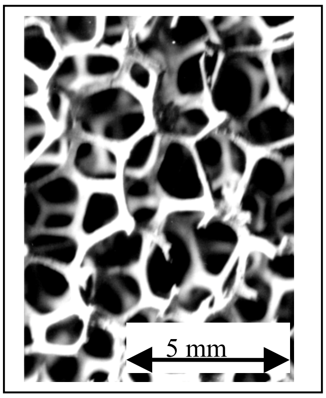
Running case study: the '*Innovative Metal Foam Company*'

The 'Innovative Metal Foam Co.' has developed a novel process for making metal foams. They have mechanical properties that resemble those of woods and the denser polymer foams, but they are exceptional in their stability at higher temperatures and their ability to conduct both heat and electricity. Target applications are therefore those filled by these materials: light-weight structures and sandwich panels, packaging and crash padding, and filters. Their exceptional properties are:

- Usable at temperatures far above those of polymers
- Chemical and dimensional stability
- Corrosion resistance
- High thermal conductivity through the metal cell walls and edges
- Much more expensive (requiring high-value applications)

This suggests applications in

- Packaging and crash padding with good long-term stability
- Cores for light-weight sandwich panels for use above room temperature
- High temperature filters
- Heat-exchange applications using the conductivity and high surface area.



A metal foam. Copper aluminium, lead, nickel and stainless steel can all be foamed

Stage 2
Will it work?

We now have an idea of the existing material with properties like that of the new materials, and the applications they fill. The new material is attractive from a purely technical standpoint if its performance in an application exceeds that of competing materials. Performance is measured by a **performance metric**. In light-weight structures, the metric might be stiffness per-unit-weight, or strength per-unit-weight.   In low cost structures it might be stiffness per-unit-cost etc. The best choice of material is that which meets all the **constraints** of the design and has the best values of the relevant **performance metrics**.

Inputs (from Stage 1):

- List of existing commercial materials with properties similar to those of the new material.
- List of applications of these commercial materials.
- List of exceptional properties of the new material.

Key steps:

- Formulate design requirements for each potential application as a set of **constraints** and **objectives**.
- Identify material limits imposed by the **constraints**.
- Identify **performance metrics** based on **objectives**, and evaluate.
- Compare the properties of the new material with the material specifications developed in the two previous steps.
- Prioritise the potential applications.

Outputs:

- A list of technically feasible applications that the new material can fill.
- Technical benchmarking of new material against existing materials.
- An estimate of the performance gain offered by the new material.

Tools/techniques

- The analysis of **constraints** and **objectives**, and the modelling of **performance metrics** – see *Appendix for Stage 2* for details**.**

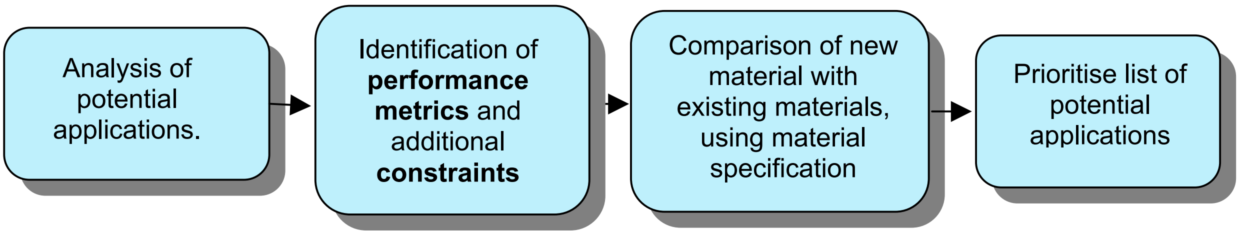
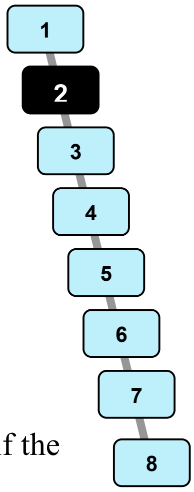


Figure 2.1. The steps in implementing Stage 2 of the method.

Guidelines for key steps ***(Appendix to Stage 2 gives details)***



Formulate design requirements for each potential application as a set of constraints and objectives

- Identify the key **functions** that the material must perform.
- Identify **constraints**: the conditions that the material MUST meet in order to perform the functions.
- Identify **objectives** (i.e. minimise weight or volume or cost); these define the **performance metrics.**

Identify material limits imposed by the constraints

- **Constraints** impose 'go/no-go' criteria on the use of a material. For example, if the component must operate at 300 C, all materials with a maximum working temperature less than this are rejected. If it must conduct electricity, all materials that are insulators are rejected.

Identify performance metrics based on objectives, and evaluate

- Model the **performance metric** (derive expression for the weight, volume or cost of material needed to fill the function).
- Identify **material indices** (the property groupings that appear in the expression for the **performance metric**).

Compare the properties of the new material with the material specifications developed in the two previous steps

- Does the new material meet the **constraints**?
- Does it have exceptional values of the **performance metrics**?

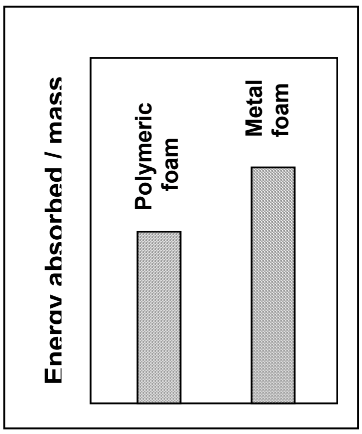
Prioritise the potential applications

- Identify applications in which the new material offers a performance gain over the existing material.

Running case study: the '*Innovative Metal Foam Company*'

Metal foam energy absorbers – a possible application

In designing energy absorbing units for crash protection inside cars, the objective is to minimise both the mass and the volume of padding needed to absorb a specified amount of energy – that of the occupant thrown against the padding in an accident. Conventional energy absorbers are hollow sections (tubes) or polymeric foams that crush at a prescribed pressure when hit. Metal foams have mechanical properties that make them good for absorbing energy. The figure shows that they absorb more energy per unit mass than polymeric foams. In addition, their properties do not deteriorate over time and they are non-flammable.



Here, then, is a potential application – one in which the metal foam performs a technical role better than an existing material. The next questions are: how much will it cost? And if it is more expensive than existing solutions, is the improved performance worth the additional cost?

Stage 3
How much will it cost?

Cost modelling enables a cost comparison between functionally similar components made with competing materials and processing methods. It identifies **cost drivers** – the steps in manufacture that add most to the unit cost – and it shows how unit cost depends on production volume. **Technical cost modelling** goes further but is more time consuming. It predicts how changes in technology will affect unit cost, guiding decisions on whether or not to adopt the changes. The main output of either model is an estimate of the cost of making a part using the new material. This can be compared with the cost of the part using existing materials.

Inputs:
- Dimensions and complexity of the component to be made.
- List of materials and processes for which the comparison will be made.
- Data for capital cost, tooling cost, production rate and scrap rate for each step of the manufacturing process (a site visit may be necessary).
- Estimate of potential production volumes (kg of material or number of parts).

Key steps:
- Build a **cost model** in standard spreadsheet format.
- Run the **cost model** for different ranges of input assumptions.
- Compare the unit cost of the component when made of the new material with that made of existing materials.

Outputs:
- Estimate of unit cost for alternative scenarios and production volumes.
- Cost comparison with existing or competing materials.
- Identification of **cost drivers** for each scenario.

Tools/techniques
- **Cost modelling** and **technical cost modelling** methods– see *Appendix for Stage 3.*

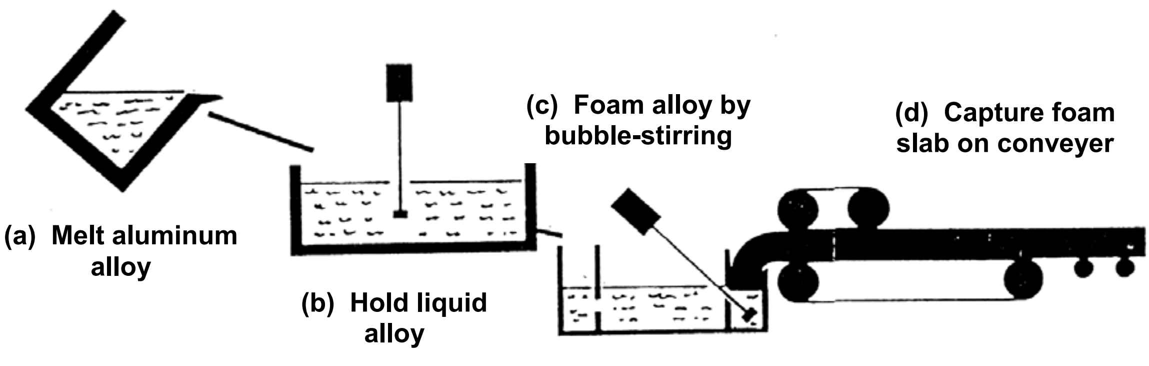
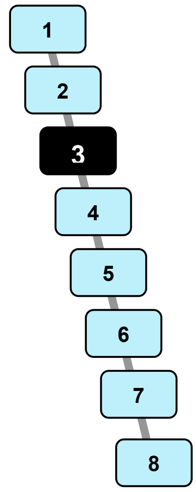


Figure 3.1. Schematic of a liquid-state process for making metal foam. The costs associated with each step are modelled separately, then coupled to ensure that the throughputs match.

Guidelines for key steps ***(Appendix for Stage 3 gives details)***



Build a cost model in standard spreadsheet format

- List equipment and labour requirements for each stage of the process.
- Estimate the capital cost of equipment and the cost of tooling.
- Determine probable scrap or reject rate.
- Determine **rate-limiting steps** and their **technical constraints**.
- Model each stage of the process as a separate spreadsheet page.
- Link pages to calculate overall rate and cost of manufacture.
- Use standard accounting categories to document cost origins.
- Test model for validity.

Run the cost model for different ranges of input assumptions

- Explore the effect of production volume on unit cost.
- Explore the effect of alternative equipment and labour costs on unit cost.
- Explore the effect of process innovations on unit cost.

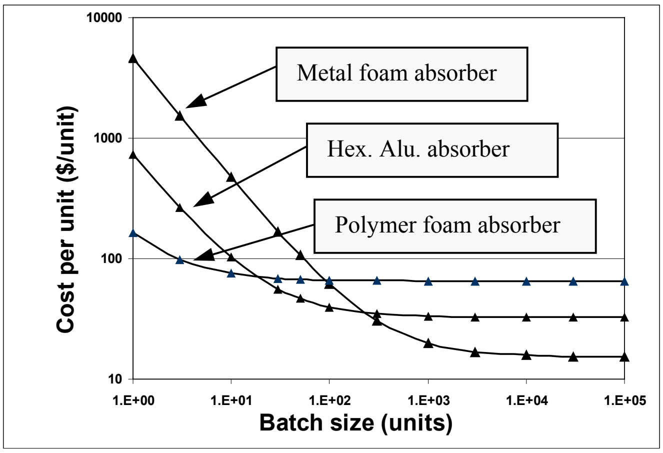
Compare unit cost of the component when made of new material with that made of existing materials.

- Identify unit cost of making the component using existing materials at various production volumes.
- Compare this with unit cost when made of the new material.
- Identify ranges of production volume, component size and complexity for which the new material is most economically attractive.

Running case study: the '*Innovative Metal Foam Company*'

The output of a cost model

The A-pillar is the rigid member on either side of the windscreen of a cart. US and EU legislation requires that the A-pillar be faced with and crushable energy-absorbing unit to give head protection in an accident. A hypothetical cost analysis for three A-pillar energy absorbing units is shown, right: a unit made of metal foam, one made of polymer foam and one in the form of a hollow hexagonal extrusion. The unit cost is high for small production volumes because tooling and die costs must be written off against the number of units made.



Schematic cost-estimates for 3 alternative energy absorbers

As the production volume increases, the unit cost falls until it reaches a plateau determined mainly by the cost of material and labour. More efficient processing, reducing the production time-per-unit, together with automation, can lower this cost plateau. The analysis requires data for the cost of equipment, tooling and labor. The *Appendix for Stage 3* gives details.

Stage 4
What will the consumer pay?

When new materials are first introduced, they are frequently more expensive than those that well established. But the customer will pay this extra cost if the gain in performance offered by the new material is perceived to be worth it. The key question, then, is: *how much does the consumer value performance*? **Utility analysis** seeks to answer this question. Four techniques are useful here: a life-cost analysis assessing the cost of ownership as well as that of initial acquisition; an analysis of historical pricing data for products that perform the same function, but at differing levels of performance; market research to establish consumer reaction to a new product; and structured interviews with the key decision-makers (both designers and managers) in control of new product development, drawing on their experience.

This stage – which can be difficult – can be omitted if simpler methods are sufficient (see Stage 5). For a detailed investment analysis, however, this stage may be unavoidable.

Inputs:
- Information for initial cost and operating cost of the application in its current form.
- Historical price data for the application.

Key steps:
- Construct a life-cost analysis, ***or***
- Analyse historical pricing data for a product family, ***or***
- Undertake a market survey of end users, ***or***
- Conduct structured interviews with key decision-makers.

Outputs:
- The "**exchange constant**" or "**utility value**" for the application: a measure of how much is the consumer willing to pay for unit change in performance

Tools/techniques
- Approximate life-cost estimation methods.
- Extrapolations from historical pricing data for products that perform the same function but at different levels of cost and performance.
- Market survey techniques.
- Multi-attribute **utility** analysis.

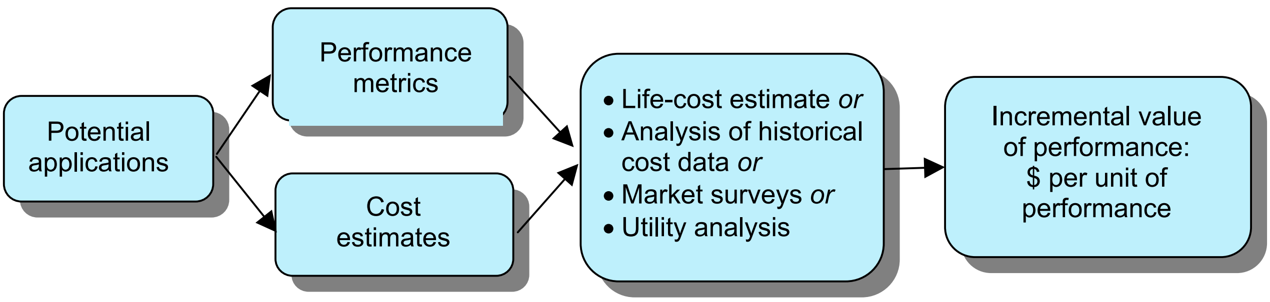
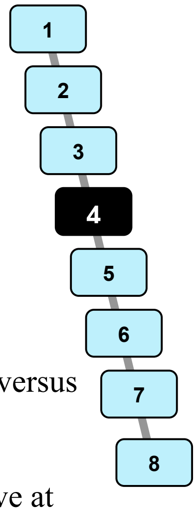


Figure 4.1. The steps in implementing Stage 4 of the method. This stage is only needed when a detailed investment analysis is undertaken.

Guidelines for key steps ***(Appendix for Stage 4 gives details)***



Construct a life-cost analysis

- Estimate the cost advantage of unit change in performance over the life of the product – the saving in fuel-cost of a transport system per kg of weight reduction, for example. This is the exchange constant.

Analyse historical pricing data for a product family

- Plot price against **performance metric** for the product family range (the cost versus weight for bicycle frames, for example).
- Draw curve enclosing the data.
- Estimate the **exchange constant** by the slope of line that is tangent to this curve at relevant price and performance co-ordinates (the *Appendix for Stage 4* gives an example).

Undertake a market survey of end users

- Gather consumer **utility** data from a wide range of end users through methods such as internet questionnaires, phone surveys, direct mail questionnaires, workshops or market trials, seeking to establish how much more the consumer would be prepared to pay for unit increase in the performance metric, or how much performance he would be prepared to sacrifice for unit change in price.
- Calculate the **exchange constants** from the data.

Conduct structured interviews with key decision makers

- For mass produced products, determine key product design decision-makers (platform manager for automotive models, for instance).
- Develop a questionnaire that elicits quantitative preferences for products with specific performance and cost combinations.
- Interview key decision maker(s).
- Calculate the **exchange constants** from the interview data.

Running case study: the '*Innovative Metal Foam Company'*

Exchange constants for weight saving in transport systems

Metal foams may enable weight saving in transport systems, both by allowing lighter crash-protection systems and by their use as cores for light, stiff sandwich panels. But if their using also increases the cost of the vehicle, will the consumer wish to pay the extra? The Table, right, shows the approximate value of weight saving in a number of transport systems. The first 5 classes are based on the calculated fuel saving or payload increase that reduced structural weight allows. The last – the bicycle – is based on historical pricing data.

Transport System	Utility (US $ / kg)
Family Car	0.5 - 1.5
Truck	6 - 20
Civil Aircraft	100 - 500
Military Aircraft	500 - 2,000
Space Vehicle	2,000 - 8,000
Bicycle (depends on type)	20 - 2,000

Stage 5
Is there profit in it?

If using a new material delivers products with better performance at lower cost than existing solutions, the innovation is certainly **viable** and has market potential. But it is commonly the case that a new material offers enhanced performance but costs more, or is cheaper but has lower performance, than existing solutions. The **market potential diagram** is a way of exploring the type of market into which the new material will best fit. It takes the form of a 2 x 2 matrix, shown in Figure 5.1. This is a simple form of **trade-off plot**. **Trade-off methods** can be refined, making use of the **exchange constant** from Stage 4, to give more precise assessment of market potential. The *Appendix for Stage 5* gives details.

Inputs:
- Potential applications, with **performance metric**s from Stage 2.
- **Cost estimates** from Stage 3.
- **Exchange constants** from Stage 4, but only if needed for a full value analysis.

Key steps:
- Construct a **market potential diagram** for each potential application (Figure 5.1).
- Proceed, if necessary, to a full **trade-off** analysis (see *Appendix for Stage 5*).

Outputs:
- **Market potential** assessment of new material in alternative applications.
- Prioritised list of potential applications.

Tools/techniques
- **Market potential diagrams**.
- **Trade-off methods** (see *Appendix for Stage 5*).

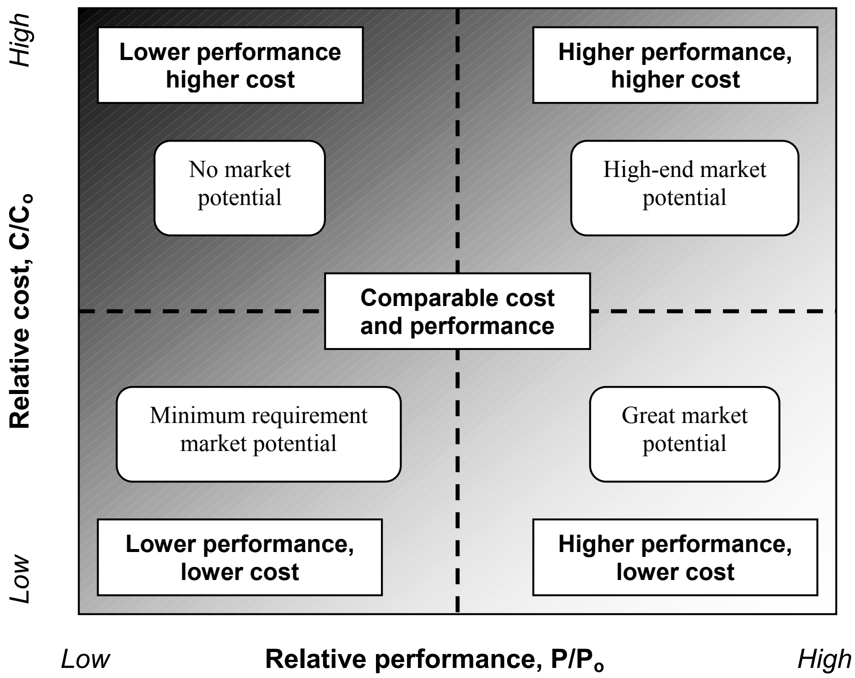
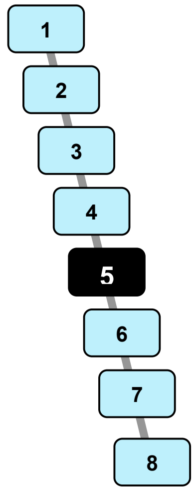


Figure 5-1: The **market potential diagram**. The most attractive markets lie in the light-shaded area. Here P and C are the metrics of performance and cost for the innovation, and P_o and C_o are those of the currently used material.

Guidelines for key steps *(Appendix for Stage 5 gives details)*



Construct a market potential diagram for each potential application

- Plot relative **performance metric** P/P_o against relative cost C/C_o for both the new material and existing one for each potential application, where P and C are the metrics of performance and cost for the new material, and P_o and C_o are those of the currently used material (Figure 5-1).
- Establish in which quadrant the new material lies.
- Compare the potential of the new material with that of competing materials using the diagram.

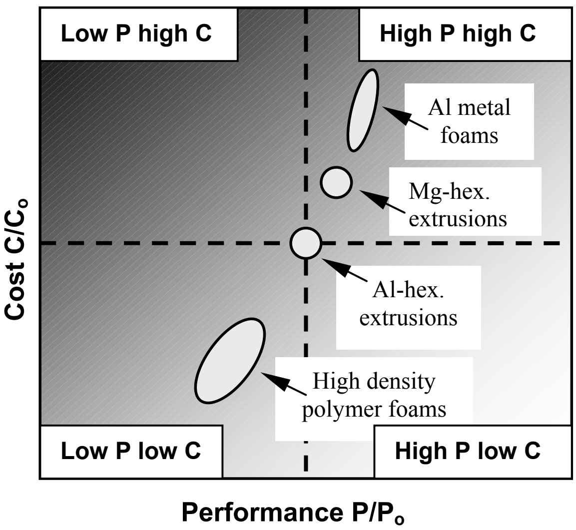
Proceed, if necessary, to a full trade-off analysis (see Appendix for Stage 5).

- Construct a **trade-off plot** of **performance metric** against cost for all alternative solutions.
- Construct a **value function** combining the **performance metric** with the cost and the **exchange constant,** detailed in Stage 4..
- Plot **value** contours onto the plot using the **exchange constant** to establish the slope.
- Identify the solution that lies nearest to the point at which the value line is tangent to the trade off surface – see *Appendix for Stage 5* for an example.

Running case study: the '*Innovative Metal Foam Company'*

The market potential of metal foams

Current US and European legislation dictates the minimum energy that the A-pillar head-protective padding must absorb without serious injury. An initial survey suggests that metal foams can achieve this, and be lighter than the hollow hexagonal extrusions are (the current industry standard) or high-density polymer foams (an alternative), but at an increase in cost. Here the constraint is the required absorbed energy; the objective is that of minimising mass. The **market potential diagram**, right, shows performance measured by "lightness" (1/mass) and cost for these alternatives divided by that for the currently used solution – the hexagonal aluminium extrusion. It suggests that the primary market for metal foams is the high-end, high performance or luxury car market.



But will metal foams succeed even there? That depends on the value the consumer attaches to low weight– and that requires a market survey and the use of **trade-off methods**. See the *Appendix for Stage 5* for details.

Stage 6
How big is the market?

Market assessment seeks to establish how the market will value a product with a given performance (the output of Stage 5), the size of that market and the probable take-up or "adoption" time. The results guide the choice of markets on which to concentrate, suggest how fast production must grow to keep pace with demand, and allow assessment of anticipated timing and size of potential revenues.

Inputs:
- Prioritised list of potential applications (from Stage 5).
- Historical **adoption curves** for material innovations.

Key steps:
- Estimate the market sizes for potential applications.
- Position the applications on the **innovation categorisation map** – see Figure 6.1.
- Estimate time-scale of substitution using historical **adoption curves**.
- Construct an initial implementation plan.

Outputs:
- Estimates of market sizes.
- Estimates of market time-scale.
- Initial implementation plan.

Tools/techniques (see *Appendix for Stage 6*)
- Public information sources for market data.
- The **innovation categorisation map** (Figure 6-1).
- Historical **adoption curves.**

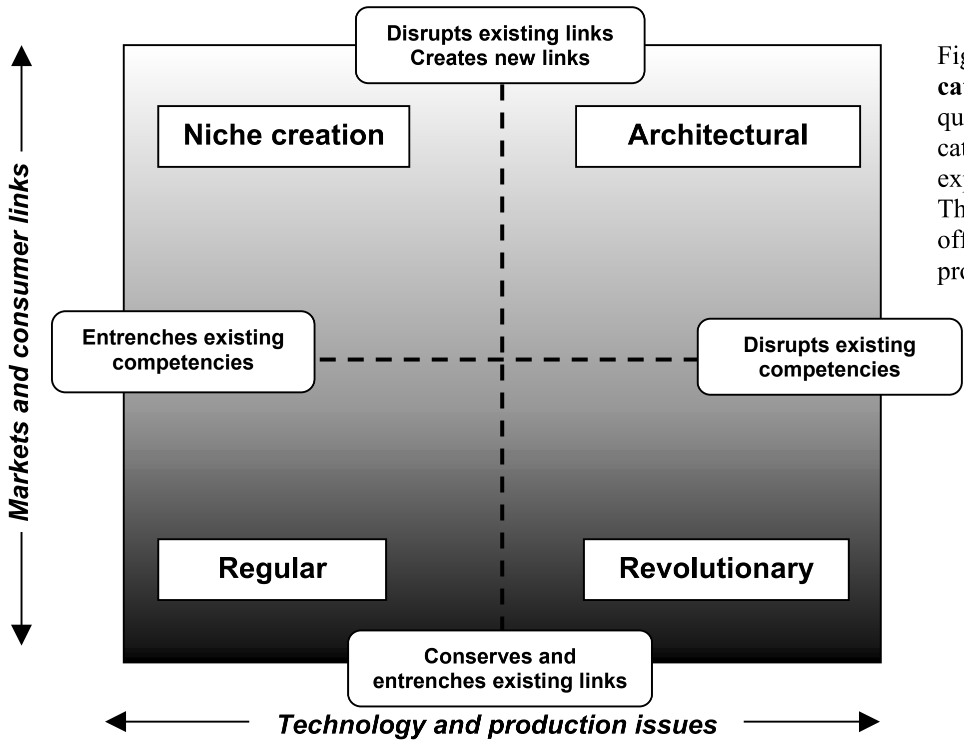


Figure 6-1: The **innovation categorisation map.** Each quadrant defines a different category of innovation, explained on the facing page. The lightly shaded sectors offer the greatest potential for profit.

Guidelines for key steps ***(Appendix for Stage 6 gives details)***

Estimate the market sizes for potential applications

- Information about market size can be found in news releases in technical journals, the Financial Times and Wall Street Journal, press releases from research organisations such as SRI, Web-based news services such as Lexis-Nexis and through Web-searches using Google.com or Northernlight.com.
- Triangulate from available sources to bracket the approximate market size.

Position the applications on the innovation categorisation map – see Figure 6.1

- Does the innovation require technology and production methods that build on or disrupt existing the capabilities of the company? Will it, for instance, be necessary to hire new R&D personnel or invest in unfamiliar production methods?
- Does the innovation build on or disrupt the existing customer base? Can existing customer relationships be exploited in commercialising the innovation?
- Position the innovation on the **innovation categorisation map** (Figure 6-1) using the answers to these questions.
  "Regular" means the innovation builds on existing technology and customer base.
  "Revolutionary" means the innovation builds on existing customer base but requires new technology.
  "Niche creation" means the innovation builds on existing technology but requires that a new customer base be created.
  "Architectural" means the innovation requires both new technology and a new customer base.

Estimate time-scale of substitution using historic adoption curves

- Identify a historical **adoption curve** with similar **market potential and innovation category** – examples are given in the *Appendix for Stage 6*.
- Estimate rate of take up based on this historical **adoption curves**.

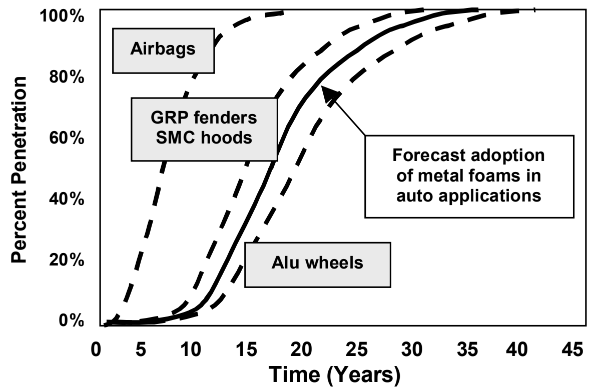
Construct an initial implementation plan

- Preliminary ordering of target markets, prioritising those with low risk.

Running case study: the '*Innovative Metal Foam Company'*

Adoption of metal foams

Adoption curves for four innovations in the automobile industry are shown as broken lines. The adoption time for airbags was short, driven by the public perception of safety. That for the use of composites in cars was slower, driven by weight saving – a less obvious benefit to the consumer. That for aluminium wheels is slower still, driven more by aesthetics and fashion than by practicality.



It is anticipated that the adoption of metal foams in cars, saving weight might parallel that of composites.

Stage 7
Who will get the profit?

Value capture refers to a company's ability to retain the value created by an innovation. The degree to which the innovator controls the intellectual property through patents, proprietary knowledge or special means of manufacturing, effectively protecting themselves from competition or imitation, is called the **appropriability regime**. It is ranked as high, medium, low or none. If the target market is attractive (Stage 6), the **appropriability regime** is high, and the commercialising company has an entrepreneurial **organisational structure**, then the likelihood of **value capture** is high.

Inputs:
- Target markets (the output of Stage 6).
- **Innovation category** (the output of Stage 6).
- Company-specific information about its **organisational structure**.

Key steps:
- Assess the **industry-attractiveness** of the innovation.
- Determine the **appropriability regime.**
- Review the **organisational structure** and competitiveness.

Outputs:
- Assessment of potential for **value capture**.

Tools/techniques
- The **five-force analysis** (sometimes called Porter's Five Forces).
- The concept of **appropriability.**
- Check-list for **organisational structure**.

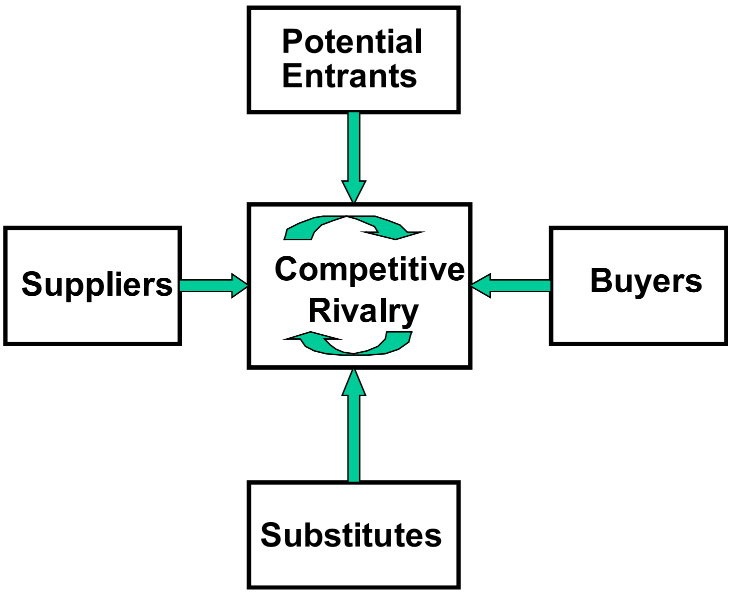
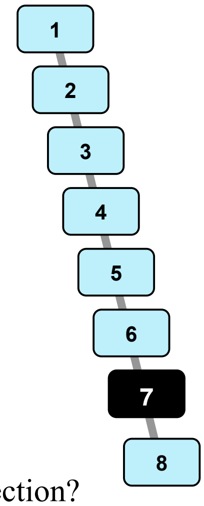


Figure 7.1. Schematic of the **five forces analysis** to assess **industry-attractiveness**

Guidelines for key steps *(Appendix for Stage 7 gives details)*



Assess the industry-attractiveness of the innovation

- Assess the strength of **supplier power** and **buyer power** relative to the company exploiting the new material.
- Assess **barriers to entry** that competitors must overcome if they are to imitate the innovation.
- Assess the threats posed by future substitutes.
- Estimate current competitive rivalry in the targeted industry.

Determine the appropriability regime

- Does the innovator have strong **intellectual property** and trade-secret protection?
- Does the innovator have access to **specialised assets** or **co-specialised assets?**
- Does an **experience curve** exist in the design and production process?
- What is the innovation category (see the **innovation categorisation map** of Figure 6.1).
- Is the new product development cycle time slow or fast?
- Is it a protectable industry?

Review the organisational structure and competitiveness

- Review the competency of the exploiting company in performing strategic tasks.
- Assess the level of entrepreneurial experience.
- Check for the presence of a visionary deal-maker.
- Assess organisational flexibility.
- Assess knowledge-management skills.
- Assess evidence for operational efficiency.

Running case study: the '*Innovative Metal Foam Company'*

Assessment of appropriability regime for metal foams

← Tightening Appropriability Regime

IP & trade secret protection	High	Medium	**Low**	None
Access to specialised assets	High	**Medium**	Low	None
Experience curve	High	**Medium**	Low	None
Innovation category	Architectural	Niche Product	**Revolutionary**	Regular
New product cycle time	**Slow**	Medium	Fast	Continuous
Protectablity of industry?	**High**	Medium	Low	None

This table shows an analysis of the **appropriability regime** of the Innovative Metal Foam Co's plan for energy absorption applications of their material. The shaded boxes identify the company's position in each of the 6 categories determining the **appropriability regime**. The overall level of **appropriability** is only moderate, largely because the of a low level of IP protection. Investment is justified only if the Company has an **organisational structure** that has demonstrated entrepreneurial ability.

Stage 8
Is it a good investment?

The eight stages described in this workbook constitute an investment methodology for materials. The methodology can help lower the market risk associated with investing in a new material by weeding out applications with little promise and by identifying those with the greatest potential for success. It can help to increase the gain from investing in a new material by decreasing the time to market. And it can provide guidance in planning research and development within a company. Here we assemble the information that it generates to formulate **three key questions**, the answers to which determine future action.

Inputs:
- **Viability** assessment (output of stage 5).
- **Market assessment** (output of stage 6).
- **Value-capture** assessment (output of stage 7).

Key steps:
- Address the three "go / no go" questions listed on the facing page. Investment is justified if the answer to all three is “go”.
- Determine market approach.
- Determine necessary collaborations, strategic alliances, or partnerships.

Outputs:
- Investment decision.
- Market appraisal.
- Desired collaborations.

Tools/techniques
- Strategic discussions with senior management.
- The methodology developed in this work book and summarised in Figure 8.1.

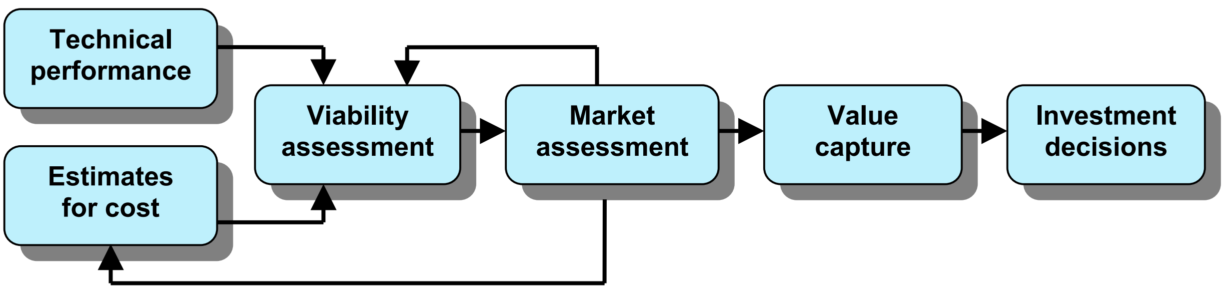
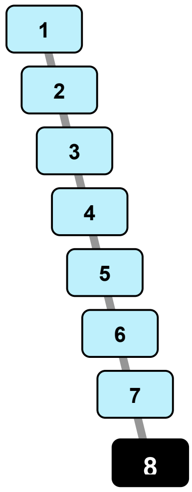


Figure 8.1 Schematic of interactions between inputs and output in the Investment Methodology for Materials (IMM)

Guidelines for key steps ***(Appendix for Stage 8 gives details)***



Address the three "go / no go" questions.

- Is the material innovation technically and economically **viable**?
- Is the market size sufficiently large and the payback-time sufficiently short to justify investment?
- Is there a high probability of capturing the value created by the innovation?

Determine market approach

- Prioritise markets to minimise risk and liability.
- Stage market approach to build credibility for entry into further markets.
- Choose entry market to provide initial cash flow and establish a market presence.

Determine necessary collaborations, strategic alliances, or partnerships

- Assess company weaknesses that could be overcome by collaborations.
- Explore whether the innovating company could benefit from alliances with suppliers or distributors.
- Consider whether complementary expertise or strategic goals justify a partnership arrangement.

Running case study: the '*Innovative Metal Foam Company'*

The 3 key "go / no-go" questions for aluminium foams in energy-absorber applications

- **Viability?** The application of metal foams for energy absorption applications in the automotive industry is technically and economically **viable**, particularly for A-pillar, side impact and front-end protection.
- **Market size and timing?** There is a potential market size of up to $100 million annually, with 50% take-up in 12-18 years.
- **Value Capture?** The **appropriability** position of the Innovative Metal Foam Co. is not strong. The technology is not well protected and is relatively easy to reproduce, making the application vulnerable to new entrants and to substitutes.

Conclusion: investment is justified only if the Company is in a position to negotiate strategic alliances, giving it preferred supplier status, develop **specialised assets**, and ensure total IP protection for all future developments.

Succeeding with New Materials

Appendices

Appendix for Stage 1
Sources of materials data

The task

The first step in assessing the potential of a new material is to compare its properties with those of existing materials. This allow us to:

(a) identify other materials that have similar property profiles – the applications they fill become possible targets for the new one;

(b) identify particular properties of the innovation that are better than those of existing materials – it might be an engineering property, an ability to be processed, an environmental quality, or just cost.

Who should do it?

Any qualified mechanical, materials or design engineer within the company.

How long will it take?

A few hours, given the right resources.

The inputs

Sources of materials data, listed below.

The method

Reference sources and handbooks (listed under A, below) give data for material properties, but the information they contain is not structured in a way that enables the kind of broad comparisons we seek here. The best way to get an overview of the world of materials is through the use of **material property charts**. These are diagrams in which two properties are plotted for representative materials drawn from the different classes: metals, polymers, elastomers, ceramics, glasses, composites and foams. Figure A1 is an example: it shows the range of two properties – Young's modulus and density – for 50 materials. Materials of a given class grouped together – the bold outlines enclose the classes. Metal foams are shown as a cross-hatched bubble. It is immediately obvious that they have values of these two properties that differ greatly from those of solid metals, and lie close to those of woods and dense polymer foams. Hard copy charts like Figure A1 on which other properties appear can be copied from Ashby (1999) or downloaded from Granta Design.com without restriction or copyright.

Software systems are available that create **material property charts** onto which the properties of new materials can be superimposed. They draw on large databases of material properties and allow comparison to be made between a far larger number of materials – 1000s rather than 50. Further, they identify typical applications of each material. Figure A2 is an example of the output of one such system: the CES4 (2002) materials and process selection platform. It shows the same two properties as Figure A1, here with the some 70 materials shown for clarity; it has the capacity to allow a similar comparisons to be made with some 30 properties for over 2500 materials quickly and efficiently.

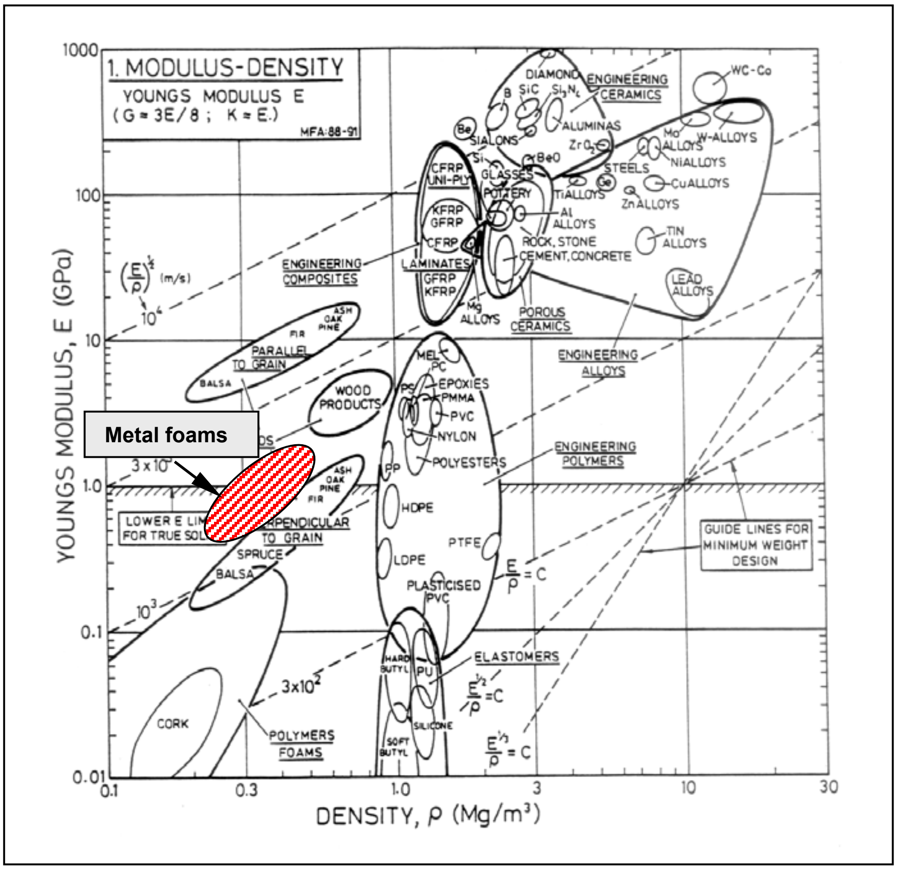


Figure A1. A hand-drawn chart allowing the properties of a new material – here a class of metal foams – with existing materials. A set of these charts can be found in the book by Ashby (1999), and are free of copyright.

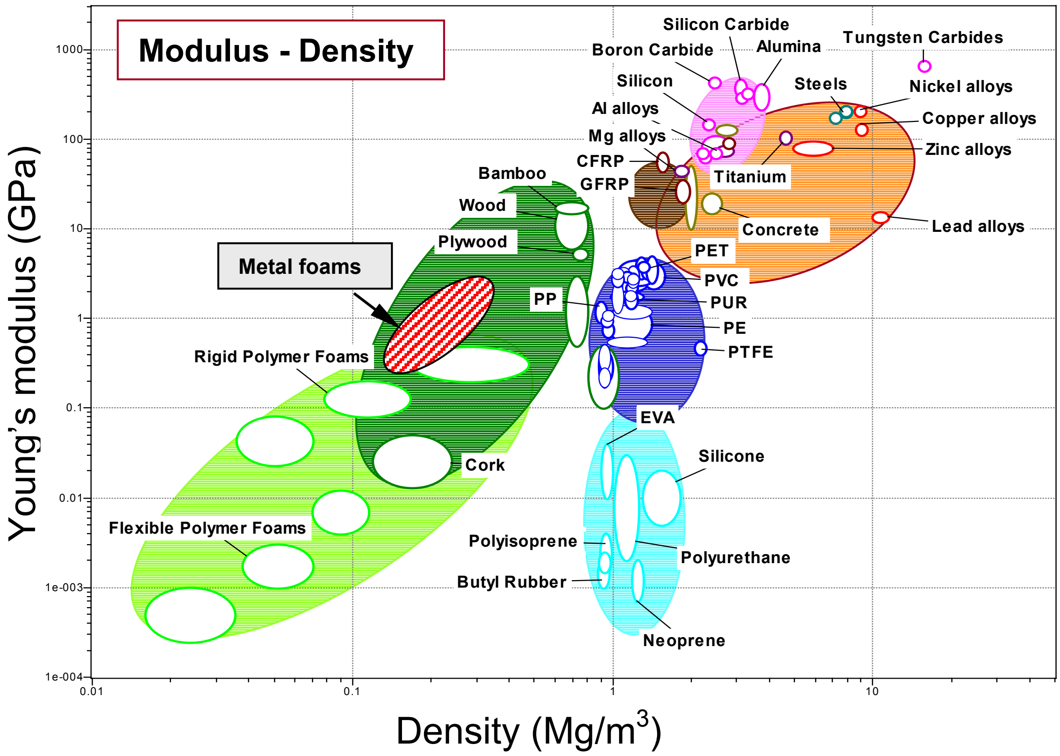


Figure A2. The same chart, created with the CES4 software, showing where metal foams lie. Similar comparisons can be made with many other properties.

Sources of property data for existing materials

A. Reference sources and handbooks

- "ASM Engineered Materials Reference Book" 2nd Edition (2001), editor: Bauccio, M.L., ASM International, Metals Park, Ohio 44073, U.S.A. *Available on-line from ASM International.*
- "ASM Metals Handbook" (1990 - 2001) 10th Edition. ASM International, Metals Park, Ohio, 44073 U.S.A. *Basic 20 volume reference work, continuously upgraded and expanded, now available on-line from ASM International.*
- "Handbook of Industrial Materials" (1992) 2nd Edition, Elsevier, Oxford, UK. *A compilation of data remarkable for its breadth: metals, ceramics, polymers, composites, fibres, sandwich structures, leather*
- "Materials Handbook" (1986) 12th Edition, editors: Brady, G.S. and Clauser, H.R., McGraw Hill, New York, NY, USA. *A broad survey, covering metals, ceramics, polymers, composites, fibres, sandwich structures and more.*
- "Materials Selector" (1997), Materials Engineering, Special Issue. Penton Publishing, Cleveland, Ohio, U.S.A. *Tabular data for a broad range of metals, ceramics, polymers and composites, updated annually.*
- Smithells, C.J. (1992), "Metals Reference Book", 7th Edition, editors: E.A. Brandes and G.B.Brook, Butterworth Heinemann, London, U.K. *A comprehensive compilation of data for metals and alloys. Basic reference work.*
- "The Chapman and Hall Materials Selector" (1996), editors: N.A. Waterman and M.F. Ashby. Chapman and Hall, London, UK. *A 3-volume compilation of data for all materials, with selection and design guide. Basic reference work.*

B. Material selection charts and software to enable comparisons

- Ashby, M.F. (1999), "Materials Selection in Mechanical Design", Butterworth Heinemann, Oxford, UK. *A text developing methods for materials selection. It contains 18* ***materials selection charts*** *that can be copied without restriction.*
- CES 4 (2002), The CES Materials Selection Software, Granta Design, 62 Clifton Road, Cambridge, UK (www.grantadesign.com) *Software that allows rapid comparison of materials based on their* ***property profiles****.*

C. The Worldwide Web.

There are now some thousands of web sites that offer information about materials and processes, but finding the information you want can be slow, uncertain and frustrating. Among the most useful are:

- www.grantadesign.com *The entry point for Granta Design's suite of databases and software tools for materials selection.*
- www.matweb.com *A site listing suppliers data for some thousands of materials; data often incomplete, and in differing formats.*

A4

Appendix for Stage 2
Performance metrics and modeling

The task

To identify and if possible quantify the **constraints** and **performance metrics** that a material must meet if it is to succeed in a given application. This allows us to

(a) attach a value to the gain in performance (if any) offered by the new material in each target application;

(b) establish what other materials would compete with it in those applications.

Who should do it?

A mechanical, materials or design engineer within the company.

How long will it take?

A few hours, given the right resources.

The inputs

Modelling methods.

The method[i]

Any engineering component has one or more **functions**: to support a load, to contain a pressure, to transmit heat, and so forth. This must be achieved subject to **constraints**: that certain dimensions are fixed, that the component must carry the given load or pressure without failure, that it can function in a certain range of temperature, and in a given environment, and many more. In designing the component, the designer has an **objective**: to make it as cheap as possible, perhaps, or as light, or as safe, or some combination of these. **Function**, **constraints** and **objectives** define the boundary conditions for selecting a material.

Table A1. Function, Constraints and Objectives

Function	*"What does component do?"*
Constraints	*"What non-negotiable conditions must be met?"*
Objective	*"What is to be maximised or minimised?"*

The performance of a material in an application is measured by one or more **performance metrics**. If the **objective** of the design is that of minimising weight, the metric is simply the mass, m. If it is that of keeping the volume to a minimum, the metric is the volume V. If it is that of maximising thermal insulation, the metric is the heat lost per unit area of insulation.
Any engineering component has one or more **functions**: to support

An example: materials for crash protection

A crash-protection unit on the interior of a car must crush at a stress that is sufficiently low that a body thrown against it is not severely damaged, and it must absorb a prescribed energy. These are **constraints**, ruling out all materials with crushing strength bigger than the critical, damaging, value and defining the amount of material that must be used. The **objective** is to minimise the mass of the unit while meeting the constraints. This defines a **performance metric**: energy absorbed per unit mass. The best choice is the material with the largest value of this metric that crushes below with the damaging stress. The new material is technically acceptable if it meets the **constraints**, but it is the best choice only if it absorbs more energy per unit mass that other existing materials that also crush below the critical damaging stress.

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[i] Details of the method, with many worked examples, can be found in Ashby (1999) and Cebon and Ashby (1996).

Material Indices

Material indices are groupings of material properties that measure the performance of a material in a given application. Thus the best materials for light, stiff structures are those with the largest values of E/ρ or $\sqrt{E}/\rho$ where is E is Young's modulus and ρ is the density. The best materials for light, strong structures, similarly, are those with the largest values of σ_y/ρ or $\sigma_y^{2/3}/\rho$ where σ_y is the yield strength of the material. By making property charts with these as axes, the new material can be compared with existing materials by these criteria. Other groups of properties measure the relative performance of materials in a wide range of mechanical, thermal and electrical applications – they provide another route to the identification of promising applications for new materials. Table A2 lists some of the indices. They are fully documented in Ashby (1999).

Table A2. Material-indices (performance metrics for a given **function, constraint** and **objective.)**

Function, Constraints and Objectives	**Index – maximise**
Tie, minimum weight, stiffness prescribed (*cable support of a light-weight tensile structure*)	E/ρ
Beam, minimum weight, stiffness prescribed (*aircraft wing spar, golf club shaft*)	$E^{1/2}/\rho$
Beam, minimum weight, strength prescribed (*suspension arm of automobile*)	$\sigma_y^{2/3}/\rho$
Panel, minimum weight, stiffness prescribed (*automobile door panel*)	$E^{1/3}/\rho$
Panel, minimum weight, strength prescribed (*table top*)	$\sigma_y^{1/2}/\rho$
Column, minimum weight, buckling load prescribed (*push-rod of aircraft hydraulic system*)	$\rho/E^{1/2}$
Spring, minimum weight for given energy storage (*return springs in space applications*)	$\sigma_y^2/E\rho$
Precision device, minimum distortion, temperature gradients prescribed (*gyroscopes; hard-disk drives; precision measurement systems*)	λ/α
Heat sinks, maximum thermal flux, thermal expansion prescribed (*Heat sinks for electronic systems*)	λ/α
Electromagnet, maximum field, temp. rise and strength prescribed (*ultra high field magnets; very high speed electric motors*)	$\kappa C_p\rho$

(ρ = density; E = Young's modulus; σ_y = elastic limit; λ = thermal conductivity; α = thermal expansion coefficient; κ = electrical conductivity; C_p = specific heat)

Appendix for Stage 3
Cost modeling

The task

Cost modelling can be tackled at two levels

(a) A quick survey using a simple model to estimate for unit cost at a range of projected production volumes, using existing equipment and running costs, (**simple cost modelling**) described below.

(b) A detailed analysis using a **technical cost model**[ii] to refined estimates for a range of production volumes, component dimensions, and scenarios of potential improvements in production methods. For example, the introduction of new technology might reduce the cure time of a polymer composite; the **technical cost model** predicts the impact of cure time reduction on unit production cost of a given component.

Who should do it?

A materials, mechanical, or manufacturing engineer.

How long will it take?

(a) A quick survey: 1 to 5 days.

(b) A detailed analysis: one month or more.

The inputs

(a) A quick survey: estimates for the costs of the resources listed in Table A3 using historical data for equipment cost, production rate, etc. for a range of production volumes.

(c) A detailed analysis: more accurate estimates of the six resources (through procurement catalogues, and information gathering by telephone, web sites, and on-line information databases) and an analysis of the **technical constraints** of each production step, generally requiring a site visit to a pilot scale production facility, input from R&D development team, and exploration of alternative or emerging technologies to assess the changes these could make to production costs.

Table A3. Symbols, definitions and units for the simple co**st model**

Resource		**Symbol**	**Unit**
Materials	inc. consumables	C_m	\$/kg
Capital	cost of tooling cost of equipment	C_t C_c	\$ \$
Time	overhead rate, including labour, administration, rent …	$\dot{C}_{oh}$	\$/hr
Energy	Power cost of energy	$\dot{P}$ C_e	kW \$/kW.hr
Information	R & D or royalty payments	C_i	\$/year

[ii] Field and de Neufville, (1988); deNeufville, (1990) Clark, Roth and Field, (1997).

The method

The manufacture of a component consumes resources, each of which has an associated cost. The final cost is the sum of those of the resources it consumes, detailed in Table A3. Thus the production of a component of mass m entails the cost C_m (\$/kg) of the materials and feed-stocks from which it is made. It involves the cost of dedicated tooling, C_t (\$), and that of the capital equipment, C_c (\$), in which the tooling will be used. It requires time, chargeable at an overhead rate $\dot{C}_{oh}$ (thus with units of \$/hr), in which we include the cost of labour, administration and general plant costs. It requires energy, which is sometimes charged against a process-step (particularly if it is one that is very energy intensive) but more usually is treated as part of the overhead and lumped into $\dot{C}_{oh}$ (as we shall do here). Finally there is the cost of information, meaning that of research and development, royalty or licence fees; this, too, we view as a cost per unit time and lump it into the overhead.

Imagine now the manufacture of a component (the "unit of output") weighing m kg, made of a material costing C_m \$/kg. The first contribution to the unit cost is that of the material mC_m magnified by the factor $1/(1-f)$ where f is the scrap fraction – the fraction of the starting material that ends up as sprues, risers, turnings, rejects or waste:

$$C_1 = \frac{m\,C_m}{(1-f)} \tag{A1}$$

The cost C_t of a set of tooling – dies, moulds, fixtures and jigs – is what is called a *dedicated cost*: one that must be wholly assigned to the production run of this single component. It is written off against the numerical size n of the production run. Tooling wears out. If the run is a long one, replacement will be necessary. Thus tooling cost per unit takes the form

$$C_2 = \frac{C_t}{n}\left\{\mathrm{Int}\left(\frac{n}{n_t} + 0.51\right)\right\} \tag{A2}$$

where n_t is the number of units that a set of tooling can make before it has to be replaced, and 'Int' is the integer function. The term in curly brackets simply increments the tooling cost by that of one tool-set every time n exceeds n_t.

The capital cost of equipment, C_c, by contrast, is rarely dedicated. A given piece of equipment – a powder press, for example – can be used to make many different components by installing different die-sets or tooling. It is usual to convert the capital cost of *non-dedicated* equipment, and the cost of borrowing the capital itself, into an overhead by dividing it by a capital write-off time, t_{wo}, (5 years, say) over which it is to be recovered. The quantity C_c/t_{wo} is then a cost per hour – provided the equipment is used continuously. That is rarely the case, so the term is modified by dividing it by a load factor, L – the fraction of time for which the equipment is productive. The cost per unit is then this hourly cost divided by the rate $\dot{n}$ at which units are produced :

$$C_3 = \frac{1}{\dot{n}}\left(\frac{C_c}{L\,t_{wo}}\right) \tag{A3}$$

Finally there is the overhead rate $\dot{C}_{oh}$. It becomes a cost per unit when divided by the production rate $\dot{n}$ units per hour:

$$C_4 = \frac{\dot{C}_{oh}}{\dot{n}} \tag{A4}$$

The total shaping cost per part, C_s, is the sum of these four terms, taking the form:

$$C_s = \frac{m\,C_m}{(1-f)} + \frac{C_t}{n}\left\{\mathrm{Int}\left(\frac{n}{n_t} + 0.51\right)\right\} + \frac{1}{\dot{n}}\left(\frac{C_c}{L\,t_{wo}} + \dot{C}_{oh}\right) \tag{A5}$$

The equation says: the cost has three essential contributions – a material cost per unit of production which is independent of batch size and rate, a dedicated cost per unit of production which varies as the reciprocal of the production volume $(1/n)$, and a gross overhead per unit of production which varies as the reciprocal of the production rate $(1/\dot{n})$.

The cost C plotted against the production volume n has the form shown in Figure A3. When the production volume n is small, the cost per unit of production is totally dominated by the dedicated tooling costs C_t. But as the production volume grows, the contribution of the second term in the cost equation diminishes; and if the process is fast, the cost falls until, often, it flattens out at a level determined by the first and third terms in Equation (A5) – those describing materials and overheads.

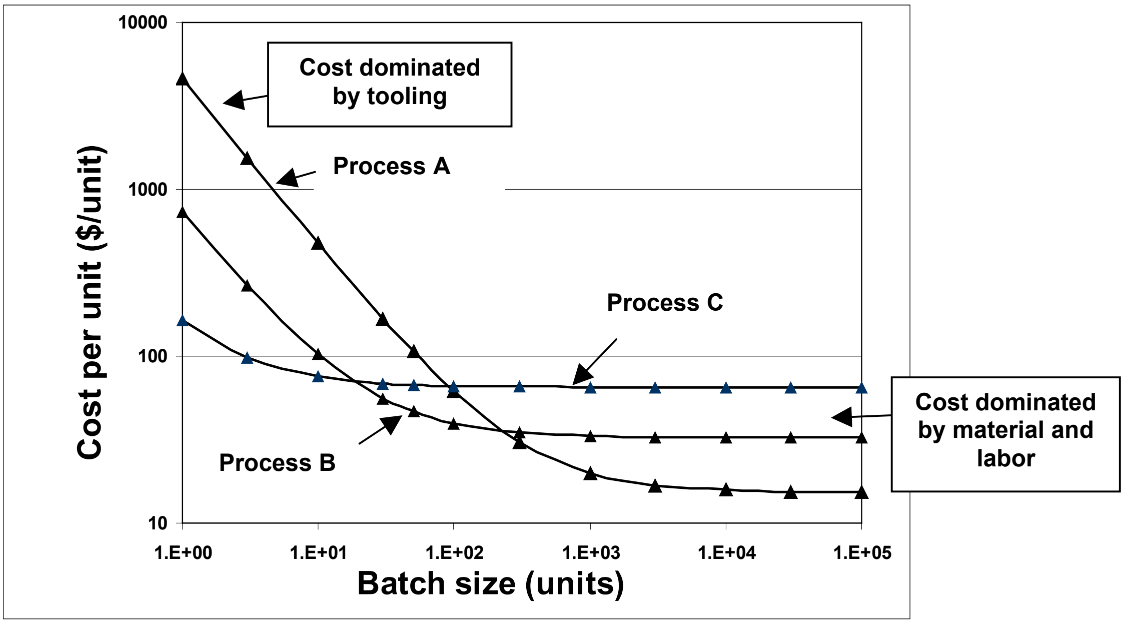


Figure A3. The variation of unit cost with production volume.

Technical cost modelling. Equation (A5) is the first step in modelling cost. Greater predictive power is possible by introducing elements of **technical cost modelling**, which exploits the understanding of the way in which the control-variables of the process influence production-rate and product properties and the way in which the capital costs of equipment and tooling scale with output volume. These and other dependencies can be captured in theoretical and empirical formulae or look-up tables that are built into the **technical 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 fuller description is give in Field, and de Neufville, (1988); deNeufville, (1990) and Clark, Roth and Field, (1997).

Appendix for Stage 4
Utility analysis and value functions

The task

To assess the degree to which performance adds value in a given application. This allows us to decide if the cost-performance combination made possible by a new material will be attractive or unattractive to the consumer. *This Stage is not required in a first analysis of an innovation.*

Who should do it?

Utility analysis requires expertise in market research methods.

How long will it take?

A full **utility analysis** could take one man-month.

The inputs

Information on initial price and operating costs of the target applications; historical pricing data for the target applications.

The method

When people says that a product is "good value for money" they mean that, in their view, its value is greater than its price; if, instead, they says that it is "not worth the money" they mean that the price is greater than the value. **Utility analysis**, in the broadest sense, is the technique of quantifying the value of performance. The information plays an important role in guiding judgements about the **viability** of a technical innovation.

Our interest here is in assessing whether the greater performance offered by a new material justifies the added cost that generally comes with it. The cost may not always increase, of course, but elaborate techniques are not needed to reach decisions about enhanced performance at lower cost. Thus the critical quantity is the incremental increase ΔC of cost C associated with a change ΔP in performance P. We call this the **exchange constant**, and give it the symbol α:

$$\alpha = \frac{\Delta C}{\Delta P} \qquad \text{(A6)}$$

The **exchange constant** is a measure of the value of performance.

In engineering applications **exchange constants** can sometimes be derived approximately from technical models for full-life cost. Thus the value of weight-saving in transport systems is derived from the cost of the fuel saved or that of the increased payload which this allows over the life-time of the vehicle. For the family car it is small, for trucks, larger, and for aerospace it is much larger still (Table A4). The value of heat transfer can be derived from the cost of the energy conserved over the lifetime of the product by unit change in this metric.

Table A4. Exchange constants for weight-saving in transport systems.

Transport System	Utility (US $ / kg)
Family Car	0.5 - 1.5
Truck	6 - 20
Civil Aircraft	100 - 500
Military Aircraft	500 - 2,000
Space Vehicle	2,000 - 8,000
Bicycle (depends on type)	20 - 2,000

Approximate **exchange constants** can sometimes be derived from historical pricing-data. Thus the value of weight-saving in a bicycle frame can be approximated by plotting the price R of existing bike frames against their mass m, using the slope (dR/dm) as a measure of α as illustrated in Figure A4. But value can, sometimes, be perceived, meaning that the consumer, influenced by advertising, or fashion, or aesthetics, will pay more than the cost-based value of these metrics. Then the **exchange constant** is more difficult to estimate, requiring interviewing techniques that elicit the value the consumer perceives a change in performance to offer. Market surveys and interview-based methods are time-consuming, require considerable expertise and may not lead to definitive results. More information about **utility analysis** can be found in the papers of Field, and de Neufville, (1988); deNeufville, (1990) and Clark, Roth and Field, (1997).

The **exchange constant** allows performance to be weighed against cost. To do this we formulate a **value function**. The **value function** combines metrics of the performance, P_1, P_2, P_3….., with cost, C, to form an overall **objective function**, V. The best choice is the one that maximises V. Here we limit the discussion to a single metric P, and make use of a locally linear function, defined by:

$$V = \alpha P - C \qquad \text{(A7)}$$

Here cost is measured in $, and the role of the **exchange constant** is to give performance a $-value. The change in V when an existing material (subscript 'o') is replaced by new one (subscript '1') is:

$$\Delta V = \alpha (P_1 - Po) - (C_1 - C_o) = \alpha \Delta P - \Delta C$$

If ΔV is positive, the innovation is **viable** – it is seen as better value for money than the incumbent material. Thus the condition for technical **viability** is $\Delta V > 0$ or:

$$\frac{\Delta P}{\Delta C} > \frac{1}{\alpha} \qquad \text{(A8)}$$

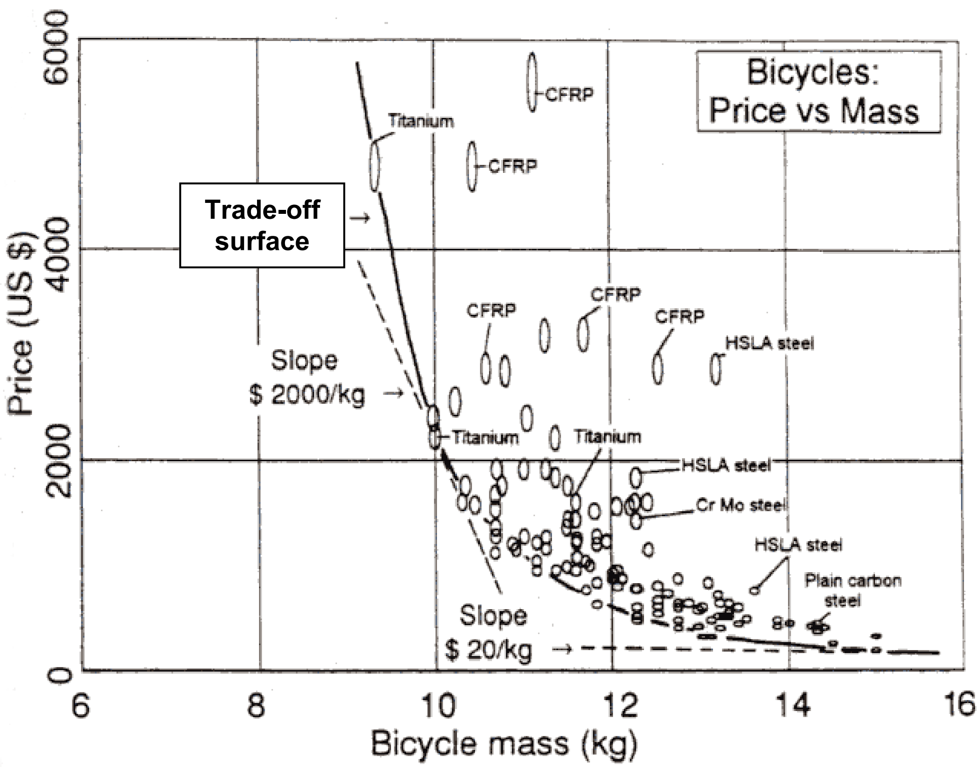


Figure A4. Finding **exchange constants** from historic pricing data. The price of bicycles is plotted here against their mass, some of which are labelled with the material of which they are made. The trade-off line encloses those with the most attractive combination of price and mass. The slope of the tangent to this line is a crude measure of the **exchange constant** – the amount someone will pay to save 1 kg in the weight of a bicycle. It varies with mass because the market for the heavier bikes differs from that for the very light ones.

Appendix for Stage 5
Trade-off methods

The task

To guide decision-making when (as is very often the case) there is a conflict between performance and cost.

Who should do it?

A mechanical, materials or design engineer within the company.

How long will it take?

A few hours, given the outputs of Stages 1 to 4.

The inputs

Information on performance and cost of alternate solutions to a design problem.

The method

There are two approaches to the problem. The simplest is the **market potential diagram**. The more complex, but more powerful, is the use of **trade-off methods**.

Market potential diagrams

If a new material gives 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. However, it is commonly the case that the new material enables enhanced performance but costs more, or is cheaper but has lower performance, than existing solutions. An example of technological innovation allowing for performance enhancements but at higher cost is carbon fibre reinforced plastic boat hulls substituting for wood hulls. Lower cost / lower performance innovations serve the minimum requirements of customers for the application. For substitution to occur, this lesser functionality must be provided at a reduced cost. Oriented strand-board substituting for plywood in furniture and construction is an example of this type of substitution.

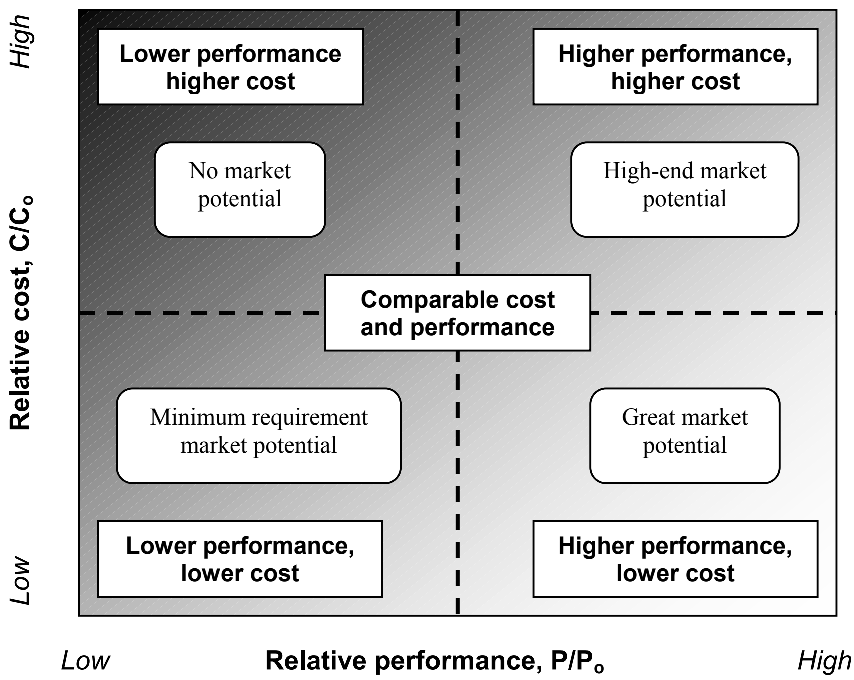


Figure A5. The **market potential diagram**. The most attractive markets lie in the light-shaded area. Here P and C are the metrics of performance and cost for the innovation, and P_o and C_o are those of the currently used material.

The **market potential diagram** is the simplest way of displaying this information for a potential substitute into an existing application. It takes the form of a 2x2 matrix (Figure A5), comparing the performance and cost of a new material with that of the existing one in a given application. Higher performance with lower cost has great market potential, for obvious reasons. Higher performance at higher cost has potential only if the consumer values the increase in performance sufficiently highly. Low performance at lower cost, too, has potential; it is in applications in which performance is not highly valued. Lower performance at higher cost has no potential. It is helpful to plot not only the new material but all others that compete onto the diagram. The sector into which each falls influences the investment decisions that come later.

Market potential diagrams are the simplest forms of trade-off plots. More definitive guidance can be found by using **trade-off methods** described next.

Trade-off methods

Expressed formally, the problem is one of finding a compromise between two conflicting **objectives** – that of maximising performance and at the same time of minimising cost; solutions rarely exist that optimise both at once. The situation is illustrated by Figure A6 in which a **performance metric** P and the cost C are plotted for a number of alternative material-solutions for a design. Each bubble describes a solution. The solutions which maximise P do not minimise C, and *vice versa*. Some solutions, such as those shown as open bubbles, are far from optimal: other solutions exist which have lower values of both P and C. These are said to be **dominated solutions** – other solutions exist that are better. Solutions like those shown shaded have the characteristic that no other solution exists with lower values of both P and C. These are said to be **non-dominated solutions**. The line or surface on which they lie is called the **non-dominated** or **optimum trade-off surface**.

The **trade-off surface** identifies the subset of solutions that offer the bests compromise between performance and cost, but it does not distinguish between them. Frequently intuition can be used to select between **non-dominated solutions** – other facets of the choice often point to one part of the **trade-off surface** as having the most attractive solutions. If our interest is in substitution, seeking to replace an existing material, then the diagram can be segmented as in Figure A7 with the existing material at the origin, when it becomes a simple **market potential diagram**. If more rigor is required, it is necessary to use the **value function** V of the Appendix to Stage 4. There we defined V as

$$V = \alpha P - C$$

where α is an **exchange constant** measuring the value associated with performance in a given application. For a given value of V this equation describes a linear relationship between C and P, with slope $1/\alpha$ and intercept V. If the value of α is known from Stage 4, then contours of constant V can be plotted onto **Figure A6**, giving **Figure A8**. The optimised choice is that which minimises V, that is, the one that lies at the point where the value contour is tangent to the **trade-off surface**. More information about trade-off plots for materials selection can be found in Ashby (2000).

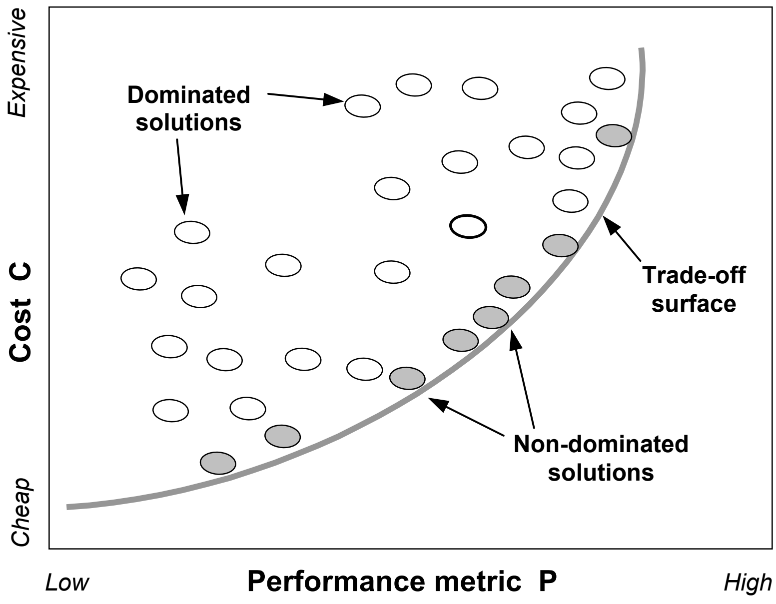


Figure A6. **Dominated** (open symbols) and **non-dominated solutions** (full symbols), and the **trade-off surface**.

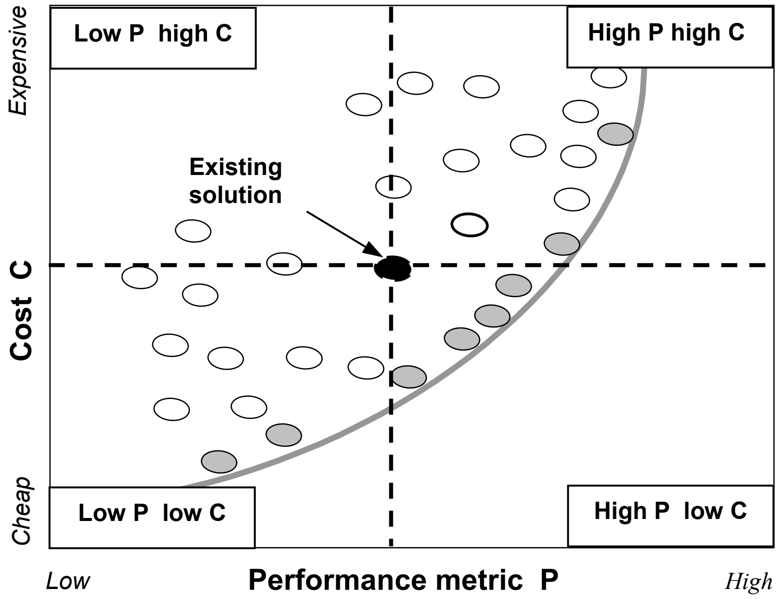


Figure A7. The **trade-off plot** divided into four sectors by lines passing through the existing solution – the one made from the currently used material – showing the relationship with the **market potential diagram** of Figure A5.

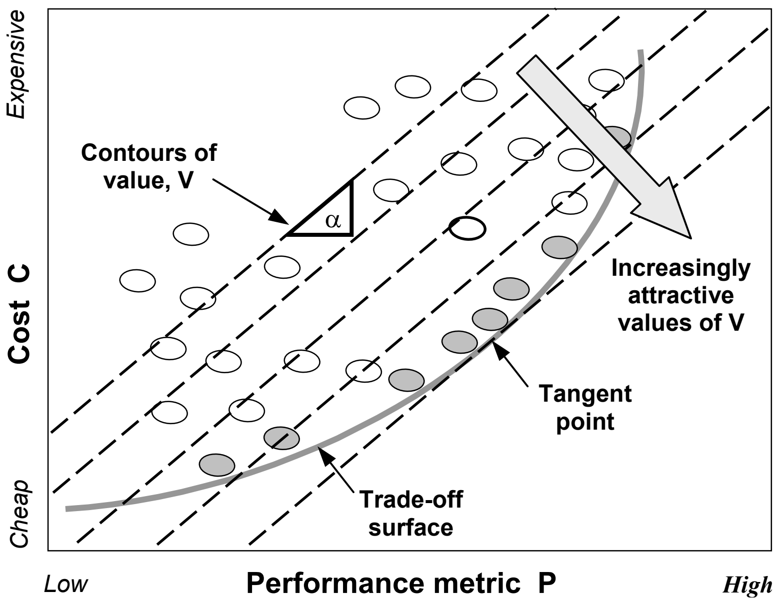


Figure A8: The equation for value V relates P to C for a given value of V, as shown by the diagonal contours with a slope of α. The best solution is the one with the lowest V, where the V contour is tangent to the trade-off surface.

Appendix for Stage 6
Market size and timing

The task

To estimate of market size, revenue flows and their timing, and prioritise the potential markets.

Who should do it?

A marketing researcher with technical understanding of the material and potential applications.

How long will it take?

One week.

The inputs

Information from Stages 1 through 5, and access to external information sources such as web sites, library resources, industry and company information.

The method

Sometimes a new material creates completely new markets or applications, satisfying a consumer desire that is not currently met. Examples of this include the novel processing of PTFE to create Gore-tex^{TM} offering performance in combined winter/rain/sports/casual jackets; the development of rare earth magnets that enabled ultra lightweight earphones and miniature DC motors; and the development of light emitting polymer diodes that allow flexible, large area, displays.

But these are rarities. More usually, a new material substitutes into existing markets. As explained in Stage 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 identified as potential markets for the new material. Two important questions them follow: how large are these markets? And how fast will the take-up be?

Market size is established through public information sources and news search services such as the Financial Times and Wall Street Journal, press releases from research organisations such as SRI, Web-based news services such as Lexis-Nexis, technical journals and through Web-searches using Google.com or Northernlight.com. Rates of take-up are estimated by matching the **innovation category** to that of a historical innovation of the same category with a known **adoption curve,** described in the next 4 pages. Estimating market size and rate of take-up is an iterative process, with refined estimates becoming possible only after a **viability** analysis is performed. If necessary, the **utility** of each market is assessed using the methods of Stage 4.

The two steps allow the innovation to be prioritised according to size and speed of take-up. This initial prioritisation step provides input for the technical assessment, **cost modelling,** and **value analysis** modules. Finally, an implementation plan is created for the order of markets to be entered. Figure A9 summarises the steps.

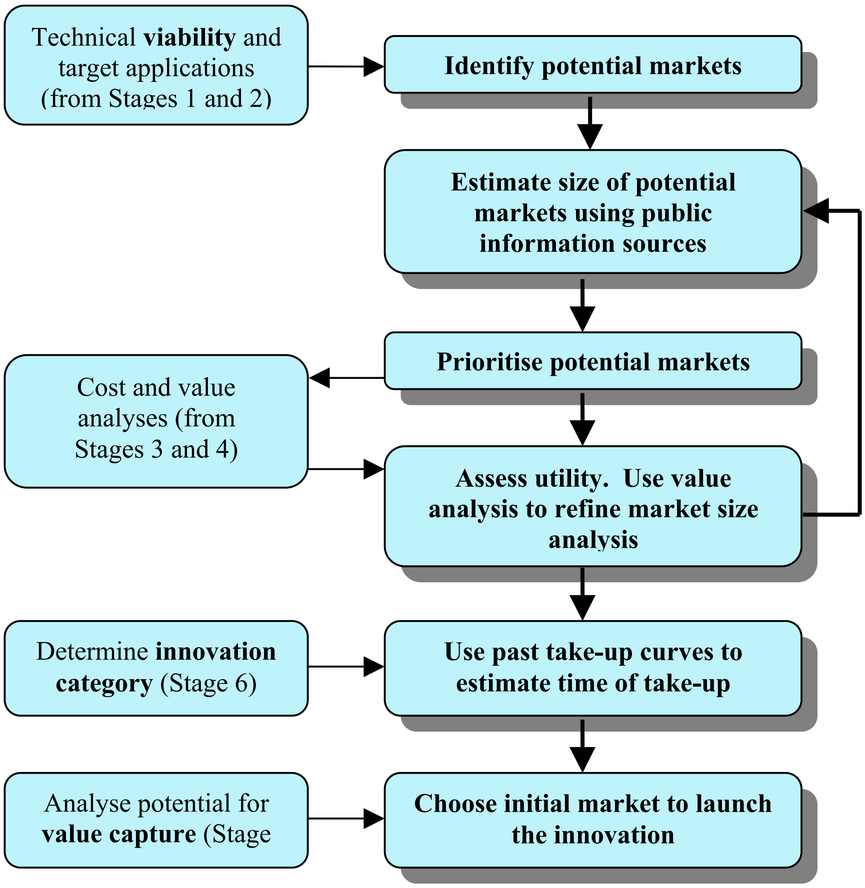


Figure A9. Steps of **market assessment**

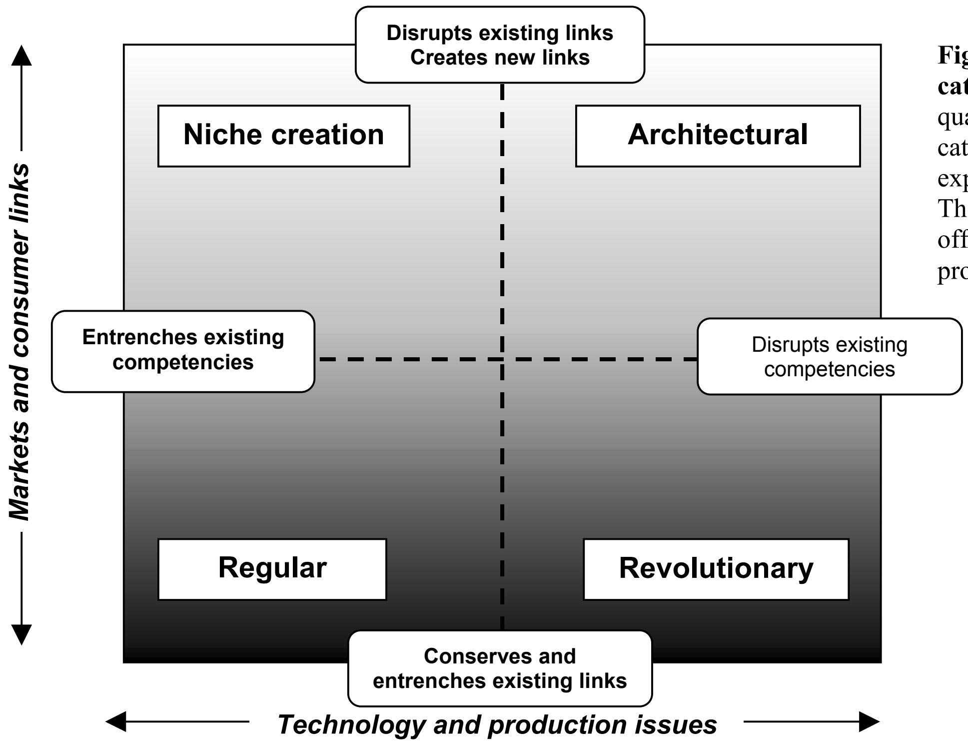


Figure A10. The **innovation categorisation map.** Each quadrant defines a different category of innovation, explained on the facing page. The lightly shaded sectors offer the greatest potential for profit.

Categorising innovations

Categorising past innovations can provide a method for selecting relevant historical precedents to help with predicting market substitution and **appropriability**[iii] (Abernathy and Clark,1985). Innovations can be assigned to one of the four quadrants of the 2x2 matrix shown in Figure A10. *Regular innovation*, in the bottom left quadrant, refers to incremental 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 displace established technical and production competencies, but allow a manufacturer to sell to their existing markets and customers. *Niche creation* is the application of existing technologies to capture new markets, often by adapting or developing them in a way that appeals to a particular user-group. Lastly, *architectural innovation* involves new technology that disrupts existing competencies used to make a product that disrupts existing market and customer linkages. Examples the invention of the radio and the development of the Ford Model T. Abernathy and Clark use these four types of innovation to characterise the extremes of **innovation category** in what they term a **transilience map** (Figure A10). **Transilience** is defined as "the capacity of an innovation to influence the established systems of production and marketing", but it is an obscure and confusing term. We shall refer to it simply as the "**innovation category**".

Historical Adoption (Logistic) Curves

A successful innovation displaces an existing material or product, but it takes some time to do it. An estimate of the rate of substitution helps plan the production volume needed to meet the demand, and allows an estimate of the revenue that will be generated. Fisher and Pry (1971) analyse competitive substitution using historical **adoption curves** (or 'logistic' curves); giving a basis for market forecasting. They argue that competitive substitutions can be modelled by a curve with the form,

$$\frac{f}{1-f} = \exp\left\{2\alpha\,(t-t_o)\right\} \qquad \text{(A9)}$$

where f is the fraction already substituted, 2α is the annual fractional growth, t is time, and t_0 is the time at which $f = 50\%$. Historical substitution curves for commercially successful innovations are fitted to this equation, giving α and t_o, and are characterised in the way described in the last paragraph. The new innovation (for appropriate target markets) is then matched to the curve for the past successful innovation with the same **innovation category**.

A case study: light emitting polymers (LEPs)

Consider the estimation of market size and timing for a contemporary materials innovation – that of light emitting polymers (LEPs). LEPs such as polyphenylene vinylene (PPV), developed in the late 1980s, appear to be suitable for high quality, thin, flat panel displays, with high efficiency (>10%), low operating voltage, wide view angle, and competitive cost (Friend et al, 1999; Burden, 2000). Competing display technologies are the cathode ray tube (CRT), the 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 displays that are lighter and thinner than CRTs, cheaper and with better viewing angles than LCDs, and cheaper and more efficient than plasma displays (Mentley, 2001).

[iii] Appropriability – tha ability to capture profits – is the subject of Stage 7 and its Appendix.

LEPs are currently aimed at five major markets, each with different technical and cost requirements: flat panel televisions, computer monitors, mobile phones, wireless communication devices ("WAP"s), and large-area advertisement screens. In each application, the performance and manufacturing cost predictions for LEP technology must be compared with existing technologies. When compared with the CRT[iv], LEPs, have the potential to raise the demand for televisions, computer monitors, and portable computers by offering good quality, light, portable, and fashionable flat panel displays. Compared with the LCD, LEPs have the potential to lower the cost and raise the demand for portable computers, mobile phones and wireless application protocols (WAPs) where portability is important. Compared with the PDP, LCDs have the potential to lower the cost for flat panel televisions and computers (for small to medium size screens) but may also reduce demand curve due to inferior quality. Figure A11 shows some of these, positioned on the **market potential diagram**.

Figure A12 does the same for the **innovation category map**. It suggests that the uses of LEPs in television screens and computer displays are revolutionary innovations, while LEPs aimed at the emerging WAP market are an architectural innovation. Their take-up is expected to follow the **adoption curves** of past innovations that fall in these categories.

Some historical examples of adoption of innovations in the consumer electronics industry are shown in Figure A13. Black and white television adoption is an 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 is slower. VCRs can be viewed as a lower cost / higher performance, *revolutionary* innovation substituting into the movie market space. Digital LCD watches substituting for analogue watches is an example of a lower cost/ lower performance *revolutionary* innovation (Hegarty, 1996; Wilder, 1998). If LEPs in the major flat panel display applications follow substitution patterns like those of the historical precedents identified in Table A5, they could be expected to capture the market in 10 to 15 years.

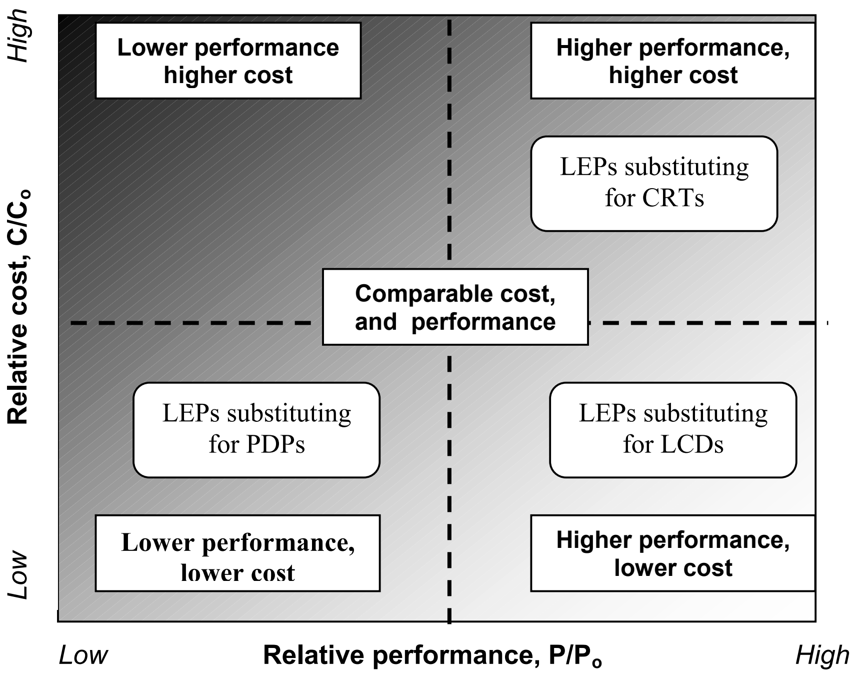


Figure A11: The performance / cost assessment for selected LEP applications using a **market potential diagram**

[iv] 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.

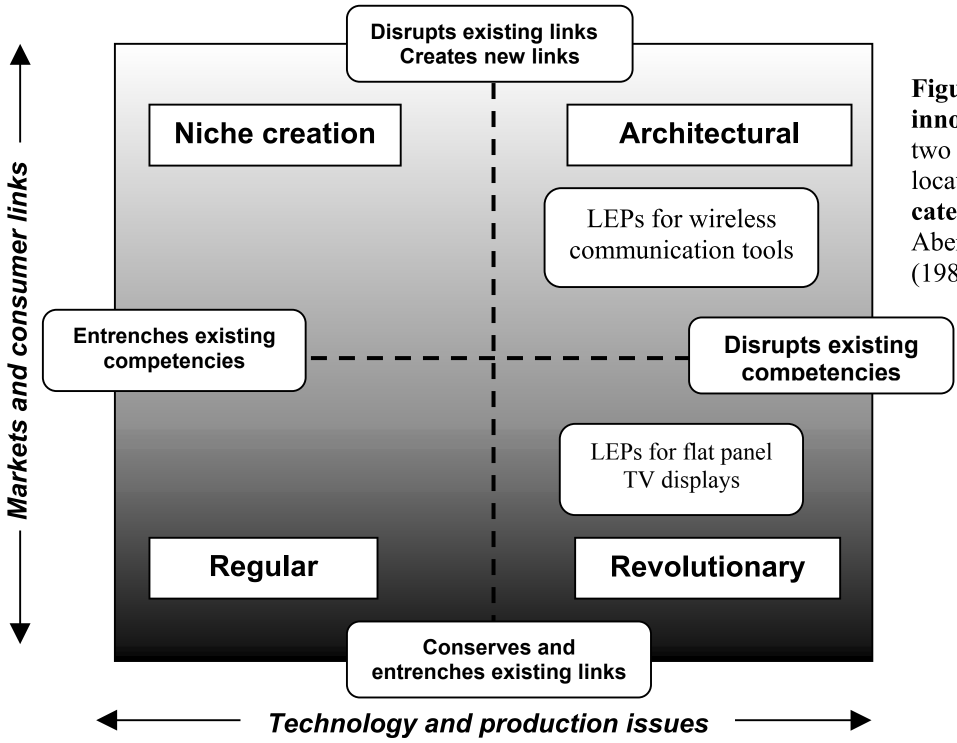
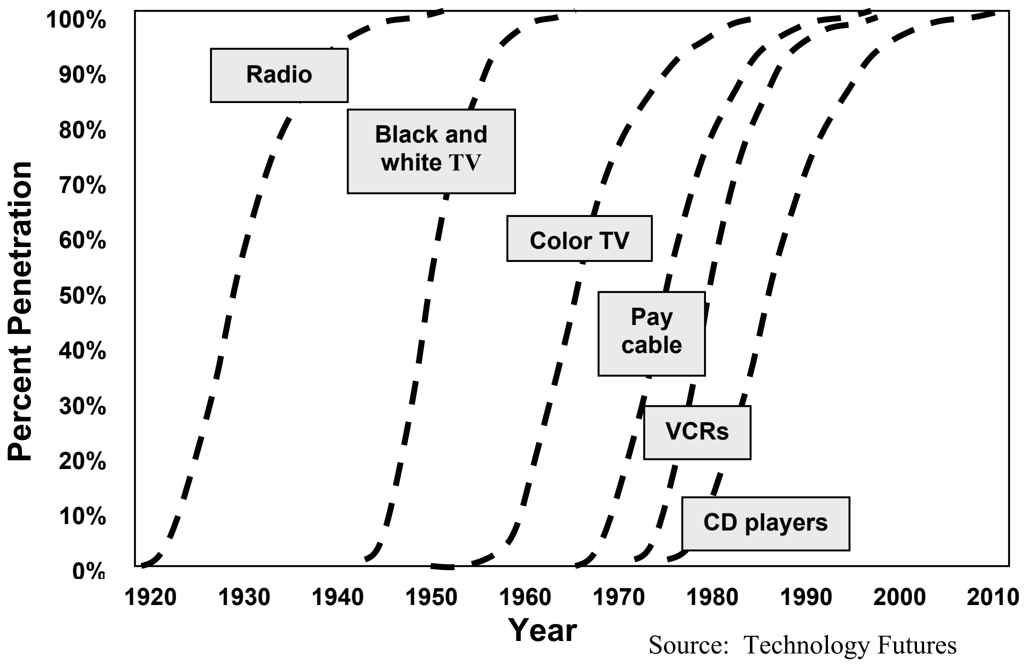


Figure A12. The **innovation category** of two LEP applications locate on the **innovation categorisation map** of Abernathy and Clark (1985).



Source: Technology Futures

Figure A13.: Historical **adoption curves** of innovations in the consumer electronics industry

Table A5: Target Applications for LEP Flat Panel Displays

Application	Size of Target Market[v] ($M)for LEPs	Cost / Performance	Innovation category	Historical Precedent	Expected Year of First Commercialisation
Flat Panel TVs	$15,000	Higher / Higher vs. CRTs[vi] Lower / Higher vs. LCDs[vii]	Revolutionary	Colour TV VCRs	2003
Desktop computer Monitor	$5,000	Higher / Higher vs. CRT Lower / Higher vs. LCDs	Revolutionary	Colour TV VCRs	2003
Portable computer monitor	$7,500	Lower / Higher vs. LCDs Lower / Lower vs. Plasma	Revolutionary	VCRs Digital watches	2003
Mobile phones	$20,000	Lower / Higher vs. LCDs	Revolutionary	VCRs	2000
WAPs	$60,000	No Incumbent	Architectural	B&W TV	2001
Advertising Displays	$500	LED Plasma	Revolutionary	Colour TV Digital Watches	2003

[v] The analysis incorporates data from the following sources: The Display Search Monitor (2000); Electronic Buyers News (2000); Mentley, (2001); Cambridge Display Technologies (2001); Chen (2001).

[vi] Higher performance in the sense of lighter weight, lower volume and lower power consumption.

[vii] Higher performance in the sense of better viewing angle and lower power consumption.

Appendix for Stage 7
Value capture

The task

To assess the probability that the innovating company will capture the profits that the innovation will generate.

Who should do it?

Strategist, Vice President or Senior Manager for Strategy, Vice President or Senior Management Consultant.

How long will it take?

For internal managers, a single day. For external analyst, a few days.

The inputs

Information about the competitive environment in which the innovating company must operate. Information about the management structure of the innovating company, its organisational chart, knowledge of senior management (or interviews with them); evidence of entrepreneurial skills and details of the extent of protection of the intellectual property relating to the innovation.

The method

Viability assessment and **market assessment** may demonstrate that the innovation has the potential to create value, but a company or investment capitalist may still decide that it is a poor investment. To justify investment, investors must be convinced that they will capture a significant portion of the value created by the innovation. Concepts of ***industry attractiveness***, ***appropriability***, ***competitive advantage***, and ***organisational structure*** are utilised to predict the likelihood of capturing value.

Industry attractiveness

Porter (1985) suggests a methodology to provides an assessment of **industry attractiveness**. Here we are not speaking of a particular product, but of the industrial environment in which the innovating company must work. The assessment is done by examining the rivalry of competitors in the industry, **supplier power**, **buyer power**, barriers to **new entrants** and the threat of **substitute products** (Figure A14). Take, as an example, the industry-environment of the single large supermarket in a small town. Being part of a national chain, it is in a more powerful position than its suppliers, the farmers; and being the only supermarket in the town, it is in a more powerful position than its customers, the general public. The consumer could, of course, drive to another town or grow their own food (the 'substitutes' in Figure A14) but few would wish to do so. The only threat to profit capture for the supermarket is that of competition from a new entrant – the arrival of a new supermarket in the town. By most standards, the **industry attractiveness** of the supermarket is high. But now repeat the reasoning for the small farm that sells to the supermarket (its buyer), and that must purchase seed and fertiliser from large, multinational, industries (its suppliers). The **industry attractiveness** of the small farm is not so good.

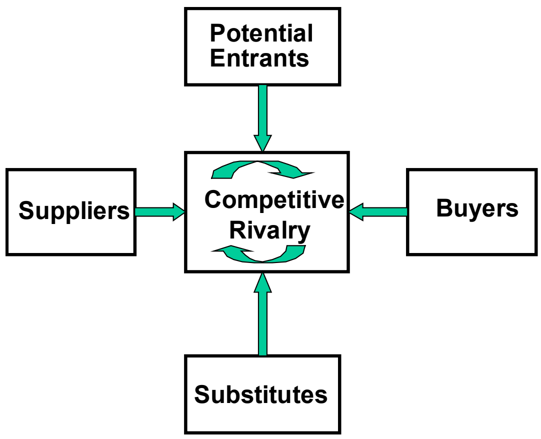


Figure A14. Schematic of the five forces analysis to assess **industry attractiveness** (Porter, 1985).

Technological innovation can alter the attractiveness of an industry by changing one of the five forces of Figure A14. The process innovation of continuous casting of aluminium is an example. It took away the scale advantage that large semi-fabricators had with capital-intensive hot mill plants, reducing manufacturing costs, and lowered the barriers to new competitors entering the industry by reducing the capital investment required to compete. In ways like this, the five forces analysis can help inform investors whether a selected industry is competitively attractive and whether the technical innovation is likely to increase or diminish this.

Appropriability of profits

Ownership of intellectual property (IP) is a key factor in capturing value from an 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 to measure the degree of IP protection and market control. Teece (1987) divides **appropriability regime**s into *very tight* and *tight*, where strong patent or trade secret protection, asset type, and the **innovation category** combine to enable the capturing of innovation profits, and *weak or very weak* where the opposite is true. **Innovation category** here refers to the position of the innovation on the **innovation category map** of Figure A10. This helps identify an appropriate past example of substitution on which to base both market forecast and appropriability comparisons. Tight appropriability regimes are attractive because they allow for monopoly conditions for a period of time. Table A6, which is a sort of check-list, gives further guidance in assessing appropriability. Generally, tight appropriability is found on the left, weak on the right-hand side of the table, the six rows of which make reference to the following points.

- **IP/ trade secret protection**. The extent to which the innovation is protected from a legal point of view.
- **Specialised and co-specialised assets**. **Specialised assets** are those that are not generally available and need to be tailored to the innovation: custom-made capital equipment for manufacturing, for instance. **Co-specialised assets** are assets managed by others without which it cannot function, and *vice versa*, creating a mutual dependence that is hard to break into. As an example, a fleet of cars powered by natural gas needs a network of natural gas fuelling stations for the innovation to be successful – the fuelling stations exist solely because of the natural gas powered vehicles and the vehicles' market success depends on an acceptable refuelling infrastructure.
- **Experience curve**. Production costs tend to fall as experience is gained. A company that is well along the **experience curve** has costs that are significantly lower than those of a new entrant. Lead innovators can protect their initial advantage by exploiting their experience effectively.
- **Innovation category**. Innovations that are categorised as architectural or niche on the **innovation category** map offer tighter **appropriability** than those that are revolutionary or regular.
- **New product cycle time.** The length of time before the product model becomes obsolete. Long cycle times give the innovator a period of protection from competition; short cycle times allow a predator to pounce quickly.
- **Protectablity of the industry.** An assessment of the degree to which the innovation is protectable in the market segment and geographical region of interest. If, for example, patent protection will expired before the innovation has been fully commercialised, protectability is low.

Organisational structure

The most attractive innovation opportunity can be squandered by a company without an effective **organisational structure** (Amabile, 1998). In the materials industry in particular, organisational competencies are required to exchange knowledge between disciplinary fields, functional roles, organisational boundaries, and the marketplace. Entrepreneurial management, the presence of a visionary deal-maker, flexibility of organisation, effective knowledge acquisition and management, and operational efficiency are important ingredients for successful innovation.

One of the larger differentiators in **organisational structures** is size. Small firms generally exhibit a more flexible and opportunistic approach to their decision making than large ones. The presence of a "deal-maker" in senior management is critical to a small firm's success in commercialising technological innovation to compensate for its financial limitations. In larger research-intensive industries, the resource allocation process is a key component of an innovative corporate culture. Henderson and Cockburn (1994) identify 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 is that of a "relatively high conflict committee" that decide on resource allocation through "constructive confrontation across the group".

Although it is difficult to generalise the evaluation of organisational strengths and weaknesses, it is possible to formulate a checklist of desirable attributes. For small firms, this includes: the level of entrepreneurial experience of management, the presence and competence of a visionary deal-maker, level of demonstrated flexibility of the organisation, mechanisms for effective knowledge acquisition and management, and evidence of operational efficiency. Table A6 summarises six factors contributing to (or detracting from) **appropriability**. The factors are printed in normal (roman) type. Beneath each is an example, printed in italics.

Table A6: **Appropriability** guide and examples corresponding to the **appropriability** rankings

Appropriability regime	**Very tight**	**Tight**	**Weak**	**Very weak**
IP / trade secret protection *Examples*	High *Incontestable patent*	Medium *Contestable patent / well protected trade secret*	Low *Penetrable trade secret*	None *Competitor holds key patent*
Specialised / co-specialised assets *Examples*	High *Chemical manufacturing complex*	Medium *T.V. manufacturing plant*	Low *Foundry*	None *Lemonade stand*
Experience curve *Examples*	High *Consumer electronics design and manufacturing*	Medium *Automotive design and manufacturing*	Low *Software design*	None *Well known production method or low volume production*
Innovation category *Examples*	Architectural *Ford Model T*	Niche Product *CFRP monocoque for race cars*	Revolutionary *GFRP fenders*	Regular *High strength steel automobile body*
New product cycle time *Examples*	Slow *Aerospace*	Medium *Automotive*	Fast *Computer Software*	Continuous *Information Content*
Protectability of the industry *Examples*	High *Pharmaceutical*	Medium *Computer Hardware*	Low *Publishing*	No *Computer Software*

Appendix for Stage 8
Investment strategy

The task

To formulate investment decisions and commercialisation strategies.

Who should do it?

Chief Executive Officer, Vice President or Senior Manager for Strategy, Venture Capitalist.

How long will it take?

A single meeting.

The inputs

The outputs of Stages 1 to 7.

The method

There are three key go/no-go questions. They are answered by the three main parts of the methodology. An unambiguous decision to invest in the innovation requires positive answers to all three. Investment may still be justified if the answers are less certain, provided there is credible assurance that corrective means are in place. The key questions are these.

1. Is viability assured?

The **viability** assessment combines two factors – the first that of technical performance, the second that of cost – and a method for examining the trade-off between the two, determining whether customers will judge the innovation to offer good value for money. Only if the innovation is technically and economically **viable** is an investment justified, but a positive **viability assessment** alone is not enough.

2. Are market size and timing favourable?

Investment is justified only if potential market-size is sufficiently large and the take-up rate sufficiently rapid. The market forecast feeds back into the **viability assessment** by identifying promising market segments and the value consumers attach to them, and it assesses the size of the market that is likely to adopt the innovation. Relevant past innovations are utilised as a basis for the forecast.

3. Will value be captured by the innovator?

Investment is justified only if the innovator will capture the value created by the material innovation (after considering potential collaborations). The value-capture assessment uses three strategy tools: that of exploring **industry structure**, that of analysing **appropriability**, and that of assessing **organisational structure**. A unique feature of the methodology presented here is the incorporation of this component of business analysis into the **viability assessment** of a material innovation at an early stage.

It also gives insight into the type of organisation most likely to find investment attractive. **Adoption curves** for past innovations help estimate the time-scale of payback on an initial investment. When the payback time is long, only governments, public organisations or very large corporations will be interested investors. Conversely, a staged investment with a payback time of 5 years or less, the potential for a buyout, and the promise of large "upside" profit, are attractive to venture capitalists.

Given the decision to invest, the market approach is the key to managing cash flow. A new material can first be exploited in small volume, high value-added and highly visible applications such as sports equipment. These create credibility and brand-recognition, and provide initial cash flow while plans to penetrate larger, less visible markets are developed. Gain is always possible from joint ventures with suppliers, customers, and distribution channels, since such collaborations provide financing opportunities, faster market penetration, and a more detailed understanding of the market.

Succeeding with New Materials

Bibliography and Glossary

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Glossary

Adoption curves – a graph of the market share captured by an innovative product over time. Adoption curves are also referred to as S-Curves, substitution curves and logistics curves.

Appropriability – a measure of the ability of an innovating firm to capture profits generated from commercialising a new technology. It is based on considerations of intellectual property protection, specialised knowledge or procedures.

Barriers to entry – anything which prevents other companies or individuals from becoming competitors in a particular industry. Examples include capital investment required to build a manufacturing plant, required distribution agreements, comprehensive patents, etc.

Buyer power – the ability of the companies or consumers who purchase your products to negotiate a lower price for the products.

Categorisation map – a 2 by 2 matrix classifying an innovation according to its need for new or unfamiliar technology and production methods, and the changes in consumer base that it will require.

Constraints – the conditions that must be met in order to satisfy the requirements of a design. The constraints guide the choice of materials, eliminating those unable to meet them.

Co-specialised assets – assets that form a mutually dependent relationship with the innovator. For example, a fleet of cars powered by natural gas needs a network of natural gas fuelling stations for the innovation to be successful. The fuelling stations would exist solely because of the natural gas powered vehicles and the vehicles' market success would be dependent on an acceptable re-fuelling infrastructure.

Cost drivers – those steps in the production process that add most to the overall cost of a component.

Cost estimate – an approximate assessment of the likely cost of making a product.

Cost model – a mathematical model, commonly implemented as a spreadsheet, allowing the contributions to the manufacturing cost of a component to be estimated and then summed to give the total cost.

Dominated solution – A material choice that performs less well and costs more than competing materials and is therefore an inappropriate choice.

Exchange constant (or **utility constant**) – the monetary value ($) associated with a unit change in performance. Exchange constants allow a trade-off to be found between cost and performance.

Experience curve or **learning curve** – a graph of production costs versus cumulative units of product produced. As a general rule, production costs fall as the total number of units produced increases because of experience with the manufacturing process. Innovators can consolidate their early advantage maximising the cost reductions that experience allows.

Five forces analysis – and analysis of the competitive position of a company in a given market sector. It is influenced by the relative power of its suppliers and its buyers, by the ease or difficulty with which new entrants can steal market share, by the threat posed by substitutes, and by competition with other companies already operating in the chosen market sector.

Function – the engineering purpose of a component.

Industry attractiveness - an estimate of the potential for profitability in an industry. It is assessed by a "five forces" analysis that assesses the rivalry of competitors in an industry, supplier power, buyer power, barriers to new entrants to an industry, and the threat posed by potential substitute products.

Market assessment – the exploration of a market to assess its nature, its size, and its rate of take-up of an innovation.

Market potential – a measure of the ability of an innovation to capture sales.

Material innovation – a development in material or process technology leading to a material with properties that enable products with greater performance, reliability or safety, or lower cost, or all of these.

Material property charts – a family of diagrams with material properties such as strength, density, thermal conductivity etc. as axes, showing the values of these properties for representative established materials. The performance of a new material can be assessed by plotting its properties onto these diagrams, allowing a comparison with those of established materials.

Non-dominated solution – a material choice that is either cheaper than all others offering the same performance, or offering higher performance than all others that cost less.

Objective – the measure of "goodness" of a material choice, for which a maximum or minimum is sought. In cost-limited design the objective is to minimise cost. In performance-limited design, it is to maximise performance. Almost always a trade-off must be sought between cost and performance, requiring trade-off methods. See also **performance metric.**

Organisational structure – the entrepreneurial, management and organisational skills, and their relationships, within an organisation.

Performance metric – a measure of the performance of a material in a given application. In lightweight design, the metric is the weight; in low cost design it is the cost.

Property profile – the set of properties (mechanical, thermal, electrical, optical etc) that characterise a given material.

Rate-limiting steps - those parts of the production process which determine the cycle time because they are the slowest portion of the production process**.**

Specialised assets – assets that are not generally available and need to be tailored to the innovation: custom made capital equipment for manufacturing, for example.

Supplier power – the ability of the companies or employees who supply your raw materials, labour and other inputs to negotiate a higher price for their products and services.

Technical constraints – any time or dimension limitations of the process or product that can be modelled by scientific means. For example, the best possible cycle time of a part moulded from a thermosetting polymer resin is determined by the cure time of the resin and the wall thickness of the part.

Technical cost modelling – a cost model containing sub-models that capture the influence of real or potential changes of technology on the cost of a manufacturing process.

Three key questions –

- Is the market size sufficiently large and the payback-time sufficiently short to justify investment?
- Is the material innovation technically and economically **viable**?
- Is there a high probability of capturing the value created by the innovation?

Trade-off method – a procedure for arriving at a compromise between conflicting objectives, frequently those of maximising performance while also minimising cost.

Trade-off surface – the line enclosing the **non-dominated solutions** on a trade-off plot. The most attractive choices are those that lie on or near the trade-off surface. Distinguishing between them requires judgement or the use of a **value function**.

Transilience – "the capacity of an innovation to influence the established systems of production and marketing" (Abernathy and Clark, 1985), but it is an obscure and confusing term. We shall refer to it simply as the "**innovation category**".

Utility – a measure of the value of a material or product to a consumer.

Utility analysis – an interview-based technique for establishing the value associated with a change in performance, thus determining the **exchange constant** or **utility value**.

Value – the worth that a consumer perceives a product to offer. If the value is greater than the price, the product is perceived to be good value for money. If the reverse is true, it is perceived to be not worth the price.

Value capture – the ability of the originator of an innovation to gain the profits made by its exploitation.

Value function – a mathematical function aggregating the objectives of cost and performance into a single, global, objective function.

Viability – an innovation is viable if the combination of performance and cost it offers is as good or better than those of the competition.

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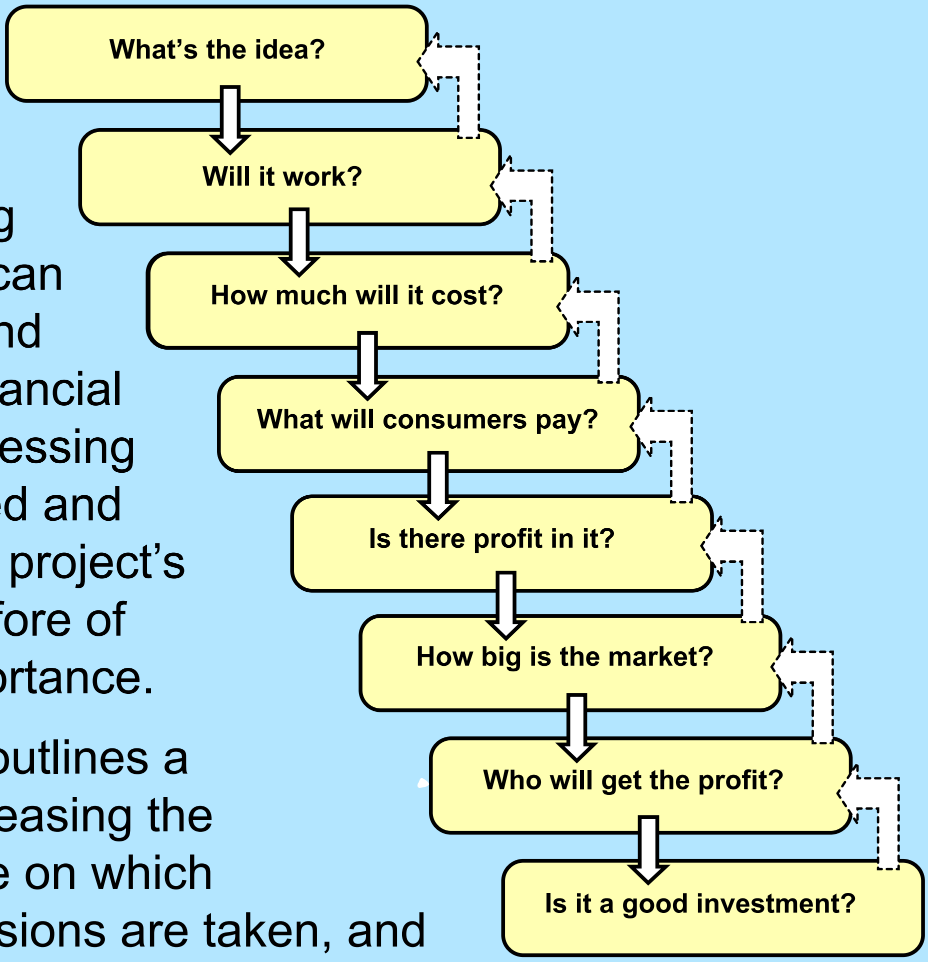

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