Visualisation and visual modelling for R&D Investment Management

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Successful valuation of individual R&D projects and managing a R&D portfolio is a key advantage for technology firms whose product competitiveness rely on the technologies supported with R&D activities. The R&D management process requires a high level of collaboration and communication between the key stakeholders in organisations. The lack of a well-designed process and insufficient use of appropriate tools account for inefficiencies in R&D management. The objective of this paper is to explore and evaluate visual representations and visual models utilized in current R&D management practice, and to suggest other tools which have potential benefits.

1. Introduction

The highly competitive nature of the new economy pushes companies to invest heavily in R&D in order to develop new technologies in a timely fashion to maintain competitive advantage. There are two challenges for effective R&D management. The first one is to determine in which new projects to invest. It involves valuation of individual projects and determining when and how much to invest. However, there are usually more than one ongoing R&D projects and the second challenge is to maintain an optimal balance of projects in the R&D portfolio. To maintain the desired portfolio risk-return profile, it is essential to have an active portfolio management approach where the portfolio is constantly being reviewed, some projects pushed forward, some postponed and some killed altogether.

Both individual valuations of R&D projects and maintaining an optimal portfolio are complicated tasks. There are both external and internal stakeholders in the valuation and decision-making process. Justification of R&D management decisions depends on successful communication between stakeholders.

The external stakeholders (investors) and industry analysts (i.e. equity researchers) are interested in potential strategic and financial implications of R&D management decisions. The internal stakeholders may consist of the R&D, finance, marketing and strategy directors, and the top management. They are mainly interested in making sure that (Goffin, 2005): (1) the projects have potential value, (2) they fit well with the overall strategy of the organisation, (3) project and portfolio risks are manageable, (4) the timing is right, and (5) the required resources are available.

The current internal valuation and decision making process is predominantly a bottom-up one in which the R&D department develops business cases for new projects and seeks to gain buy-in from the key decision makers. The problem with this bottom-up approach is two fold. First, there is the problem of conflicting objectives. For instance, the R&D department may not be on the same page with the finance department which has a budget constraint and financial objectives to meet. The objectives of the two departments may conflict in the short-term. It takes a long time before R&D projects start generating cash and this cash inflow usually lags behind cash outflow which increases the liabilities side of the balance sheet.

On the strategic level, the marketing strategy department is more knowledgeable about the dynamics in the industry, products that sell well and the projections for the future. The main concern of the marketing strategy department is whether the R&D portfolio supports the strategic vision of the company, instead of whether short-term financial gains are maximised or not. Thus, its expectations from the R&D department as compared to finance may be different. Moreover, what the R&D department plans to offer may not be in parallel to either department if close communication between these departments does not exist. The solution to this problem, namely the conflict of objectives, requires a well-designed collaborative R&D management process and means of communication. Visual representations and models play an important role in improving cognition and serve as aids to successful information sharing and transfer.

Second, the bottom-up process is vulnerable to communication breakdown between the key stakeholders and decision-makers. The priorities of the R&D, finance and marketing strategy managers are different. Whereas a marketing strategy director is interested in the strategic implications of R&D practices, the finance director is usually more interested in the detailed financial projections of the costs and returns.

The extent of the second problem can be minimised through carefully created documents and presentations incorporating an adequate amount of appropriate visual representations and models. The key stakeholders receive information in various types including textual, verbal and visual forms, and process them by mostly linear, sequential ways. They are required to process and synthesize the information they are presented with in a prompt manner and reach judgements based on this synthesis.

Nevertheless, proper valuation of R&D projects in terms of financial and strategic context is essential and precedes communication. Decision-makers face the challenge of understanding the uncertainty that is associated with new R&D project investments and the potential value that the new technology would add to the organisation compared to the cost of developing the technology. There are difficulties in comprehending financial and strategic implications of potential R&D projects. Bullet point lists, written statements and complicated financial calculations are often not sufficient to clearly analyse these implications of individual projects or the project portfolio; neither are they appropriate aids to discussing and analysing issues within the management team. The remedy to this problem requires utilization of appropriate techniques.

In this paper we will explore the visual representation and modelling tools which improve analysis, planning, valuation, decision-making, monitoring and communication processes in the context of R&D management. We will then evaluate a list of these tools according to a range of criteria.

2. Visualisation and Visual Modelling

In addition to a well-designed R&D management process, the effectiveness of an organisation's R&D practices is also related to its managers' ability to make decisions correctly. However, human intelligence is bounded by the limits of *short-term memory* and *processing capacity*. Information processing capability is limited by the: (1) working memory, (2) speed of cognitive operations, (3) retrieval of information, (4) numerical operations, and (5) projection in time and space (Hunt, 2004;Pappas, 1985;Zachary, 1988). The first constraint on human intelligence is the short-term memory, which is known to handle a maximum of five to nine (seven plus or minus two) chunks of information (Miller, 1956). Hypothetically, it is possible to pack information together and produce meaningful chunks using visual representations providing the brain with the capability to process a larger amount of information at one time. As one Chinese proverb says: "A picture is worth ten thousand words" (Larkin, 1987). About the remainder of the constraints, cognitive science literature points out the ability of the human brain to process and analyze complex information more effectively and much faster when information is represented visually as opposed to sequential textual or verbal forms alone (Larkin, 1987).

"*One cannot manage what he cannot model*" (Norden, 1993). This is also true for R&D management. Models are abstractions of reality created by using one or a combination of graphical, mathematical, verbal or physical forms. They are used to conceptualize and analyze complex systems, or to solve problems when experimenting with the real system is difficult or simply infeasible. Verbal (textual) definitions and mathematical models alone are not effective means in R&D project/portfolio valuation and decision-making due to complexity of the problem. Issues such as risk-return tradeoffs, correlations between variables, and importance-priority characteristics of projects are very difficult to comprehend when expressed in words and formulae only.

Furthermore, verbal information transfer and processing are sequential. Creating an all-inclusive conceptual understanding of the financial and strategic issues surrounding a valuation problem using sequential information processing is not possible. Visual models, on the other hand, can be either sequential or all-inclusive, and can provide a big-picture view. Visual descriptions also increase recall, support learning processes, capture attention, structure and coordinate communication, and motivate people (Eppler, 2004;Norden, 1993). They help potentially explicable tacit (implicit) knowledge to become explicit (Reinhardt, 2002).

However, it is not a straightforward task to find an appropriate tool to suit the requirements of a problem. There is a large number of visual representation and modelling tools that can be used in valuation and decision-making, and more than one tool can be appropriate in a particular situation either stand-alone or together with other tools. It is therefore important to clarify the boundaries and the relationship between visualization and modelling (Figure 1).

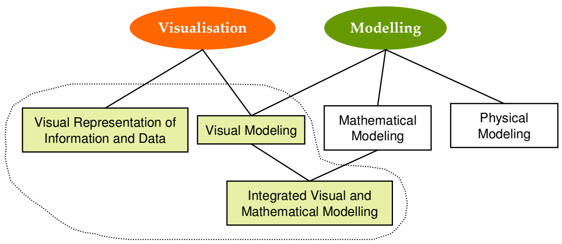


Figure 1 Visualisation, visual modelling and integrated visual and mathematical modelling (Kazancioglu, 2005).

Visual representation of information and data could be in the form of charts, graphs, tables, etc. Examples of *visual modelling* tools are cognitive maps, semantic maps, concept maps and decision trees. *Integrated visual and mathematical modelling* tools are visual representations supported with mathematical forms, or vice versa. Decision tree analysis and system dynamics are examples of integrated modelling tools.

2.1. Visual Representation of Information and Data

Visual representations are used to transfer, create, learn, document, find or assess knowledge and information. The definitions for information visualisation and knowledge visualisation are varied in the literature. Eppler *et al.* (2005) define knowledge visualisation as "all graphic means that can be used to develop or convey insights, experiences, methods or skills". They differentiate it from information visualisation which makes use of computer-supported, interactive, visual representations of abstract data to amplify cognition (Card, 1999). In this chapter, we use the term *information* rather than *knowledge* to stress those tools that help display what is already known, possibly in pure data format, in a cognitively comprehensible fashion.

Data visualisation is the graphical representation of data to provide the viewer qualitative insight into the data contents. Charts, graphs, plots and other visual data representation tools help us make sense of a large amount of data.

Charts (Harris, 1999; Zelazny, 2005) are *information graphics* which consist of graphs, maps, diagrams, tables or a combination of these forms. They are vehicles to consolidate and display information for the purpose of analysis, planning, monitoring, communicating etc. Harris (1999) classifies graphs (plots), maps, diagrams, tables under the umbrella of charts, and further classifies graphs according to the type of data displayed as: (1) original data, (2) derived data, (3) abstract data. Graphs are then members of *charts* that graphically display quantitative relationships between two or more groups of information. Graphs offer several benefits. They encapsulate large amount of information in a convenient way and make it possible for the viewers to understand the essence of the quantitative information. In addition, overall data patterns such as deviations, anomalies, trends and relationships in the data stand out clearly when represented in a graphical form.

Maps are generally defined as visual representations of information in regards to its physical position. However, here we stick to the definition as meant in mind mapping (Buzan, 2004) and conceptual mapping (Siau, 2005). Maps are discussed further in the next section.

2.2. Visual Modelling

While visual representations display what is already known, visual modelling tools support the creative task of discovering and modelling the structure of complex systems. They provide the capability for modelling the behaviour of a system through time (Pracht, 1990).

System thinking and creative problem-solving literature make extensive use of visual modelling tools. The rich pictures method (Monk, 1998) has its origins in the soft systems methodology. An effective rich picture (1) includes structure, (2) includes process, (3) includes concerns, (4) uses the appropriate language, and (5) uses any pictorial or textual device that suits the purpose (Monk, 1998). They are essentially mental maps supporting knowledge-recording, reasoning, analysis, communication and negotiation. Mind maps and rich pictures are especially useful when issues surrounding a problem have interrelationships that are difficult to model using sequential (check-list) forms of representation.

Cognitive maps (Eden, 1988, 2004;Kaplan, 2000) are similar visual tools to model one's mental picture of an issue. While rich pictures and mind maps can take many different forms, cognitive mapping is a formal modelling technique with rules for its development and may lead to later development of influence diagrams (Diffenbach, 1982) which can then be used to build system dynamics models (stock and flow diagrams) (Eden, 2004). Cognitive maps: (1) help focus attention and trigger memory, (2) help highlight key factors and priorities, (3) help supply missing information, (4) can reveal gaps in information or reasoning that need more direct attention (Siau, 2005).

Siau *et al.* (2005) discuss three cognitive mapping techniques: (1) *causal mapping*, (2) *semantic mapping*, (3) *concept mapping*. Similarly, Rasiel *et al.* (2002) describe *logic trees* and *issue trees* for problem structuring and analysis as used by McKinsey & Company consultants. The logic tree is used to structure problems into mutually exclusive, collectively exhaustive (MECE) subcomponents. The issue tree on the other hand is a different version of a logic tree in which each branch of the tree is an issue or question, and is used to lay out the issues and sub-issues into a MECE visual progression. Regardless of the type of mapping used, one should always remember that choosing an appropriate level of detail in the abstraction of the real system being modelled is key in effective management of models.

2.3. Integrated Visual and Mathematical Modelling

Integrated visual and mathematical models not only make use of visual representations but also facilitate quantitative analysis of a system. The most famous integrated modelling paradigm is *System Dynamics* (SD). SD represents cause-effect relationships using causal loop or stock-flow diagrams (Figure 9). Wolstenholme (1990) states that *causal loop* qualitative system dynamics enhances linear and 'laundry list' thinking by introducing circular causality and providing a medium by which people can externalize mental models. Creating a mental map of problems or systems is very useful but the human brain has limited capacity to understand temporal and spatial characteristics such as feedbacks, time delays and nonlinearities. The next step in systems modelling, when the system has temporal characteristics, is developing a system dynamics model. System dynamics can be used in various fields such as strategy (Lyneis, 1999; Sterman, 2000), forecasting (Lyneis, 2000), project management (Lyneis, 2001), R&D management (Cloutier, 2001), product development (Ford, 1998), insurance management (Barlas, 2000), public policy, HIV epidemic modelling, modelling human behaviour, etc.

3. R&D Management Process

R&D management involves committing resources to product and process development efforts that have uncertain outcomes. Proper valuation of R&D projects is essential to decide on the appropriate level of investment at the various stages of the development. Before we discuss the R&D valuation tools and their visual attributes in detail, it is important to understand the underlying nature of the dimensions of the possible scenarios in which these tools are being used.

There are two key issues in managing a good R&D portfolio (Goffin, 2005): (1) valuation criteria, (2) portfolio balance criteria. It is desired that each individual project represents good value to the organisation, the portfolio is balanced to have a tolerable level of risk, and the portfolio of projects fit the strategic intents of the organisation.

R&D projects can be in single-stage, multi-stage or network types (Figure 2). The suitable tools to value and analyse both individual projects and the portfolio of projects can be different depending on the type of the projects. For instance, there is managerial flexibility in multi-stage and network projects, and one can use real options and decision-tree analysis in order to be able to take this flexibility into account for a more accurate valuation.

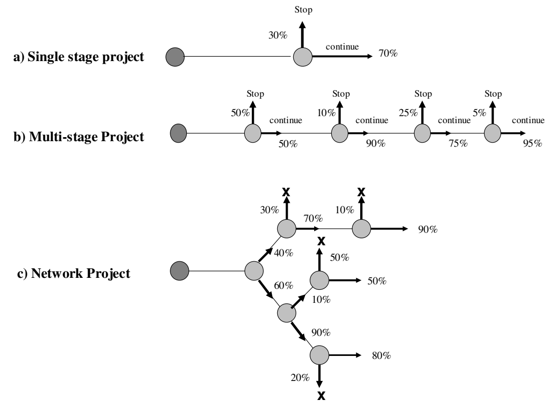


Figure 2 Types of R&D projects [Adapted from (Goffin, 2005)]

Szakonyi (1994;1994) developed a qualitative valuation framework which includes ten issues for successful R&D management:

1. Selecting R&D,
2. Planning and managing projects,
3. Generating new product ideas,
4. Maintaining process,
5. Motivating people,
6. Cross-functional teams,
7. R&D-marketing coordination,
8. Technology transfer,
9. R&D-finance coordination, and
10. Linking R&D to business planning

Three of the above issues: motivating people, R&D-marketing coordination and R&D-finance coordination require effective communication. The effectiveness of this communication depends on the means of communication. Visual representations and models play an important role in improving cognition and serve as aids to successful information sharing and transfer. However, the advantages of visual forms are not limited to communication only. For instance, soft systems methodology can be very useful in new product idea generation. Roadmaps can be used to link R&D to technologies, products and markets.

Many researchers have reviewed the one or more tools in R&D and technology management (Booker, 1985; Brady, 1997; Farrukh, 2005; Henriksen, 1999; Hunt, 2004). Building on these, we classify R&D project management tools and techniques in four main dimensions:

- Individual project valuation vs. portfolio management tools
- Valuation of projects of single-stage, multi-stage or network forms.
- Tools and techniques for planning, valuation, ranking (comparing) and decision-making.
- Qualitative vs. quantitative techniques.

For instance, individual project valuation could be quantitative (Heidenberger, 1999) using financial methods, or qualitative using scoring methods (Raynor, 2004). Likewise, portfolio management can be quantitative using portfolio optimisation methods (Stadje, 1993), or qualitative using portfolio matrices and scoring methods (Henriksen, 1999). Likewise, regardless of the type of the project (i.e. single-stage, multi-stage), both qualitative and quantitative methods could be employed. When we classify tools according to the objective for which they are used (i.e. planning, valuation, ranking, decision-making), we observe that quantitative tools are used more (in varying levels) in valuation, ranking and decision-making, whereas in the early *planning* stages mostly qualitative techniques are employed.

The word *valuation* is usually associated with techniques that are based on financial analysis and quantitative in nature. In practice, these techniques are primarily used to justify decisions and much less to actually shape the planning and judgement (Farrukh, 2005). The qualitative techniques on the other hand generally attempt to capture attributes which are not easily quantifiable but yet significant in order to determine the value of projects (Oral, 1991). Although useful throughout, the qualitative techniques are especially important in the early stages of planning where quantitative data is highly speculative.

Valuation techniques are intended to generate understanding of the value of projects, and enable those involved to make comparisons and decisions. As with all modelling efforts, there is a trade-off between accuracy and simplicity, thus an appropriate level of abstraction and detail in formulation is important. The next chapter will look at some of these tools which have visual attributes in further detail.

4. Visual representations and models in R&D Management Process

In this chapter, we will provide examples of visual representations and visual models which can aid planning, analysis, valuation, monitoring, controlling, and communication in the R&D management context.

Cognitive Mapping

Cognitive maps, influence diagrams, mind maps, rich pictures, logic trees, issue trees etc. have similar characteristics, and assist in improving attention, structuring information, inspiring thinking and creativity. These tools are especially useful in the conceptualisation and planning stages of R&D management An example on the use of influence diagrams to identify decision criteria in R&D portfolio management can be found in (Rzasa, 1990). In addition to their cognitive benefits, they are also useful in stirring discussion and bringing out creativity in a structured manner during brain storming and group problem-solving activities.

DCF

Discounted cash flow (DCF) analysis is central to the valuation of an asset when any part of its return is captured in the future, and can be found in all basic finance textbooks. The formulation can take different forms such as the net present value, return on investment, internal rate of return, payback period, and economic value added.

DCF techniques are easy-to-use, intuitive, widely applicable, credible and accepted (Hunt, 2004). However, myopic use of the technique can lead to poor decision making (Boer, 1998). Their accuracy can be poor if there are high levels of uncertainty (Hunt, 2004) and can be actively managed to reduce the impact of bad outcomes or boost the impact of good ones (Faulkner, 1996). Despite its limitations, DCF based methods are and will be part of investment valuation and decision-making. Although the accuracy of the calculations may be questionable, there are still potential benefits of visually representing cash flows using a cash-flow diagram. In Figure 3, the cash-flow diagram is combined with a product life-cycle diagram and an added initial section which shows the cash outflows during the R&D phases. This graph is useful to visually see the timing, value and relative size of the cash in-flow and out-flow throughout the life of a product, starting from the R&D which supports the technology in the development of the product.

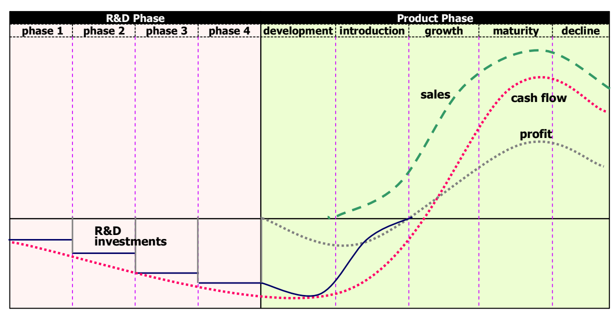


Figure 3 Cash flow diagram displaying R&D and product phases.

Real Options and Decision Trees

R&D project selection and investment process is often a multi-stage one. Real options valuation and decision tree analysis are two methods which are used to value staged investments. Real options valuation is the term usually used for mathematical evaluation techniques inspired by the modelling of options on the financial markets, and practitioners shy away from attempting to incorporate options valuations due to their complexity. However, the benefit of options thinking is indispensable in situations where managerial flexibility exists. In the recent years, scholars have drawn attention to real options and technology and R&D investment valuation problems (Angelis, 2000; Benninga, 2002; Faulkner, 1996; McGrath, 1997; Neely, 2001; Perdue, 1999; Perlitz, 1999).

Although capturing the value of managerial flexibility in a real options model is a black-box approach, the underlying premise is one of a staged decision process and this can be represented visually using decision trees (Loch, 2001;Neely, 2001;Rzasa, 1990;Sharpe, 1998). Decision trees are helpful to model managerial flexibility when sequential decisions are to be made, and are closely aligned with real options. Decision tree analysis classifies possible future outcomes and then ascribes probabilities to these outcomes. The optimal decisions can then be chosen to maximise the expected value of the return. Figure 4 shows a decision tree model of a new technology development decision process with various outcomes and decision points.

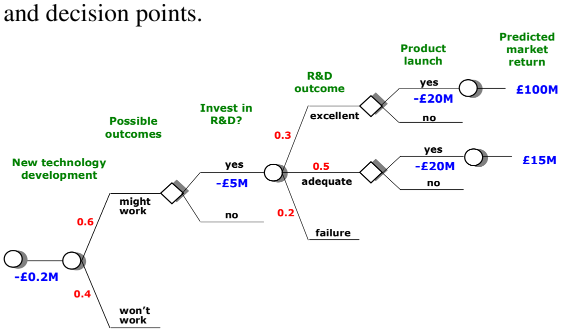


Figure 4 Example decision-tree analysis of new technology development.

Portfolio management methods

Portfolio management is a decision process where a business' list of active new products and R&D projects are constantly reviewed and updated. In an active portfolio management process, new product and R&D project ideas are evaluated, and existing ones are accelerated, killed or reprioritized. Selecting a portfolio is an optimisation problem in which the profitability is maximised while conforming to the constraints (resources, timing, risk level etc). Cooper *et al.* (2001) found that of all the possible ways of selecting projects, practicing managers had the least faith in quantitative (financial) projections. They also found that more successful companies tend to use a variety of methods, in which scoring systems and strategic considerations have an influence on, but do not entirely replace financial projections. Especially in the early stages, quantitative financial tools become infeasible due to data which is either non-existent or of dubious quality.

Many companies replace or supplement quantitative models with techniques that incorporate qualitative assessments. One such qualitative technique is the scoring methods. These techniques assess the R&D projects according to a range of criteria that are regarded as predictors of success by scoring the projects against these criteria. The criteria to assess new R&D projects can be generic or industry and company specific. Various tools can be used here such as spider graphs, column graphs, etc. Figure 5 shows four example graphs displaying relative performance of R&D projects scored against predictive criteria using a sector graph (Figure 5.a), a spider graph (Figure 5.b), and two column graphs (Figure 5.c&d). In Figure 5.d the relative importances of the criteria are equal and the performances in these criteria are proportional to the shaded areas. In Figures 5.a&c criteria have different weights. Here, the weights are proportional to the size of the slices and columns, and the scores are proportional to the shaded areas. These graphical representations provide visualisation support, but to be able to rank or choose between the projects based on these scores, relative weights of the criteria should be determined and a weighted-average of the score should be calculated to end up with a single number to make a judgement between the projects. In principle, Figures 5.a&c are more suitable to support a weighted-average decision-making process visually.

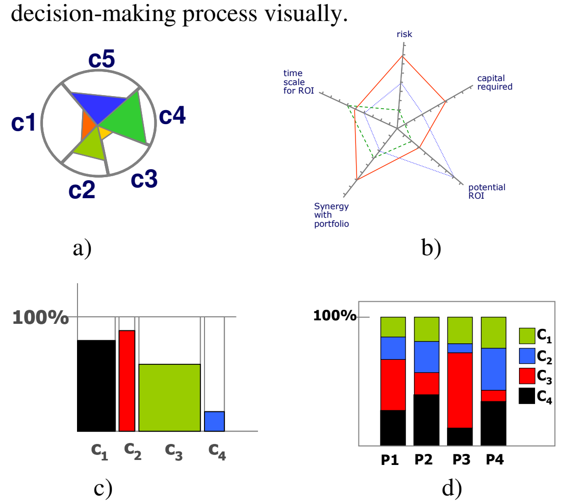
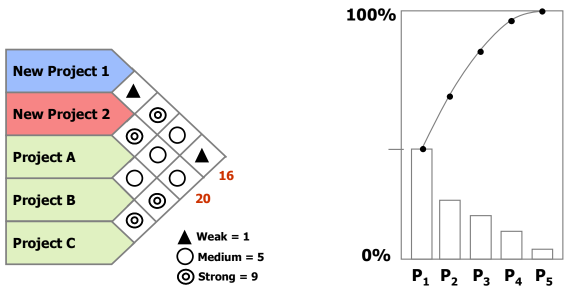


Figure 5 Risk-return matrix of R&D project portfolio with various different representations.

The R&D portfolio should reflect the company's general strategic intent ensuring that sufficient resources are allocated to potentially valuable technologies. One can also choose a more strategic angle when managing portfolio (Danila, 1989; Liberatore, 1988a). Here, the potential synergy between projects for instance becomes a significant factor in making portfolio management decisions. To make comparison depending on the potential synergy of new projects with the current portfolio and to assist this approach visually, a bidirectional table may be used. Figure 6.a shows two new R&D projects being evaluated according to the level of potential synergy they have with the existing projects in the portfolio. Furthermore, relative contributions of projects in the portfolio according to various attributes (e.g. risk, return) can be visualized using a Pareto graph (Figure 6.b).



a) b)

Figure 6 a) Portfolio synergy b) Portfolio contributions

A portfolio matrix (Figure 7) is an effective way to display projects according to one or more of their relative attributes. Cooper *et al.* (1998) list several examples of portfolio matrices such as:

- Risk vs. reward (NPV, IRR, etc.)
- Technical newness vs. market newness.
- Technical feasibility vs. market attractiveness.
- Competitive position vs. market attractiveness.
- Cost to implement vs. time to impact.
- Strategic focus or fit vs. business intent, NPV, financial fit, etc.
- Cumulative rewards vs. cumulative development costs.

In Figure 7, a range of different graphical representations are incorporated to the risk-return matrix. Some of these representations are mentioned previously. Most of these forms display static information. In addition to the current risk-return level of projects, the directional arrows shown in bottom-left box can demonstrate a change in the relative risk-return levels in time. This directional representation can be useful to monitor the evolution in the portfolio when unfolding information reveals changes in the risk-return attributes of projects.

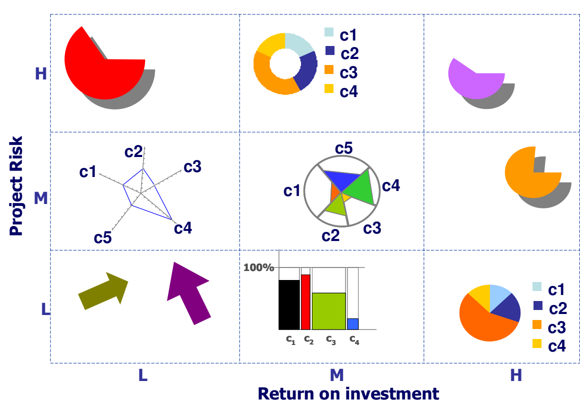


Figure 7 Risk-return matrix of R&D project portfolio with various elements to represent projects.

In all representation types demonstrated in Figure 7, addition variables can be tied to the size and colour of the graph elements. However, the graph elements used in Figure 7 are not comprehensive. There are other similar graphs which can be used in the creation of a portfolio matrix. As with all representations, finding the appropriate level of information to encapsulate in a single chart is essential for clarity.

Value Roadmapping

Value roadmaps are a way to explore and improve the value of technology projects at a very early stage (Hunt, 2004). As well as supporting communication within the project team, roadmaps can be post-processed to emphasize key messages and can then be used as a tool for communication with senior management. Roadmaps are typically used to collect and digest qualitative information and stretch over multiple years. They are particularly suited to ensure that the longer-term orientation of the business is adequately served by the selected projects by linking market opportunities to product and technology development.

The *value roadmap* (VRM) approach is based on technology roadmapping (TRM) concept which was originally developed by Motorola in the late 1970s to support integrated product-technology strategic planning (Willyard, 1987) using a simple graphical representation. The road-mapping approach has subsequently been adopted (and adapted) widely in industry, both at the company and sector levels, to support a variety of strategic goals (Kappel, 2001;Kostoff, 2001). Currently, roadmaps take a variety of forms, although perhaps the most generic and flexible is based on a time-based multi-layered architecture (Phaal, 2001).

VRMs provide a framework for supporting R&D evaluation and valuation (to explore, communicate, calculate, maximise and manage value). The approach can be used (supported by a workshop) at the early stages of an R&D project to explore the value proposition, and to improve decision-making. In principle, the approach can also be used to support the business case for R&D investments.

The VRM concept is based on the premise that, although it may not be possible to predict the value of projects precisely, the ‘richer’ the picture, the more likely it is that value will be created. The VRM does not prescribe decisions or outcomes, yet it can be used to fuel the imagination and shape the judgment of the decision maker with the aim of increasing the quality of their assumptions. An example VRM is displayed in the Figure 8. Here, the time axis is divided into five phases: (1) past, (2) short-term, (3) medium-term, (4) long-term, and (5) vision. The VRM includes three four layers. The top layer shows the market trends and business drivers. Value streams layer shows the sources of future revenues and savings. Enablers and barriers layer shows the technical and non-technical challenges and risks. And finally, the R&T programmes layer shows the technology capabilities that result from R&T investments.

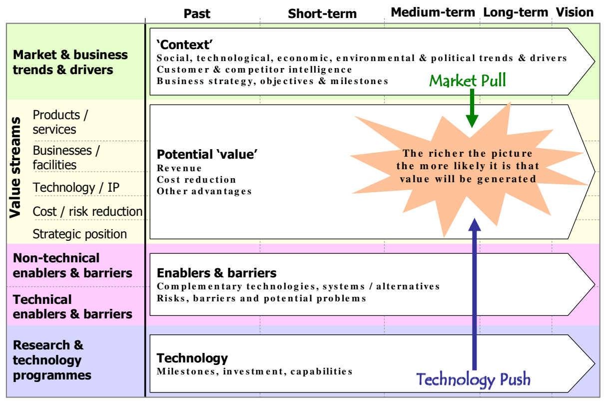


Figure 8 Roadmap showing the relationship between the R&D projects, technology, products and markets.

System dynamics modelling

Using system dynamics to model R&D management practices, it is possible to explore tradeoffs in strategic decisions, conduct scenario analysis, and display patterns of value capture through time, taking delays into consideration (Cloutier, 2001; Jan, 2000; Maier, 1998). In Figure 8, an organisation's R&D project portfolio and its related variables are modelled using a stock and flow diagram.

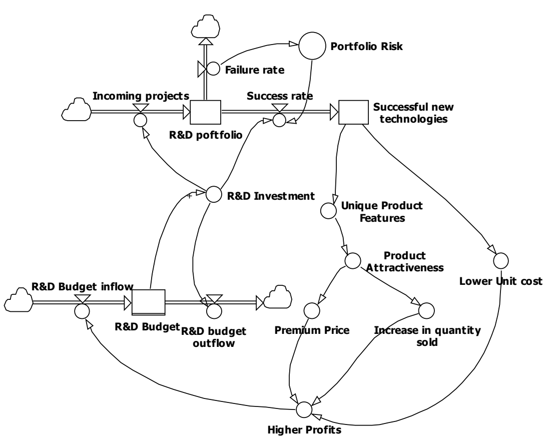


Figure 9 Stock and Flow Diagram Model of an R&D Portfolio

The stocks (levels) contain quantities describing the state of the system; such as the value invested in *R&D portfolio, R&D budget*, etc. Flows (rates) control the inflow and outflow to and from these stocks. In the above example, *success rate* and *failure rate* are flows that control the level of investment in *R&D portfolio*. Conducting a simulation analysis using such a model requires knowledge of the relationships between its elements. The functional relationships are usually established using historical data. Once the model is validated on the historical data, scenario analysis or robustness analysis using simulation becomes possible. Even though exact functional relationships between variables may not be found, building a visual causal-loop or a stock and flow diagram helps understanding the system under investigation, in this case the R&D management process of an organisation.

This model could be further expanded to incorporate more details. Although the stock and flow diagram in Figure 8 models a portfolio management practice, models which are intended to simulate individual projects can also be developed.

Finally, a collection of visual representation and modelling tools which are displayed and evaluated according to the following criteria can be found in the Appendix.

- Single-stage vs. multi-stage investment
- Portfolio vs. individual valuation
- Qualitative vs. quantitative
- Static or dynamic characteristics
- Analysis and planning
- Valuing
- Ranking and comparing
- Decision making
- Monitoring and controlling
- Communicating

Although not comprehensive, the collection provides and overview of some of the visual representation and modelling tools which would be helpful in the R&D management process. Practitioners can especially benefit from the above criteria used in the evaluation in their efforts to pick appropriate tools.

5. Conclusion

Successful valuation of individual R&D projects and managing a R&D portfolio is key advantage for technology firms. The R&D management process requires a high level of collaboration and communication between different departments and key stakeholders in organisations. This paper explored the potential of visualisation and visual modelling to analysis, planning, valuation, decision-making, monitoring and communication processes in the context of R&D management, and evaluated a selection of these tools according a wide range of criteria.

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Appendix – Evaluation of visual tools and techniques.

	Portfolio (P) or Individual (I) valuation?	Qualitative (Ql) or Quantitative (Qt)?	Multi-stage (M) or Single-stage (S)?	Static or Dynamic (S,D)	Analyzing and Planning	Valuing	Ranking and Comparing	Decision Making	Monitoring and Controlling	Communicating
Decision Trees	I	Qt	M	S	●	●	◇	●	□	●
Portfolio Matrices	I/P	Qt/Ql	M	S	●	◇	●	●	●	●
Roadmap Diagrams	P	Ql	M	D	●	◇	◇	●	□	●
Breakeven Analysis Diagrams	I	Qt	S	S	◇	◇	◇	●	◇	□
Product Lifecycle Diagrams	I	Ql	M	S	●	□	□	◇	◇	●
Cash Flow Diagram	I/P	Qt/Ql	M	D	●	●	◇	●	□	●
Conceptual Maps/Diagrams	I/P	Ql	S/M	S	●	◇	◇	□	◇	●
Rich Pictures Storytelling Diag.	I/P	Qt	S/M	S	●	◇	◇	□	◇	●
Tornado Graphs	I/P	Qt	-	S	◇	◇	●	□	●	□
Change Graph	I/P	Qt	M	D	◇	◇	□	◇	●	●
Histograms	I/P	Qt	-	S	◇	◇	□	◇	□	□
Circular Graphs	I/P	Qt/Ql	-	S	◇	□	●	◇	◇	□
Mosaic Graph	I/P	Qt/Ql	-	S	□	◇	●	◇	●	●
Bar Graphs	I/P	Qt	-	S/D	◇	◇	●	◇	●	●
Quantile Graph	P	Qt	-	S	◇	◇	●	◇	●	●
Time Series Graph	I/P	Qt	M	D	◇	□	□	◇	●	●
Difference Graph	P	Qt/Ql	S/M	D	◇	◇	●	◇	●	●
Regression Graphs	I/P	Qt	S/M	S/D	◇	◇	□	◇	●	●
Percentile Graphs	I/P	Qt	-	S	◇	◇	□	◇	●	●
Probability Distribution Graphs	I/P	Qt	-	S	◇	●	◇	◇	◇	●
Cumulative Frequency Graphs	I/P	Qt	-	S	◇	●	◇	◇	◇	●
Area Graphs	I/P	Qt/Ql	-	S	◇	◇	□	◇	□	●
Column Graphs	I/P	Qt	S/M	S/D	◇	◇	□	◇	●	●
Triangular Graphs	I/P	Qt/Ql	S/M	S	◇	□	●	◇	□	●
Line Graphs	I/P	Qt/Ql	S/M	S/D	◇	◇	□	◇	●	●
Sector Graphs	I/P	Qt/Ql	-	S	◇	□	●	◇	□	●
Point Graphs	I/P	Qt/Ql	S/M	S/D	◇	◇	◇	◇	●	□
Control Charts	I/P	Qt	S/M	D	◇	◇	◇	◇	●	□
Gantt Charts	P	Ql	M	D	●	◇	◇	□	●	●
Time And Activity Charts	P	Ql	M	D	●	◇	◇	□	●	●
Timeline Charts	P	Ql	M	D	●	◇	◇	◇	◇	●
Vector Charts	I/P	Qt/Ql	M	D	◇	□	□	◇	◇	□
Activity Flowcharts	P	Ql	M	D	●	◇	◇	□	●	●
Pie Charts	I/P	Qt/Ql	-	S	◇	□	□	◇	◇	●
Run Charts	I/P	Qt/Ql	M	D	◇	□	□	◇	●	●
Spider/Radar Chart	I/P	Qt/Ql	-	S	◇	□	●	◇	◇	●
Pareto Charts	P	Qt/Ql	S/M	S	◇	◇	●	◇	●	●

● Strong **□ Medium** **◇ Weak**