Uncertainty-reducing techniques in technological innovation

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Technology-intensive innovation is fraught with all sorts of uncertainties — uncertainties which can neither be averted nor ignored but have to be managed. This paper discusses techniques on how to handle such uncertainties in high-technology development projects under conditions of severe time pressure. The key lies in postponing decision-making if uncertainty is intolerably high, and structuring the development project in such a manner that progress is not delayed, while taking steps to rapidly and systematically reduce the uncertainty. These techniques turn out to be simple but profound.

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Tegnologie-intensiewe innovasie word gekenmerk deur allerlei soorte onsekerhede — onsekerhede wat nòg vermy nòg verontagsaam kan word. Hierdie artikel bespreek tegnieke vir die hantering van sulke onsekerhede in hoë-tegnologie ontwikkelingsprojekte onder ernstige tydsdruk. Die sleutel lê in die uitstel van besluitneming indien die onsekerhede ontoelaatbaar groot is, en in die strukturering van die ontwikkelingsprojek in so 'n wyse dat vordering nie belemmer word nie, terwyl stappe geneem word om die onsekerhede vinnig maar stelselmatig uit die weg te ruim. Hierdie tegnieke blyk eenvoudig dog diepgaande te wees.

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Innovation concerns the entrepreneurial process of converting a novel and unproved invention into a marketable product. Such commercialization of technological discoveries can have profound social and economic consequences, as seen for example in the cases of the transistor, antibiotics and nuclear power reactors. Innovation is the key to a modern and healthy economy.

We still have a lot to learn about the management of technological innovation. What we do know is mainly derived from case histories of both successful and unsuccessful innovations. For example, it is well known that an organization's innovative effectiveness revolves around its ability to recognize and exploit needs and demands in the marketplace.[1] If, in addition, innovation requires substantial scientific and technological achievements in the development, design and production of such products, the process of innovation is considerably complicated.[2]

Technology-intensive innovation, such as the high-technology product development projects to be described, are characterized by the need to make urgent management decisions in the face of severe uncertainties. Procrastination can be very costly. Decisions must be made, else the project rapidly grinds to a halt due to a lack of direction. The market might even be lost to the competition. This paper describes a method for structuring problems of this nature into manageable portions, so that the necessary decisions can be timeously made.

The paper does not claim originality. Rather, it presents a practical management philosophy synthesized from a variety of management tools developed over the past three decades in the United States military and aerospace industries. Although these techniques are part of the management folklore in these industries, they have to date not been systematically integrated into a comprehensive philosophy, nor have they appeared in generally-available, widely-circulated publications. This is a pity, since technological uncertainties are not confined to military and aerospace industries and this management philosophy thus has much wider applicability. For example, similar uncertainties could arise in the development of alternative energy sources. The objective here is to expose this management philosophy to a wider audience. Clearly these management tools will not apply directly to all situations; they will invariably require modifications dictated by specific circumstances. Such generalizations cannot and will not be attempted here.

This is not a paper on project management, although it can significantly change the way in which projects are managed. Rather, it concentrates on uncertainty-reducing techniques applicable to high-technology hardware development projects.

Uncertainties in technological innovation

What is uncertainty, and which uncertainties arise in technological innovation? In defining the concept of uncertainty, three related situations can be identified: those involving risk, uncertainty and ignorance. These situations could lead to alternative outcomes, which may or may not be identifiable in advance. Associated with each alternative outcome is an occurrence probability which may or may not be known.

- A situation is characterized as involving *risk* if it is possible to describe all possible outcomes and to assign meaningful occurrence probabilities to each one.
- A situation is *uncertain* if all alternative outcomes can be described but when there is no objective basis for assigning probabilities to the alternatives.
- *Ignorance* arises when all the alternative outcomes of a situation cannot be defined, let alone their occurrence probabilities.

Note that in principle uncertainties may be resolved into risks but the costs of such resolution is high — more often than not higher than can be justified. Only the passage of time will reveal the alternatives in a situation of partial ignorance — no amount of analysing can do it. Unfortunately this is no consolation to the manager — he has to make decisions at an earlier stage.

Decision-making theory has addressed itself primarily to decision-making under conditions of risk, but not to decision-making under conditions of partial ignorance. The problems introduced by technology-intensive innovation centre on uncertainty and partial ignorance. For the purposes of this paper these have been lumped together as uncertainties, purely for the sake of convenience.

There are three types of uncertainties associated with technological innovation, each involving both 'kunks' (known unknowns) and 'unkunks' (unknown unknowns):

- Requirement uncertainties revolve around the relative desirability, acceptability and effectiveness of the product under development — the more this product differs from existing products, the larger these uncertainties become.
- Development uncertainties revolve around: cost and schedule estimates to achieve the product specification; performance reductions and tradeoffs dictated by price and/or schedule constraints; and unforeseen technical problems arising from incomplete knowledge existing at the outset of the development project.
- Dynamic uncertainties revolve around changes in conditions external to the project, for example in markets or concerning competitive threats. The longer the development time, the larger these uncertainties become. As an example, fundamental state-of-art technological advances could render the product under development obsolete.

The main management problem in technological innovation is how to handle these uncertainties under conditions of severe time pressure. The key lies in postponing decision-making if uncertainty is intolerably high, and structuring the development project in such a manner that progress is not delayed, while taking steps to rapidly and systematically reduce the uncertainty.

Historical perspective on technological innovation

Under Project Hindsight[3] the innovation process that occurred during eight military products developed during the 1950s and 1960s was analysed. The study focused on predecessor events, and specifically the age distribution of relevant predecessor events relative to the start of product development. (An event is defined as a period of innovative technical activity producing an irreversible change in the state-of-art, in the understanding of what is feasible, or how things should be done.) The overall results are summarized in Fig. 1.

The conclusion of this and similar studies[4] is that it is the interactions of many mutually-reinforcing innovations, most of which are quite modest in themselves, that account for most of the improvements in performance and cost of new products. Most of these innovations happen long before the start of the development of a desired product, and are thus quite independent of it. This, translated into operationally-useful terms, implies:

- Successful product development depends on innovations in various constituent technologies relevant to the product. Innovations in these technologies occur independently of and prior to product development.
- During product development, problems will invariably arise which are unique to the product, arising for example from unexpected interactions between new subsystems. Innovations concerning the integration of various new subsystems clearly can only occur after product development has started.

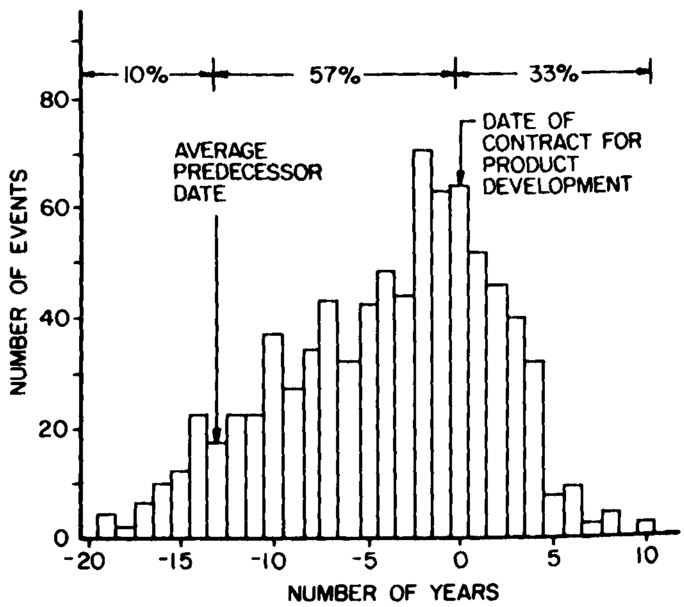

Fig. 1: The age distribution of predecessor events in constituent technologies, relative to the start of product development[3]

- Failure is virtually guaranteed if one combines technology development with product development. Do not start product development until the subsystem technologies have been substantially mastered. For example, do not attempt developing a new generation aircraft if you have not already mastered the various constituent technologies such as airframes, propulsion and avionics. Product development can only proceed from a mature and relevant technology base.

Uncertainty-reducing techniques

The techniques which can be used to reduce requirement and development uncertainties include (not in order of importance or priority):

- configuration management
- limited state-of-art advances
- successive limited objectives
- distinct development models and prototypes
- early and repeated testing
- incremental improvements
- parallel development.

The techniques which can be used to reduce dynamic uncertainties include (not in order of importance or priority):

- keep the options open
- technological transparency.

After these techniques have been discussed, their application will be illustrated by means of a hypothetical example from the automobile industry.

Configuration management[5]

The fundamental idea of configuration management is that the configuration of a product is subject to continuous change during the development cycle, and that such changes are desirable but should be controlled. The term 'configuration' refers to a complete description of the physical, functional and performance requirements of a product. Configuration management is the discipline that ensures that a product meets carefully-defined requirements and that any changes in these requirements are thoroughly evaluated, carefully identified, rigidly controlled and accurately recorded.

The two concepts of a baseline and a configuration item translate this idea into practice.

A baseline is a set of documents which provides the point of departure for further development work. Each interim milestone in the development cycle has a baseline associated with it. As development proceeds, this baseline becomes firmer, more definitive and detailed. Each of these baselines is subject to configuration control. The process of managing the contents of and changes to these successive baselines thus caters for the desirable and natural progressive tightening up of the product configuration as development proceeds, and prevents the rubber baseline syndrome, where everything is changing all the time and is cloaked in indeterminateness. Specifications form a major portion of a baseline and describe the major technical requirements for an item and the procedure for determining that these requirements are met. The United States Department of Defence has issued a specification entitled 'Specification Practices'[6] which establishes uniform practices for specification preparation, ensures the inclusion of essential requirements and aids in the use and analysis of specification content. This is a profound document which rewards careful study. It forces one to explicitly specify the form, fit and function of a product, as well as its various interfaces to the outside world, for example functional, human, physical, and electrical interfaces. (An interface is a common boundary between two or more items, where physical and functional compatibility is required.)

A configuration item may consist of the total product, or selected subsystems thereof. The main criterion for partitioning a product into configuration items is whether such a configuration item has form, fit or functional relevance to the user, that is whether the user is directly exposed to or influenced by that configuration item. The concept of a configuration item allows one to structure the product into a physical hierarchy, thus reducing uncertainties and simplifying development activities, but it simultaneously introduces major interface problems between these configuration items. If one assigns a baseline to each configuration item and to each interface, one can now progressively refine the product as a whole, as well as its various subsystems, in a systematic manner.

Since configuration management demands a specification at the start of the development project, one is forced to make decisions which structure the product and thus the project. This specification is progressively firmed up during the project and thus decision-making under high uncertainty conditions may be postponed without delaying the project.

Limited state-of-art advances

The state-of-art is generally accepted to refer to some upper bound on achievable physical or performance characteristics at a particular time. This viewpoint is somewhat narrow. There are states-of-art for various phases in the development cycle; for example, in research the state-of-art denotes the frontier at which investigators seek to discover new phenomena and theories to explain them. For advanced development it can be seen as the interdependence of and technical trade-off between the relevant technical variables. For production engineering the state-of-art can be seen as the state of best-implemented technology as reflected in actual physical and performance characteristics of existing hardware.

It should be realized that:

- For each phase and part of a development project there exists a different state-of-art.
- The basic output of R & D is an advance in a particular state-of-art.
- States-of-art can differ from country to country, and from organization to organization.
- State-of-art changes with time.

Using these principles, one can define a set of management procedures to explicitly take into account these factors during technological innovation. These procedures revolve around three concepts[7] relating to hardware units and which are applicable at all hardware levels, for example system-subsystem, subsystem-module or module-component. (A subsystem or a combination of subsystems is usually a configuration item, although a configuration item is not necessarily a subsystem.)

The three concepts are:

- The subsystem state-of-art influences the required number of development iterations for that subsystem, and is defined in Table 1. State-of-art advances can be allocated to various subsystems in order to achieve the desired product specifications.
- The subsystem dependency matrix defines the degree of interdependence between subsystem specifications and the overall system performance. It demonstrates the propagation characteristics of a failure to meet subsystem specifications. The dependencies are defined in Table 2. The tightness of subsystem interrelatedness can be traded off against the desired state-of-art advance or the uncertainty surrounding the subsystem. The tighter the dependencies between the subsystems, the smaller the allowable uncertainty and advance in state-of-art.
- The conditional development plan is a network plan which shows in what order various subsystems should be developed so as to achieve full system integration in the shortest possible time. This plan is based on the expected number of development iterations for each subsystem and each interface.

The application of these three concepts to technological innovation is as follows:[8]

- Using only type 1 subsystems results in an old-fashioned product that is probably not worth developing. To meet the product schedule, no subsystem with type higher than 2 should be chosen. The choice of subsystem type 3 should be done if and only if such a subsystem will be critical to the overall system performance. It is out of the question to develop type 4 subsystems as part of product development.
- If it is necessary to use a type 3 subsystem because it contributes critically to the performance of the product, make the interdependence between this subsystem and the other subsystems weak.
- Strong interdependencies (level 2) should only be allowed for type 1 subsystems. It is preferable to have a product with weak dependencies between its subsystems, since strong interdependencies tend to have serious failure propagation characteristics.
- A combination of subsystems of different types results in a system type number equal to the highest subsystem type number, on condition that the dependencies are weak. If some dependencies are strong, this may result in a system whose type is even higher than that of the subsystem having the highest type number.
- The interdependence between two subsystems is not necessarily symmetrical. In other words, subsystem A can be strongly dependent on subsystem B, whereas subsystem B is only weakly dependent on subsystem A.
- If subsystems of type 3 are used, the development plan should preferably allow a system integration path in parallel with the subsystem development activity. This system integration can take place using an existing subsystem (type 1). Such a subsystem would have more primitive characteristics but would still enable integration checks to be performed.
- Ensure that the critical path of the development plan excludes high-risk development activities (type 3) and/or high dependency levels (level 2).

Successive limited objectives

By introducing a number of distinct development phases, one can systematically translate scientific knowledge into operational systems (see Table 3). In this way the development cycle is divided into a number of steps, each with a limited objective and each corresponding to an interim development milestone. For example, exploratory development establishes the feasibility of a concept, whereas advanced development determines its usefulness on the basis of field trials.

Note that objectives are forced into a priority framework — it is pointless to verify system reliability and maintainability before its feasibility has been ascertained.

Table 1 Subsystem level of know how

Type number	Definition	Development process	No. of Development iterations required
1	Subsystem available off the shelf	Minor modifications required, if at all	1 – 2
2	Considerable experience exists, specific subsystem has been designed on paper but is not yet available	Major development required, followed by minor modifications	2 – 3
3	General knowledge available but no specifics. Feasibility study shows positive result	Development could fail N – 1 iterations for unsuccessful solutions, plus 3 iterations for final solution	N + 2
4	No experience with particular subsystem technology	Some solutions are developed until success/admission of failure	?

Table 2 Subsystem dependency matrix

Dependency level	Definition	Influence of a failure on development process	
		Development not yet initiated	Development completed
1	No failure propagation (changes in a subsystem's performance do not affect performance of other sub-systems with which it interacts)	None	Repeat subsystem development
2	Serious failure propagation (changes in a subsystem's performance seriously affect performance of other subsystems with which it interacts)	Change development plan	Repeat development of all subsystems affected

The development phases are separated by checkpoints where progress can be monitored and repeat/proceed decisions can be made on the basis of laboratory tests and field trials on development models or prototypes.

Distinct development models and prototypes

Associated with each development phase are one or more development models or prototypes.[7] In this context, a model represents a partial synthesis of system components and is thus a serious abstraction of the final product. Development models are used in research, exploratory development and advanced development phases where the emphasis is on technology development. Often models are built only of those aspects or subsystems subject to considerable uncertainty, in other words, the grey areas.

A prototype on the other hand is a full-size model that can be tested in the true physical environment in which the final product will be used, and thus represents a true approximation of the product under development. Prototypes are used during the engineering development and production engineering phases when the emphasis is on product development. The results obtained from testing full-size prototypes do not have to be scaled. Since these prototypes operate in the environment in which the final products will be used, there are no calibration problems. In addition, there are no problems of visualization.

In experimenting with and testing distinct development models and prototypes, the attainment of objectives of a particular development phase can be thoroughly measured. For example, the product's feasibility can be thoroughly tested before production decisions are made.

Table 3 Development phases in technological innovation

Development phase / Characteristics	Research	Exploratory development	Advanced development	Engineering development	Production engineering
	Technology development	Technology development	Technology development	Product development	
Basic orientation	Scientific	Scientific	Scientific	Engineering (Systems engineering)	Engineering (Production engineering)
Basic purpose	Explore the unknown	Acquire knowledge of selected technical approaches via laboratory tests	Acquire knowledge through experimental test	Perform systems engineering, reliability, maintainability and cost effectiveness studies	Finalize production methods to achieve reproducability on the proposed production line using the proposed quality assurance methods
End product	Increased knowledge of fundamental natural processes	A report. A bench model for feasibility check. An experimental component	Major hardware items for experimental tests, as opposed to items developed and engineered for product use	A complete system whose engineering design and cost effectiveness has been confirmed	Production item for use
Direction of effort	Not directed toward solution of specific problems	Directed toward solution of specific problems short of developing major hardware for experimental tests. Evaluate the feasibility and practicability of proposed solutions	Directed toward solution of specific problems including development of hardware for experimental tests	Directed toward the acquisition of data needed to decide whether or not to proceed with production engineering	Directed toward reproducability, reliability and maintainability aspects
Task requirement	Does not require a specific problem	Does not require specific hardware pay-off	Begin to question utility	Specific use defined in detail. Integration with other subsystems or major components of the proposed product	Specific production line and quality assurance methods
Technical uncertainty	High	High	High	Moderate	Low
Development models/ prototype		Exploratory development model (XDM)	Advanced development model (ADM)	Engineering development prototype (EDP)	Pre-production prototype (PPP)

Early and repeated testing

In developing a new system one usually intends to exploit a new principle or a new combination of established principles. One should therefore first concentrate on proving whatever one wishes to exploit and not on developing a new subsystem with high uncertainty. Emphasis should always be put on the *earliest possible system integration in order to check overall performance as soon as possible.*[9] The existence of distinct development models and/or prototypes allows relatively rapid testing of the grey areas involved in the subsystem or the system as a whole, either in its final form or using more primitive subsystems as substitutes for new subsystems still under development. Such early and repeated testing encourages an iterative design process providing rapid feedback to the development team, and supplies quantitative data on which proceed/repeat decisions can be made at the end of each development phase.

Parallel development

The idea of a parallel development[10] is concerned with the more or less concurrent development of two or more competing products or key subsystems which represent potential alternatives for satisfying a requirement. By thus postponing a decision, one can hedge against selecting the wrong alternative. Final selection is made on the basis of quantitative tests on alternative models and/or prototypes.

The use of parallel development projects is constrained by economic considerations. The value of each approach will only be known when its development is completed and all uncertainties related to it are removed. If the rate at which uncertainty is reduced is rapid, parallel development need not be carried to completion before a rational choice can be made. In this case the cost of parallel development is low. The converse is true with a slow rate of uncertainty reduction.

If development subcontractors are to be used, and if conditions of competition between various able contractors exist, competitive prototyping can be used. This not only motivates contractors to mobilize their best efforts, but also allows alternative technical solutions to be evaluated with healthy cross-fertilization occurring between the alternative prototypes. This is a popular approach in the United States, but is often impractical in smaller countries where little or no effective competition exists.

Incremental improvements

It is better to have a product which meets only 90% of its specifications available on the marketplace when the demand for that product takes off, than to spend say another year to perfect the product but miss the demand take off. The sensible approach appears to have a systematic programme of performance upgrading, reliability improvement, design refinement and the introduction of performance options, based on extensive testing of a large number of production items.[9] Not only does this provide an earlier positive cash flow, but market acceptance and used feedback is rapidly obtained, serving as input to the product improvement programme.

Keep the options open

If dynamic uncertainties are considerable, the delay between the go-ahead and completion of a product's development should be minimized.[7] This can be done as follows:

- Support technology development activities in a large number of technologies even in the absence of specific applications. This ensures a healthy know-how base which can be deployed on a large variety of product development activities, once a specific application has been identified.
- During product development activities, avoid freezing the product configuration until the last possible moment. Avoid all but the broadest specifications to start with, and make no major commitment until a substantial jump in knowledge about the product under development has been achieved.
- Use parallel developments extensively.

Technological transparency

Technological transparency[11] involves the use of functionally-specified modular elements in the design of a system. These modular elements can be replaced in the future with functionally-equivalent modules incorporating more advanced technology to implement these functions. This allows enhanced system performance to be achieved without affecting the product's configuration. In order to configure the appropriate architectural design of the system, one has to anticipate technology trends by five to ten years.

Example

The uncertainty-reducing techniques will be illustrated by means of a hypothetical example from the automobile industry. Although the example is topical, it does not fully reflect all the intricacies and nuances present in real life — it is intended to elucidate, not enumerate.

On the basis of an incisive strategic analysis, a big automobile manufacturer has decided that it will develop a new car for introduction in three years. This car will have to exploit technological advances in automotive electronics, in high-strength, light-weight materials and in alternative fuels. The long term implications of the energy scarcity crisis, air pollution regulations, the escalating costs and increasing scarcity of steel, as well as the world-wide swing to smaller, more fuel-economic cars will have to be taken into account.

Configuration management

As a first step, the functional baseline of the new car is formulated and placed under configuration control. The functional baseline consists of specifications which include:

- Overall functional and performance requirements, including key parameters such as fuel consumption, overall size and mass, power-to-mass ratio.
- A definition of each configuration item and its broad specifications.
- A fairly detailed specification of the interfaces between configuration items.

- A specification of the car's interface to the outside, and especially the human interface to the driver and to the maintainer.

The emphasis of this specification is on functional requirements — it does not prescribe technical solutions but only constrains them. The following configuration items are defined:

- engine
- transmission
- suspension, steering and braking
- body
- electrical subsystem
- instruments and controls
- documentation (production and maintenance/repair)
- carburation and ignition
- cooling, heating, exhaust and emission control.

Note that documentation, and instruments and control are configuration items, since both of these have important form and functional relevance to the user.

Limited state-of-art advances

Working backwards from the three years deadline, it is decided that the following configuration items will be fairly standard (type 1 & 2):

- transmission
- suspension, steering and braking
- electrical subsystem
- documentation
- cooling, heating, exhaust and emission control.

Innovations will be introduced in the following configuration items (type 3):

- engine
- body
- carburation and ignition
- instruments and controls.

(The extensive use of existing subsystems requiring only fairly minor modifications is a good example of incremental improvements. Similarly, the new engine and instrument/control subsystems will be used as building blocks for future-generation cars.)

The dependencies for these subsystems are:

- engine to carburation and ignition : strong
- engine to other subsystems : weak
- body to rest of car : weak
- instrument and control to rest of car : weak
- carburation and ignition to rest of car : weak.

With a few exceptions, the dependencies for the other subsystems are weak.

The major uncertainty is the use of ethanol and methanol fuel extenders for the internal combustion engine. The design constraints are that the blend fuel economy should not be lower than for petrol alone, and that no carburation adjustments should be necessary. The major problem is the blend ratio. Its value will probably be between 10% and 30%. The output of an internal combustion engine depends on many factors: calorific value of fuel, air-to-fuel ratio, degree of completion of combustion reaction, compression ratio, flame propagation velocity, Otto cycle efficiency, etc. Extensive testing will be required to fine-tune the engine with respect to short term and long term performance. Carburation will consist of electronic fuel-injection with various operating conditions and performance sensors providing inputs to a microprocessor. The instruments and controls will also be microprocessor-based, with an all-digital display. Electronic automatic test circuits will continuously monitor critical parameters and detect operating failures. The body panels and bumpers will be manufactured from composite materials such as glass-reinforced plastics. To limit uncertainty, structural parts such as the suspension will be manufactured from conventional materials.

Successive limited objectives

Since Brazil has been operating ethanol/petrol cars for some time, second-hand knowledge and limited operating experience is available. The development project as a whole can thus be considered as being in the advanced development phase. Nevertheless, some aspects of the instrument and control configuration item and the body are in the exploratory development phase. In preparation for future generation cars, research projects are initiated on hydrogen-fuelled spark-ignition engines and compression-ignition engines using diesel-methanol blends.

Early and repeated testing

Four Advanced Development Models (ADM) of the engine and carburation/ignition subsystem will be built. ADM 1 will be used for laboratory tests, with ADMs 2, 3 and 4 being used for extensive field trials in an existing car. The instrument and control subsystem will be tested out in ADM form in an existing car. A series of ADMs will be built of the body using new materials, but final tests can only be done on a prototype of the new car. In parallel, a series of Engineering Development Prototypes (EDP) of the car will be built, using conventional engines and instrument/control subsystems. As soon as the objectives for each of the advanced development phases are satisfied, that subsystem will be incorporated in the EDP of the car.

This approach will allow development of subsystems to proceed independently of the uncertainties in other subsystems. As soon as the last subsystem completes its advanced development phase, a new baseline, the allocated baseline, will be established and placed under configuration control. This will represent a substantial firming up of the specification, since the functional requirements baseline will be allocated to the various subsystems and the specifications for each subsystem and the interfaces between them will be finalized. At the completion of the production engineering phase the product specification will be finalized. This will include the final configuration of the product as well as the detailed manufacturing instructions applicable to the envisaged production line using the envisaged manufacturing personnel.

Parallel developments

It is impossible at the outset to decide between the ethanol and methanol engines. This choice depends not only on technical performance and cost-effectiveness, but also on the relative availability of ethanol and methanol in the long term. This availability in turn depends on government incentives and regulations, as well as production efficiency and the capital investment required for the plant.

Parallel developments are launched on both the ethanol and methanol engines, with a final selection decision scheduled for the completion of the engineering development phase. To further reduce uncertainty, both approaches will be tried on the same basic engine, which in itself can substantially satisfy the requirements connected with the engine. The basic engine will thus serve as a fall-back engine in case both ethanol and methanol approaches fail.

Technological transparency

A recent forecast of automotive electronics has stated that although microprocessors and memory devices are not yet available to the environmental standards and at the prices suitable for incorporation in carburation and ignition subsystems, they will be available within two years. Because of this fact, as well as the possible availability of single-board computers, the subsystem will be designed for present-generation integrated circuits but in easily upgradable modules.

Towards a development policy package

The various uncertainty-reducing techniques are not independent of each other. To a certain extent some are partial substitutes for others, and many are mutually reinforcing. The choice of emphasis among these various techniques results in a development policy package.[7] Note that such a package is unique to the specific development project it is to support.

Examples of the issues which may arise in designing a policy package are:

- Successive limited objectives and incremental improvements require early and repeated testing.
- If the technological uncertainty is relatively low, such as in certain product improvement programmes, there will be an increased emphasis on analytical methods and model testing, reducing the need for expensive prototyping.
- Strong subsystem interdependencies coupled to large advances in subsystem state-of-art demand a much larger emphasis on analytic techniques and early and repeated testing.
- Incremental improvements are more difficult in a system with strongly interdependent subsystems, since the constraints on changes in any specific subsystem are much more severe.
- The advance in state-of-art to be allowed in a development project not only depends on the performance requirements and time available to completion, but also on the quality and quantity of the available talent pool.

Effectiveness of R & D management techniques

The effectiveness of R & D management techniques is not above suspicion. These techniques include those covered in this paper, but are not limited to them. There is mounting evidence of continuing cost, schedule and performance difficulties in high-technology development projects, while simultaneously there is increasing reliance on regulations and the specification of management processes to control and minimize such difficulties.[12] This apparent paradox can be resolved only if one applies these management techniques judiciously. Don't try to plan the unplannable or control the uncontrollable. Don't overspecify under conditions of partial ignorance. As uncertainty increases, the intensity of management control must be reduced, or the nature of such control must change. For example, techniques such as configuration management should be loosely applied at the start of the development cycle, with a systematic tightening up as the cycle proceeds and uncertainty reduces. There is no one right approach for all development activities.

Uncertainty-avoidance strategy

There is a non-trivial method of avoiding the uncertainties inherent in technology-intensive innovation — limit innovation. In a first-to-market technological strategy[13] great emphasis is placed on creating and maintaining technological leadership, and on translating this to success in the marketplace through product innovation. An organization (or even a country) can decide on a follow-the-leader technological strategy[13] where the technical leader is carefully watched, and new-product information relating to market acceptance, achievable performance specifications and appropriate technical solutions rapidly obtained. Although by no means all uncertainties will be removed from the development cycle, this strategy allows organizations to concentrate on quick-reaction copying as opposed to in-house high-technology innovations. In essence this replaces one set of problems by another.

Conclusion

This paper has presented a number of practical management techniques for reducing uncertainties in high-technology duration-limited development projects. The fundamental principle lies in postponing decision-making if uncertainty is intolerably high, and structuring the development cycle in such a manner that progress is not delayed, while taking steps to rapidly and systematically reduce the uncertainty. A close examination of these techniques and their application to the example shows them to be quite simple and full of common sense validity. Its simplicity tends to obscure the profundity of this management philosophy, and is probably the root cause of it being so often and so disastrously ignored.

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