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Bridging the Gap between Science & Technology Studies and R&D Programme Management

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Issue: R&D programme managers often do not have a way to systematically apply the "lessons-learned' from science and technology studies (STS) in their day-to-day activities. Since risk analysis has become a standard decision-making tool to evaluate cost and schedule uncertainty, STS insights can be modelled within that framework to help programme managers mitigate "strategic surprise" in non-traditional areas such as social acceptance of science and technology.

Relevance: The insights developed through Science and Technology Studies (STS) can be used as a decision-making tool for programme managers involved in the evaluation of new developments and in allocating R&D investment. The development of a subjective "risk-rating" assessment can be a means of evaluating cultural and social factors of scientific and technological systems, as a part of the overall set of decision aids available to programme managers to estimate uncertainty in programme costs and schedule. This interface between historical insights from STS and the priorities/discourse of R&D programme managers can enrich the basis of R&D policymaking.

Introduction: speaking the language of R&D managers

When C.P. Snow wrote about the breakdown in communications between the "two cultures", he was referring to science and the humanities. Today, that breakdown is arguably between the Research and Development (R&D) culture on one hand, and the Science and Technology Studies (STS) culture on the other. The people who work in and manage R&D on a day-to-day basis usually know little of the broad body of knowledge devoted to the study of the history and sociology of their profession. R&D programme managers, even when versed in STS, do not have a way to systematically apply "lessons-learned' in their day-to-day activities, specifically to estimate programme costs and schedules.

There is today something of a breakdown in communications between Research and Development (R&D) and Science and Technology Studies (STS), leaving R&D programme managers unable to apply the lessons of STS to their work

One of the principal reasons for this divide is that the language of STS has become unrecognizable to the scientists and technologists who could most benefit from the insights gained from these studies. In order to make STS knowledge relevant to R&D programme managers, it must be presented in a language that they can understand and use. STS researchers must think of R&D managers as their customers, and tailor both their language and their product – the insights from their research — to those managers. The aim of this article is to outline the process that R&D managers use to make day-to-day decisions on investment strategy, and to propose a framework for incorporating STS insights to inform that process, in a language that is familiar to these managers. That language is "risk". By framing STS concepts in terms of risk, R&D managers are more likely to incorporate them into their decision-making.

To overcome this divide, STS knowledge has to be made relevant to R&D programme managers by presenting it in a language that they can understand and use. The concept of "risk" offers just such a language

To demonstrate this risk-based approach I will use the case study of the electric ship. The purpose is not so much to analyse which theories are applicable to particular science or technology R&D, but rather to show how they may be incorporated into the development framework as perceived by R&D managers.

The linear process described here looks at decision-making from the R&D manager's point of view. This narrow focus is intentional. Although numerous studies have indicated that the precepts of Constructive Technology Assessment (CTA) can successfully incorporate a broad range of social considerations by expanding the involvement of societal actors into the design and R&D process (Schot, 1998), managers are often reluctant to add layers of review and input to their programmes that they may not be able to control. From the manager's point of view, a broad CTA approach may not be desirable because

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of the difficulty of integrating the process (which tends to be iterative and interactive rather than linear) into a planning document that can be used to estimate programme costs and schedules. The risk-based approach outlined has the value to the R&D manager of being more constrained in the extent of effort and number of participants, and rather more "straight-line" in its formulation, therefore more readily integrated into the linear decision-making process to which he or she is accustomed. At the same time, this approach may be employed as a precursor to a more general CTA programme, in that it can use the expert analysis that is specific to a risk-based analysis to refine the range of social groups that the R&D manager may call upon to provide further input.

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How do R&D managers evaluate new developments? The electric ship as a case study

The first phase of the two-phase process in evaluating R&D requirements for a new ship (Christian and Hacker, 1998; Tavener and Clayton, 2000) is to conduct a top-down analysis of requirements to help the ship programme manager decide on an overall investment strategy that will maximize the mission capability of the ship. A series of top-tier mission capabilities is defined by a team of experts according to operational objectives, and ranked using a pairwise comparison to develop a hierarchy of relative mission priorities for the ship (in this case, an aircraft carrier), totalling 1.0:

- Firepower 0.280
- Control 0.184
- Manoeuvre 0.158
- Support 0.148
- Survivability 0.142
- Intelligence 0.072

The first phase of the two-phase process in evaluating R&D requirements is to conduct a top-down analysis of requirements

The next step is to develop a series of lower-level attributes that can be correlated against the six mission capabilities, weighting the contribution of each attribute to each of the mission capabilities by the relative importance of the capability. This results in a priority list of attributes (Figure 1).

Figure 1. Priority list of attributes for aircraft carrier

No. Ship Attribute	Priority	No. Ship Attribute	Priority
1 Reliability	0.8370	20 Aircraft Suitability	0.4777
2 External Communications	0.8254	21 Aircraft Maint/Material Spt	0.4724
3 Internal Communications	0.7926	22 Endurance	0.4695
4 All Weather/Night Capability	0.7623	23 Logistics Support Footprint	0.4420
5 Data Management	0.7369	24 Seakeeping	0.4384
6 Mission Planning	0.6999	25 Shallow/Littoral Ops	0.4355
7 Lauch and Recovery	0.6397	26 UNREP	0.4328
8 Sensing	0.6299	27 Hardening & Protection	0.4139
9 Degraded Operations	0.6245	28 Agility	0.3736
10 Aircraft Turnaround	0.6054	29 Range	0.3655
11 Wpns & CM Employment	0.5631	30 Speed	0.3635
12 Ctl / Restore Damage	0.5593	31 Material Distribution	0.3392
13 System Commonality	0.5446	32 Training Implementation	0.3193
14 Maintainability	0.5372	33 Habitability	0.2545
15 Battle Group Support	0.5326	34 Space Flexibility	0.2393
16 Redundancy	0.5101	35 Accessibility	0.2167
17 Upgradeability	0.4919	36 Deployment Availability	0.0822
18 Signature Management	0.4818	37 Environmental Compliance	0.0557
19 Wpns Handling & Storage	0.4804		

The next step is to develop a series of lower-level attributes that can be correlated against the required capabilities and then, finally, to establish the relative impact of various technology areas on the list of attributes

The final step in the top-down process is to establish the relative impact of various technology areas on the list of attributes above, again weighting the contribution of each technology area to each attribute by the relative importance of the attribute. This results in a ranked list of technology areas (Figure 2). As can be seen, the electric ship technology area had a relatively high impact on mission capability. In this context, “electric ship” refers to an integrated power system used to supply propulsion, auxiliary systems and mission systems.

Figure 2. Ranked list of technology areas

No. Technology	Impact	No. Technology	Impact
1 Human Systems	0.442	15 Maintenance Concepts	0.221
2 Information Integration	0.374	16 Auxiliary Machinery	0.209
3 Electric ship	0.371	17 Elevator Improvements	0.195
4 Common Computations	0.355	18 Ship Self-Defence Air	0.189
5 Multi-Function Sensors	0.333	19 Nuclear Power Gen	0.171
6 Design Mod & Sim	0.319	20 Armor Concepts	0.155
7 Own Ship Awareness	0.313	21 Ship Self-Def - UW	0.135
8 A/C Servicing	0.283	22 Propulsion Power Gen	0.133
9 Weapons Throughput	0.280	23 Launch	0.132
10 Flight Deck	0.257	24 Production	0.119
11 Integrated topside	0.242	25 Quality of Life	0.115
12 Damage/CBR Response	0.240	26 Arresting Systems	0.102
13 Material Handling	0.237	27 Waste Disposal	0.067
14 Air Traffic Control	0.227		

The second phase of the process is to conduct a bottom-up analysis of the investment needed for each technology area

The second phase of the process is to conduct a bottom-up analysis of the investment needed for each technology area. For the electric ship, this consists of assessing the various electric ship technologies (permanent magnet motors, high-temperature superconductors, etc.) that can be used achieve the overall goal of having an integrated power system. A product model is used to evaluate the technologies from a total-systems standpoint (Figure 3). In general, this evaluation is done against a known baseline, e.g. a ship with conventional propulsion and electric distribution. For each technology or set of technologies, a new total-ship design is developed to compare against the baseline ship. The effects of the new technology, including mission capability, survivability, signatures, life-cycle cost, etc. is evaluated by comparing the new ship with new technologies against the baseline ship. The output of this phase of the process is a comparison of the cost (both in capital outlay and development schedule) versus relative operational effectiveness for each technology.

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The third and final phase of the overall investment strategy process is to rank each technology by its cost-benefit, and to apply the technology impact from Figure 2, to determine the ranking and valuation for R&D investment in each technology.

For an R&D programme manager, "risk" is typically translated into subjectively evaluating the likelihood that a technology will be available for the programme, and the consequences if it is — or is not— available

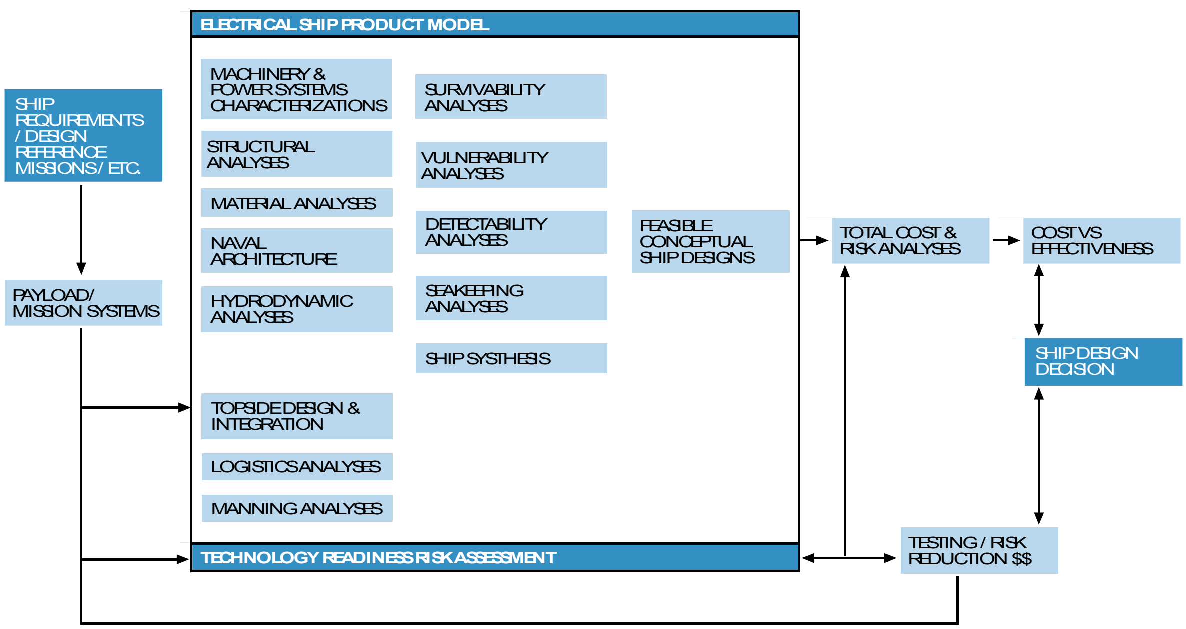
Risk management as part of the product model

In the past thirty years, risk management has matured from a relatively simple assessment of probability, to a broader view that incorporates both probabilities and consequences. For an R&D programme manager, "risk" helps define the uncertainty in the programme cost and schedule, and is typically translated into subjectively evaluating the likelihood that a technology will be available for the programme, and the consequences if it is — or is not — available. Technology Readiness Levels, originally developed by NASA, are generally used to characterize the state of development, on a scale of 1 to 9; Level 1 signifying that basic phenomena have been reported, and Level 9 showing that the technology has been applied in its final form and under mission conditions (DoD Deskbook, 2001). Similar numerical scales for consequence are also used (e.g., 1 = not critical, 9 = critical). In Figure 3, at the bottom of the product model is a "Technology Readiness Risk Assessment" which is used to quantify:

- Level of readiness of technology
- R&D cost required to bring the technology to required level of maturity
- Importance of the technology to the mission

This results in a risk management plan and assessment of the cost required to "de-risk" the technology. This approach is well-understood by R&D managers, and should be the model used to incorporate STS as a means of informing the technology decision-making process

Figure 3. Total system product model for evaluating technologies



This results in a risk management plan and assessment of the cost required to "de-risk" the technology, e.g. using a land-based test site or performing at-sea testing, and a characterization of its mission impact. These are fed into the overall evaluation of cost versus relative operational effectiveness for the technology.

This risk-management model of defining likelihood, consequence and "de-risking" contingencies, is well-understood by R&D managers, and should be the model used to incorporate STS as a means of informing the technology decision-making process.

Cultural and social factors of technological systems

How can STS insights be formulated in terms of risk? The approach would be defined by STS researchers on a case-by-case basis, but in order to provide a notion of how a risk-rating system for STS factors could be applied within the R&D evaluation process, I will use three approaches derived from STS research — normal accidents, technological momentum and symbolic meanings — to develop the outlines of a possible risk-rating scheme.

The normal accidents theory argues that an engineering approach to ensuring safety – that is, by adding safety systems and increasing redundancy — fails because systems complexity makes failures inevitable

- *Normal accidents* (Perrow, 1999): This theory argues that an engineering approach to ensuring safety – that is, by adding safety systems and increasing redundancy — fails because systems complexity makes failures inevitable. Rather than protecting the system, safety precautions may lead to new types of accidents. The theory examines two factors in determining risk:
- Coupling
  - Tight (direct and immediate interaction between components)
  - Loose (buffering of interactions between components)
- Interactions
  - Linear (orderly, step by step, easy isolation of components)
  - Complex (many connections and interrelationships)

Risk increases as the system becomes more tightly coupled and the interactions become more complex.

The technological momentum theory argues that the amount of capital invested in a system has a direct effect on the continued reliance on the system

- *Technological momentum* (Hughes, 1994): This theory argues that the amount of capital invested in a system has a direct effect on the continued reliance on the system. At the beginning of system development, when investment is generally small, social factors play a larger role in technology development and it is relatively adaptable to change. As the technology evolves and supporting infrastructure (skills, specialized institutions, networks, etc.) grows, the technology itself becomes a driving force and change is harder.

The symbolic meanings theory explains how the cultural significance attached to a technology can influence its development

- *Symbolic meanings* (Schatzberg, 1999): This theory explains how the cultural significance attached to a technology can influence its development. In the case of the transition from wood to metal in aeroplanes, the contrast in the symbolic meaning of metal (technological progress) with wood (pre-industrial craft traditions) was a major factor in the support for research into metal structures, even though there was no demonstrable advantage over wood at the time.

Incorporating STS risk-rating inthe electric ship product model

An STS risk-management model for a technology will also consist of subjectively evaluating likelihood and consequence (preferably on a numerical scale) for the development programme and establishing de-risking options. This evaluation would be done using the expert opinion of STS researchers, who could reasonably compare the development of the technology at hand with recent or past examples, and select specific STS factors that would be applicable to the programme. The overall STS risk rating would be made up of multiple factors, and each factor would likely have several component parts. The STS risk-rating and de-risking schemes would be used to inform the technology selection process (see Box 1).

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Box 1. Evaluating an electric ship

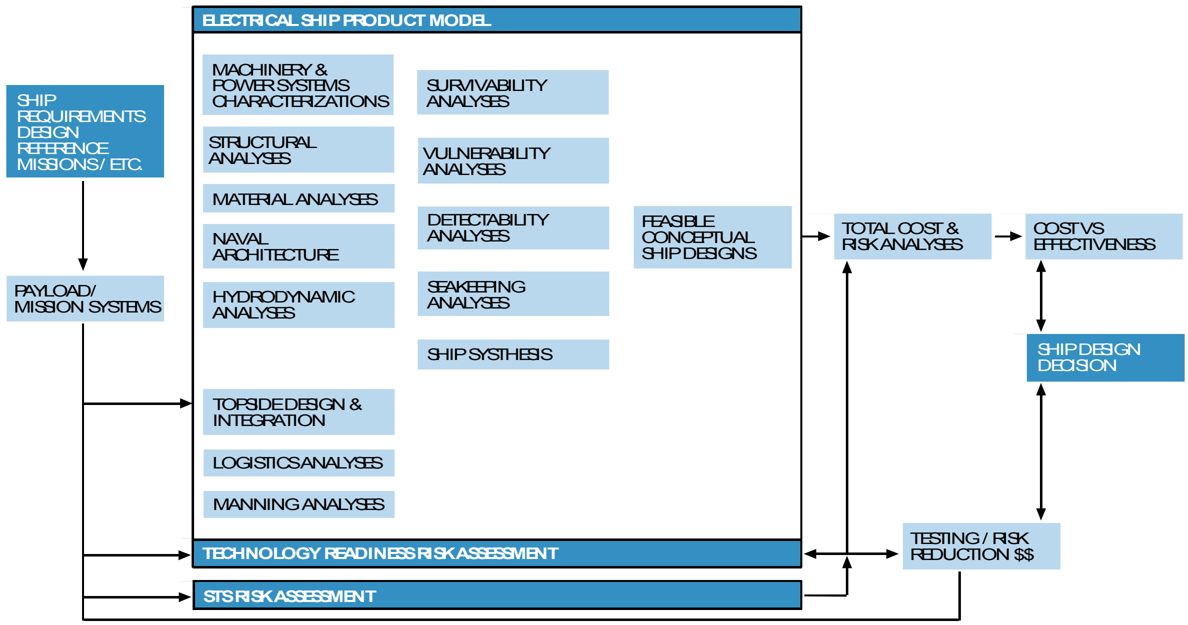
In this example, we will assume a new motor type is being evaluated for the electric ship. The three STS factors cited in the text could be evaluated as follows:

- *Normal accidents:*
    - Likelihood: Are contingencies accounted for with multiple safety systems or intrinsic in the design? What is the level of interaction of the motor with other systems, on the continuum of loosely -coupled / linear (risk level = 1) to closely-coupled / complex (risk level = 9)?
    - Consequence: What is the impact on other systems to changes in the motor development?
    - De-risking: Can the interaction between the motor and other systems be made more loosely-coupled and linear? How much would it cost?
- *Technological momentum:*
    - Likelihood: Are there other competing motor types? What is their state of development? Is their "momentum" greater, which could lead to higher costs for this motor (risk level = 1 for a new type, = 9 for a saturated field)? Conversely, is there another utility for this motor that could be used to gain momentum?
    - Consequence: What would the additional infrastructure cost be (specialized training, unique repair parts) if other motors are used more widely?
    - De-risking: Can the programme wait to see if other motor types gain momentum? Are there other programmes that can use this motor?
- *Symbolic meanings:*
    - Likelihood: Is there a "gee-whiz" factor in the proposed motor technology, especially in the popular scientific press (risk level 1 = little press coverage, risk level 9 = major press coverage)?
    - Consequence: What are the reverse salients (components of the system that have lagged behind in development) that may be glossed over by R&D managers?
    - De-risking: Ensure that the specific rationale for the motor technology is clearly laid out.

Certainly, not all the factors will be equally critical, and these would have to be subjectively weighted to provide an overall STS risk-rating. In many cases, these factors are already considered indirectly by R&D managers; the advantage of an STS risk-rating scheme is that it provides a systematic framework to improve our understanding of these factors in the decision-making process. This proposed process is shown in Figure 4; STS risk factors are analysed in parallel with technology readiness to evaluate the uncertainty on programme cost and schedule.

Although the example given here is used within the second (bottom-up) phase of individual technology assessment, a similar analysis of STS factors could be incorporated as part of the first (top-down) phase of assessing the impact of technology areas on mission capabilities.

Figure 4. Total system product model with STS risk assessment



Limitations to the process

The most obvious limitation to this risk-based approach is that, compared with the CTA approach, the breadth of input into the decision process is greatly reduced because it depends on expert opinion rather than a wide range of societal actors. The second limitation is that the process is very linear and not inherently iterative and interactive between managers, policy-makers and users, as the CTA approach tends to be; thus the capacity of the risk-based approach to substantially alter the dynamic of an R&D programme is smaller.

The most obvious limitation to this risk-based approach is that, compared with the CTA approach, the breadth of input into the decision process is greatly reduced, although this may make it more attractive as it is easier to integrate into the linear decision-making process

Yet as described in the introduction, these very limitations may make a risk-based approach more attractive to an R&D manager than the full-blown CTA programme, in that a straight-line method of developing STS risk ratings, may be easier to integrate into the linear decision-making process to which he or she is accustomed. In this model, the expert opinions offered by STS researchers act as a substitute for a greater diversity of societal actors. For R&D programmes where such social input is relatively small (the electric ship being a case in point, as it is aimed at developing a military, not consumer, product), such an approach may be sufficient.

But for other R&D programmes that will impact a wider range of users and policy-makers, and where the broader approach offered by CTA is called for, the risk-based methodology may be employed as a precursor to refine the range of social groups that the R&D manager may call upon to provide further input (see Box 2).

Box 2. Risk-based methodologies in the electric ship example

Some examples of the use of risk-based methodologies in the electric ship example could include:

- Ferry lifeboats: A "normal-accident" assessment of ferry evacuation may reveal that more hazards are posed by boarding lifeboats than by the initiating accidents, because the margins for error are small in boarding and deploying lifeboats. An expert-panel risk assessment could be employed during the design phase of the ferry, to consider alternative safety measures that may allow for looser coupling of systems that permit greater tolerance of errors. These alternative measures could then be evaluated by a larger set of actors (e.g., passengers, coast guard, etc.) for integration into the ferry safety system.
- Automotive fuel cells: A close analysis of the technological momentum of the petroleum fuel + internal combustion engine model could reveal higher-risk social factors that may inhibit wide-spread adoption of the technology; e.g. limited acceptance by "fix-it-yourself" truck industry drivers who form a large percentage of the potential market. A further CTA programme could then be focused on such higher-impact societal groups.
- Telecommunications: "Mobile" carries a youth-oriented cultural significance beyond just "portable". Telecommunications R&D managers strive to create new products that increase the on-the-move capability for features such as Internet and video. A detailed assessment by experts could reveal whether R&D managers may be overly influenced by the symbolic meaning of "mobile" when trading off greater bandwidth per product against the potential number of users; further study using select focus groups (engineers, managers, customers) could then help define the appropriate balance of the two.

Making it work

Under what circumstances would an R&D manager, already faced with time and budget constraints, agree to incorporate yet another level of analysis in his or her programme plan, especially one that is considered "soft" like STS? The best argument is that STS can help avoid "strategic surprise" in areas not normally considered by R&D managers, such as social factors of acceptance.

STS can help avoid "strategic surprise" in areas not normally considered by R&D managers, such as social factors of acceptance

The purpose of this article is to highlight the importance of a fluid interface between STS and R&D programme management. Implementation mechanisms would deserve separate treatment. Nevertheless, the first step in incorporating a risk-based STS assessment into the R&D management process would be to organize workshops or conferences at the university level that bring R&D managers and STS researchers together, in order to help the former understand how STS research can help them avoid strategic surprise, and to help the latter frame their investigations for use by R&D decision-makers. In order to enact the concept on a broad scale, the second step could be to enact pilot programmes to demonstrate the actual utility of this approach. These could be joint efforts by both the STS and engineering/science faculty at a university as part of an industrial product development team. Should those programmes prove successful, guidelines for incorporating STS into R&D management should be developed and promulgated on a wider scale.

Keywords

research and development, programme management, risk assessment, strategic surprise

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