Disciplines of innovation in engineering design

Marian Petre

Innovation happens deliberately more often than it does by inspiration. This paper describes disciplines applied by effective multi-disciplinary engineering firms in nurturing innovation in order to produce intellectual property in a variety of domains, from telecommunications to medical instruments. The report arises from a series of *in situ* observations and interviews in 12 engineering consultancies in the UK and US over 2 years. It describes strategies that expert designers use to 'get out of the box' of familiar thinking, to identify gaps in existing products, and to go beyond 'satisficing'. It describes the supportive engineering culture in which these strategies are embedded. Finally, it identifies the characteristics which distinguish the highest-performing teams.

Although the 'Eureka!' effect has its place in radical innovation in engineering, and many design engineers experience moments of inspiration during design, innovation is more often incremental than radical. This paper concerns a further observation that, in high-performing engineering teams and companies, innovation happens deliberately, and moreover that such teams have developed a number of systematic practices that support innovation and feed inspiration

This paper draws on a number of *in situ* observations and interviews over two years, of effective engineering consultancies whose business is the generation of intellectual property. The companies are viewed as effective because they are profitable, viable, and consistent. The observations were conducted as part of a larger project examining conceptual design in multi-disciplinary concurrent engineering, where the concern is reducing time-to-market, and the approach is to run different aspects and stages of the design process in parallel. Although the sample was opportunistic (because we observed companies that would give us access), the companies and projects were all multi-disciplinary, involving the cooperation of more than one discipline such as mechanical engineering, electrical or electronic engineering, software engineering, and industrial design.

Walker's (1993) summary of common characteristics among three pioneering consultancies provided a foretaste of what we might find:

- "They are small;
- They are multidisciplinary;
- They are well connected to local academic institutions;
- They work an intense round-the-clock regimen;
- They are led by visionary enthusiasts."

His analysis highlights factors that stimulate creativity in terms of "the soup" (creative people, small teams, the right mix of skills, the right environment), "the bowl" (a management structure that nurtures creativity), and "the place at the table" (the leadership and vision which provide motivation and focus).

All of the companies we studied introduced themselves as reflective practitioners (Schön 1983), who engaged in the examination and evaluation of their own work and working. This was no accident, as their reflective practice motivated their participation in our research. All expressed consciousness of their need to 'get out of the box' of familiar thinking. They all sought deliberately to identify opportunities or gaps in the marketplace, and they all sought to do more than 'satisfice' (Simon 1957), to get past the first, 'good enough' solution and instead generate a variety of alternatives for comparison. Hence all of the companies had adopted or evolved practices to help them nurture innovation and to meet these needs (as will be discussed in detail in section 3).

However, the nature of the teams and company culture affected how they interpreted those practices. We came to see that two inter-related phenomena – the way in which multi-disciplinarity was managed and used, and the extent of the companies' use of deliberate practices or 'disciplines' to support innovation – were distinguishing factors even among these effective consultancies, between the exceptional and less exceptional.

Innovation tends to emerge at the 'edges', at the boundaries between domains. "Much creativity consists of a new combination of existing ideas. Where the existing ideas are present in different people, it requires some kind of interaction to produce the combination." (Langrish 1985) Highly collaborative multi-disciplinary teams had an edge (as will be discussed in section 5), because they used the 'disciplines of innovation' to help them exploit inter-disciplinary communication, transfer, reasoning, and insights.

1. Context: empirical evidence

This work is based on empirical studies of 12 engineering companies conducted over 2 years in the engineers' own work environments. The studies, encompassing observation and interview, were conducted in the context of a research project examining communication between disciplines in concurrent engineering teams during conceptual design. Hence, particular attention was given to interactions, both formal and informal, and to representations, both documented and ephemeral.

The companies, in the UK and the US, were all small (up to 250 people), multi-disciplinary, engineering consultancies, or small autonomous subsidiaries of larger companies. All were in the business of generating intellectual-property (IP). All were effective in doing so, as evidenced by consistency of turnover, completed projects, and often design prizes. About half of them were exceptional. The projects covered a broad range of domains, including telecommunications, high-performance engines, medical instruments, computer-aided design and manufacturing (CAD/CAM), consumer electronics and white goods, retail delivery systems, high-tech sporting garments and equipment, and manufacturing equipment and processes.

The teams were themselves multi-disciplinary and small (usually 3-6 members, exceptionally up to 12 members). Many of their projects were relatively short-term (typically 1 to 18 months, with some extending to 3 years). Individuals were usually involved in more than one project at a time, where each project had a different team. In the exceptional companies, management remained directly involved in design, contributing to at least one project.

They tended to work in two modes:
- first-to-market, generating new ideas which they marketed to select clients, and
- designing solutions for customer-identified problems.

The two modes fed each other, so that new techniques and technologies were customised to address customer needs, and customer needs gave rise to new technologies that were often subsequently re-applied elsewhere.

2. Data collection

Visits to companies varied in duration and depth, depending on what access was permitted by the companies and by circumstance:
- one UK company: observations and interviews one to two days per week over a year, with access over time to a number of teams and projects;
- one UK company: observations and interviews at month to two-month intervals over a year, with access to a number of teams and projects;
- one US company: observations and interviews over a week, with access to several teams and projects;
- others: interviews and sometimes observations, one to three days, with access sometimes to one team and project, sometimes to more.

All visits were governed by confidentiality agreements with the individual companies, and the data collected depended on what rules the companies set. Data included:
- contemporaneous field notes;
- extensive copies of project documents, including ephemera;
- audio tapes of discussions, meetings, and interviews, when permitted;
- photographs of whiteboards and workspaces, when permitted.

Data was subjected to a variety of analyses, depending on its nature. For example, the assembled design sketches (numbering over 1000 sheets) were subjected to a corpus analysis by experts who categorised the sketches in terms of the representations used. One team, studied long-term, used Lotus Notes to mediate its communication, and the entire archive was analyzed to identify decision patterns (including patterns of closure, of re-visiting decisions, of rationale), to track any propagation (or failure of propagation) of decisions across the Lotus Notes discussion structure, and to identify roles adopted by different team members (e.g., initiator, summariser). Field notes fed an inductive analysis of communication and behaviour patterns. And so on. The practices reported here were drawn from a focused inductive analysis of all materials.

3. Disciplines of innovation

These companies don't just wait for inspiration to strike, and they don't just wait for customers to deliver problems to them. They actively seek opportunities for the sort of innovation that will produce IP that they can sell. What was interesting was that this search was not just an individual, *ad hoc* process, but was something deliberate and thoughtful, and that the companies developed methods for pushing their thinking and then propagated those methods across the company. We observed a number of disciplines, of deliberate practices, designed to support innovation. Most of them are ways to expand the search space, either by admitting more potential solutions, or by broadening the definition of the problem. Some are ways to change perspective, to alter the view of the problem or of what might constitute a solution. Some are ways to maintain the knowledge base. Some of these (such as patent searches) are routine and wide-spread practices even in much less innovative companies, but some (such as reasoning about 'essences') require exceptional information or expertise.

3.1. Systematic knowledge acquisition

Characteristic of all the observed companies is an *active* programme of searching external sources for information, in four broad categories:

i) *Patent searches*. Just about any company with an interest in intellectual property conducts patent searches on a regular basis. Most companies, including the consultancies studied during this project, 'farm out' these searches to a patent agent. These searches play a role in suggesting what's available by identifying new exploitable technologies – and what isn't available, because someone else got there first.

ii) *Technical literature reviews*. Individuals in the companies 'never stop reading', reviewing the technical literature within their disciplines and often beyond, and attending key conferences and exhibitions. These reviews keep up-to-date both their knowledge of the latest developments and their awareness of who the 'key players' are in the field. Seminal papers are often distributed to other colleagues. Often team members are deputed early in a new project to conduct a review oriented to the project or to specific aspects of it; the results of such a search are summarised and reported to the team.

iii) *Analysis of legislative requirements and regulatory standards*. Awareness of such requirements and standards satisfies more than legal obligations for conformance; sometimes grappling with the constraints they impose leads to reformulation and innovation; sometimes it simply improves performance by focusing efforts on what is realistic within the rules. (Vogel 1993)

iv) *Review of the competition*. At the start of a project, competing products – or related existing products – are analysed, with attention to technology, customer requirements, and market forces.

The key is that innovative engineers are 'hungry' for input and work actively to maintain and update their knowledge base.

Sonnenwald (1996) identifies the "environmental scanner" as a communication role that supports collaboration during design, with the purpose of providing team members with information about technologies, products, competitors, and customers "from outside the design situation". Sonnenwald notes that the "environmental scanner" is an *expert* role, requiring many years of experience. More than one team member of the teams studied tended to provide intelligence of this sort, a reflection of the expertise of the teams.

A further characteristic of the exceptional companies is routine investigation beyond domain boundaries; engineers actively explore ideas and technologies outside their own areas of expertise. This exploration is sometimes problem-oriented but sometimes open-ended. Often they find 'pointers' by consultation and discussion with colleagues in other domains; clearly this is facilitated in a multi-disciplinary environment.

3.2. Collection of 'loose possibilities'

Innovative engineers habitually collect problems observed in the use of existing technology, and interesting phenomena remarked in their reading or experience. Many simply maintain 'mental stores' of such possibilities, but some keep records such as 'ideas diaries'. Some groups amass (usually selective) collections of such possibilities.

3.3. Record keeping

Teams have a record-keeper, usually official but sometimes *de facto*, some one team member who keeps and organises a comprehensive collection of design documents of all sorts, meeting notes, informal notes of design rationale, photographs of whiteboards, search and research results, and so on. Sometimes this is a junior member of the team, sometimes the project leader, sometimes just whoever has a knack for it. At the end of a project, the collection is typically rationalised, put in order, and assembled into a summary record such as 'project book' which is put on file. Traditionally companies do this using paper documents and filing cabinets, but some companies do this using electronic documents and a database, and some use a hybrid system. These project logs are design histories distinct from the product documentation.

3.4. Reflection on completed projects

The observed teams, especially those in exceptional companies, take time for deliberate reflection at a variety of times and levels:

i) *Debriefing on recently-completed projects*. At the close of each project, the team discusses process and outcomes: what went well or less well, what they might do differently 'next time', what aspects of the design or the process might be re-applied, whether the project suggests any spin-off projects.

ii) *Review of potentially-relevant past projects*. At the start of a new project, the team considers whether any past projects might have relevance, either in suggesting solutions or excluding them. The review is usually based on memory (although it might include consultation beyond the team), even when good project records are available, and even when project records are computer-based and easily searchable.

iii) *Review on general themes*. Sometimes companies hold a session to reflect on experience with particular classes of problem (e.g., what do we know about physical distribution systems), often when trying to identify a new niche or to attract new clientele. When the company's experience with the class of problem spans a number of years, such reviews can lead to re-assessment of old solutions in terms of recent technological advances.

The pattern here is that completed projects are not forgotten, but have a continuing role in the company's thinking about innovation. And rather than tying companies to old solutions through repetition and re-use, the reflection tends to have the effect of moving the team or company into new thinking.

3.5. Systematic re-use or re-application of recent innovations

In these companies, the dust rarely settles on an innovation; IP exists to be exploited. Part of the reflection at the end of a project, and part of the general ethos of the companies, is to consider systematically what potential an innovation has in new contexts. This practice is enhanced greatly by genuine multi-disciplinarity, because effective collaboration between disciplines fosters inter-disciplinarity, the transfer across domain boundaries. For example, it facilitates transfer of technologies across typically unrelated fields (e.g., robotics applied to medical products) and transfer of techniques in a way that retains enough information about the original setting, assumptions, and constraints to make the transfer successful. Informed collaboration between disciplines promotes a crucial sensitivity in the translation between contexts and domains.

3.6. Identification of barriers

One line of reasoning started from 'what do we really want?' – instead of 'what's possible?' – and then considered 'what's in the way of us getting it?' Identifying barriers and seeking to remove them helped to identify previously unnoticed assumptions, to review the status of existing limitations on technologies, and sometimes to innovate.

3.7. Attention to conflicts

One of the places engineers look for insight is in the conflict zones, for example between technology and cost, between functional engineering and industrial design, between designer and customer interpretations of the problem. Cross (2001) echoes this: "…perhaps innovative design arises especially when there is a conflict to be resolved between the (designer's) high-level problem goals and (client's) criteria for an acceptable solution." Sometimes the analysis of such conflicts shifts thinking about the design and reveals potential for innovation; sometimes it re-aligns design imagination with real-world constraints.

3.8. Brainstorming

In the 1950's Alex Osborn (1953) advocated "brainstorming" as a group interaction technique that produces more and better ideas. In brainstorming, quantity rather than quality of ideas is emphasised, criticism is forbidden, wild ideas and "free-wheeling" are welcomed, and modification and combination and improvement of ideas is sought. The companies used both face-to-face and electronic brainstorming, typically inviting contributions from across the company. Brainstorming was always time-limited, for example 15 minutes face-to-face (one company held all its brainstorming sessions standing up) or 1 day via email. Ideas were filtered by one or two engineers using a variety of grouping and sifting strategies. Brainstorming was always only to the contributors' credit; discarded ideas were simply deleted, but promising ideas were retained with attribution. This interpretation of brainstorming contributed to a supportive culture: because only the favoured ideas were retained, it cost nothing to suggest an idea, and the time limitation actually increased the level of involvement.

3.9. Systematic exploration of possibilities: gap finding

Companies harnessed their information-gathering and reflective activities in systematic explorations to identify market gaps and development opportunities. Awareness of problems (3.2) and market trends (3.1), supported by awareness of new and old techniques/ technologies (3.1), allowed teams to explore potential combinations. Much of that exploration was systematic, with two main vectors:

- starting from a characterisation of problem types, seeking particular examples to solve, or
- starting from a characterisation of a particular problem, seeking novel solutions.

Companies had gathered or devised a variety of representations (often simple) to support this sort of exploration, e.g., graphs, matrices, multi-dimensional spaces, thumbnail juxtapositions, and tabular feature comparisons. Representations of solution spaces (of varying complexity) were typical. A simple example was a graph with technologies along one axis and problem interpretations along the other, where existing products were positioned in the space. Systematic exploration of the under-populated areas of the graph provided a way to question assumptions and notice advances. A number of researchers have portrayed the importance of external representations in design (e.g., Fish and Scrivener 1990, Schön 1988, Flor and Hutchins 1991, Scaife and Rogers 1996), both to support design reasoning and as a medium of communication among designers. This use of representations to depict a space of design possibilities (rather than a design solution) is a significant, enabling use of representation to assist the thinking 'out of the box'. It is one that requires considerable knowledge, since the discussions associated with this sort of exploration of solution spaces draw on understanding of technologies, particular implementations, technology costs, and histories of design rationale.

3.10. Scenarios and consequences

In problem-driven explorations, some companies use scenario-based reasoning to explore assumptions and consequences. Different scenarios demand different tactics, and hence shifting among well-chosen scenarios can have the effect of revealing consequences of design choices and sometimes of revealing opportunities.

3.11. Stripping down to fundamentals

Engineers deliberately set aside the ‘noise’ of different detailed and contextualised formulations of problems and strip the problem down to its fundamentals: what essential functionality must be addressed and how it might be achieved. This allowed them to explore the underlying problem in terms of fundamental principles, e.g., of mechanics, or electronics, or functional design. Cross (2001) describes this in his case studies, noting that "…all three designers either explicitly or implicitly rely upon ‘first principles’ in both the origination of their concepts and in the detailed development of those concepts." The observed practice of stripping down to fundamentals was an explicit activity, one that required expertise.

3.12. Considering ‘essences’

Another strategy for exploring the underlying problem was to identify one functional abstraction, to capture it as an ‘essence’, typically an analogy that embodied some insight about functionality. For example, to consider that ‘a shoe is a cushion’ might lead to innovations in sole design. Characteristic of this method is a certain ‘wackiness’ – often the ‘essence’ is a surprise to other members of the team. But this discipline highlights the importance of abstraction and simplification; these are expert abilities. Akin (1990) makes a complementary observation: "To summarize, creative designers formulate their problems in unusual ways, often arriving at solutions that are not only unusual but articulate aspect(s) of the problem which were not considered before. And often these realizations lead to generalizations which go beyond the immediate problem being solved, and revolutionize the way similar problems are approached from there on."

3.13. Systematic variation in constraints

Engineers talk about ‘throwing away’ constraints. They tend to employ this tactic when there is a design blockage (e.g., can’t make progress because there are irreconcilable constraints) or when the proposals are too staid (‘It’s all been done before’). By setting aside constraints – including unavoidable ones (‘throw away gravity’) – they open alternative avenues of exploration. This is one area where artificial intelligence techniques have had some impact; the application of genetic algorithms sometimes has the effect of 'throwing away' constraints that are taken for granted and hence providing fresh views on a problem.

Not all of the companies practiced all of these disciplines, but the exceptional companies practiced more of them, more systematically, than the less exceptional ones.

4. Relationship to expertise

It is striking how many of the disciplines require expertise, either in terms of breadth and depth of experience, or in terms of expert reasoning, such as the identification of deep structure in problems and solutions. There is a well-established literature on expertise (and on expert-novice differences) that recognises as characteristic of expertise both an extensive, accessible experience of examples and the abilities to recognise underlying principles and form abstractions. Studies consistently find the same features across domains (for a review, see Kaplan et al. 1986), among them that:

- Expert problem solvers differ from novices in both their breadth and organisation of knowledge; experts store information in larger chunks organised in terms of underlying abstractions.
- When categorising problems, experts sort in terms of underlying principles or abstract features (whereas novices tend to rely on surface features) (e.g., Chi et al. 1981, Weiser and Shertz 1983).
- Experts remember large numbers of examples – indeed, the literature suggests that experiencing large numbers of examples is a prerequisite to expertise (e.g., Chi et al. 1988). Experts' memories of previous examples include considerable episodic memory of single cases, particularly where these are striking. Implicit learning requires large numbers of instances with rapid feedback about which category the instance fits into (Seger 1994).
- Experts form detailed conceptual models incorporating abstract entities rather than concrete objects specific to the problem statement (Larkin 1983). Their models accommodate multiple levels and are rich enough to support mental simulations.

Akin (1990), addressing expertise in creativity, calls attention to three key behaviours: recognition of creative solutions (by using their discernment of chunks to move more effectively through the search space), problem (re) structuring in a way that facilitates creative discovery, and formulating heuristic procedures that translate passive knowledge into active exploration. The observed practices are resonant with these behaviours.

Jewkes et al. (1969) identify four key contributions which individual inventors bring to innovation:

1. the uncommitted mind, not constrained by existing thinking and practice
2. outlandish exploration of unorthodox ideas
3. the importance of skilled observation and relatively intuitive recognition of the significance of unexpected variations

4. the advantages of large numbers: "…that each new invention multiplies the possible combinations of existing ideas and thereby widens the scope for originality."

Although Jewkes and colleagues were focusing on individual inventors outside organisations (and indeed argued that working in a research organization tends to weaken individual creativity) the resonance between the first three criteria and the disciplines described above is striking. The fourth highlights the case for multi-disciplinary collaboration, because it brings together different ideas for combination.

5. Distinguishing characteristics of exceptional teams

Just as many of the disciplines require expertise, it is notable that many of the disciplines are more powerful in the context of a collaborative, multi-disciplinary team, where inter-disciplinary interaction amplifies creative potential by bringing into proximity different information sources, different methods and technologies, different representations, different perspectives, different fundamental principles, and so on. The demands of interaction across specialisms can nurture surprises and help engineers 'get out of the box' of familiar thinking, as well as helping them reflect on their own knowledge, reasoning, and processes.

Exceptional companies hire the best possible people and immerse them in a cooperative, communicative culture where exploration is supported. The supportive cultures in the exceptional companies shared key characteristics:

- The culture was 'heads up' – only the good ideas count, so it's safe to 'put one's head above the parapet (in contrast to 'heads down' cultures, where failures are remembered). 'Heads up' and 'heads down' map well onto Rothwell's (1992) 'organic' and 'mechanistic' organizations. There were no 'heads down' companies among those studied – but other 'heads down' companies hired some of these consultancies to train them in innovation.
- Recognition was given at all levels for good ideas: team, leader, individuals.
- Management was committed to and involved in innovation and reflective practice. In the exceptional companies, managers remained active in design projects. The less exceptional companies often had managers who had become divorced from the design process.
- The people who had the ideas were the ones who followed them through, contributing to a continuity throughout the design process and to an awareness of consequences.

Highly-collaborative multi-disciplinary teams were co-located or in close proximity whenever possible, facilitating immediacy and spontaneity of communication. This was reinforced by a management style that avoided formal meetings, favouring regular interaction and informal discussion, with the project leader ensuring that decisions were clearly communicated throughout the team. Exceptional teams always had someone in charge of two key coordination roles: keeping track of decision making and rationale, and record keeping. The collaborative multi-disciplinary teams included expert, 'multi-lingual' members who could communicate effectively with specialists from other domains. Sonnenwald (1996) similarly talks about "interdisciplinary stars", who interact to share knowledge across domain boundaries. Walker (1993) observes: "Connectivity arises naturally from the right number and right mix of people in close proximity." In less exceptional companies, although the companies were multi-disciplinary, members of a given domain (e.g., mechanical engineers, industrial designers) remained within their own departments.

Careful attention was given to knowledge dissemination. A balance was maintained between team cohesion and knowledge dissemination, so that effective teams remained largely intact from project to project, but there was some reassignment and re-distribution of expertise to keep knowledge flowing around the company. In most of the companies, engineers worked on more than one project – and hence more than one team. Exceptional teams take care over the deliberate induction of new members into local culture and practice, while eliciting fresh perspectives from them. Care is also taken over deliberate knowledge recovery from exiting members before they leave, although the collaborative, reflective culture tends to ensure that project and process knowledge is disseminated among personnel.

Exceptional companies were confident, but not complacent. They reflected on their practice at individual, team, and company levels. They maintained an openness to – and continual search for – new information and methods, supported by systematic information-gathering practices. They attended conferences, read widely, and interacted with academia.

This characterisation echoes and elaborates Walker's (1993) 'soup, bowl, and table' characterisation. It should be remarked how fragile this cooperative, communicative culture can be. It requires energetic, high-quality personnel, with high levels of expertise and creativity, capable of assimilating and evaluating high-quality information. It requires trust, sharing and open-minded communication. It requires careful management of resources, workload, practices, and team dynamics. It is a complex system of factors, easily perturbed by a dissonant element or by a lapse in momentum.

6. Conclusion

It seems almost contradictory that deliberate, systematic practices should foster inspiration and innovation. And yet that is just what was observed in a number of effective – sometimes exceptional – engineering firms and teams. This paper has presented 14 observed practices, covering knowledge gathering, exploring combinations and possibilities, expanding the search space, and changing perspective about the nature of the problem or about what might constitute a solution. It has discussed the reliance of many of these practices on expertise, particularly on expert skills such as evaluation, recognition of deep structure, and abstractions and reformulations of problems. It has discussed how these practices are amplified by a reflective, supportive culture and by highly collaborative multi-disciplinarity, facilitating inter-disciplinary communication, transfer, and insight. The observations give some account of why exceptional performance is rare, not just because of the requirements for high-quality input and creative expertise, but also because of the complex balance among contributing factors.

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