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MANAGING UNCERTAINTY AND AMBIGUITY IN GATES: DECISION MAKING IN AEROSPACE PRODUCT DEVELOPMENT

Abstract

This paper investigates decision making in the stage-gate process used by an aerospace manufacturer. More specifically, it focuses on the way decision makers deal with uncertainties and ambiguities when making decisions. The stage-gate model was found to be a discussion trigger—a boundary negotiating artefact—through which stakeholders bring issues to the table, reflect on uncertainties, and decide in what areas more knowledge is needed. Managers should be aware that the knowledge base might not always be perfect and should make use of the sensemaking capabilities of the stage-gate model and the gate meeting to mitigate and improve the knowledge base. This paper elaborates on formalized knowledge-based criteria so as to support this evaluation of the knowledge base.

Keywords: New product development; decision making; stage-gate; uncertainty; knowledge management; project management; sensemaking

1. Introduction

To reduce lead times without sacrificing quality and performance, the decision-making process needs to be more effective and efficient [Larsson et al. (2006)]. In response to this challenge, many companies adopt the stage-gate process [Cooper (2001); (2008)] in order to manage the development effort and to aid effective decision making. In a stage-gate process, information and knowledge assets of many different kinds (e.g., analysis results, technical reports, drawings, lessons learned, rationale, physical and digital mock-ups) are created, collected, and shared during the different stages of engineering work, reflecting learning about the product. In addition, tacit knowledge [Polanyi (1967)] and experience play a crucial part since decisions need to be made even when the available documentation is scant and decision makers must thus rely more heavily on experience-based opinions and even on assumptions. Tacit knowledge often comprises the main body of knowledge; Polanyi proposes that "we can know more than we can tell" [Polanyi (1967), p.4], signalling that all tacit knowledge is difficult to capture in documentation, given that it instead resides in people's minds [Polanyi (1967)].

The objective of this paper is to investigate decision making in the stage-gate process—more specifically, to examine how decision makers deal with information and knowledge, as well as uncertainties and ambiguities, when making decisions.

The context for this study is the aerospace industry, which differs significantly from many other industries (e.g., automotive, consumer products). The complex nature of the products [Acha et al. (2007)] and of the industry (i.e., engineering-intensive products that require a breadth of skill and knowledge and that are usually quite costly) [Prencipe (2004)] is such that a single company cannot manage investments and risks, let alone train workers in all the necessary skills. Payback times (i.e., the amount of time before an aircraft program breaks even) can be very long, stretching to as many as 10 years [Buxton et al. (2006)], thus companies tend to be hesitant to take on the financial risk that the investment entail. In addition, various product and service-bundled offerings (i.e., product-service systems [Mont (2002)]) in which customers pay for the use of the product and buy only its function [Alonso-Rasgado et al. (2004)] are becoming more and more popular, thus distributing the customer's expenditure—and the manufacturer's income—over the life of the product.

Manufacturing companies are usually closely intertwined in strategic partnerships (e.g., virtual [Davidow and Malone (2003); Hardwick and Bolton (1997); Browne and Zhang (1999)] and extended enterprises [Boardman and Clegg (2001); Browne and Zhang (1999); Ericksen and Suri (2001)]) with other companies, sharing risk and revenue in order to deal with the challenges of time, investment, and skill [Prencipe (2004)]. Companies work in a mode of *coopetition* [Brandenburger *et al.* (1995)]—that is, they are collaborators and competitors at the same time.

In such product-development projects, the effort of the partnering manufacturers is highly collaborative and hence contract driven [Johansson *et al.* (2009)]. Before commitments are made and before product development starts as a project, the partners sign contracts to regulate participation, responsibility, and delivery, thus obliging the companies to deliver on time to the other partners and to customers.

In previous work focusing on the role of knowledge and information in the stage-gate process in the aerospace industry, as well as in the metal-cutting tools industry [Johansson *et al.* (2009)], one main finding was that the status and quality of the information and knowledge assets brought to gate meetings was not an explicit point of discussion. The main focus at the gate meeting was instead on product attributes, such as performance and function. The results brought forward at the gate denote knowledge that the team has created regarding how the product is likely to perform in operation and what features it will have. Uncertain placeholder values are occasionally mistaken for exact requirements, and similarly, exact values are sometimes mistaken for placeholders [Stacey and Eckert (2003)]; this lack of process rationale poses risks related to the traceability of decisions throughout the process and increases the likelihood that decisions will be based on ill-founded assumptions. Further, in terms of the gate's role, decision makers rarely opt to terminate a project once it has passed the first gate and been approved to go ahead.

An issue in the context of gate review meetings is the role of ambiguity and uncertainty. Carleton, Cockayne, and Leifer [2008] define ambiguity as "not knowing what to measure, how to structure any measurements, or possibly even where to start looking for variables" [ibid., p.1], and uncertainty as "the state in which variables are identified, although the parameters may be incomplete, insufficient or imprecise" [ibid, p.1]. In product development, especially from an innovation perspective, ambiguity should be preserved in order to maintain a wide and open design space [Bucciarelli (1994)], thus avoiding premature closure. However, from a project risk-management perspective, when the project passes the gate to the next stage, ambiguity and uncertainty can also be negative [Stacey and Eckert (2003)], posing the risk that decision makers will have to deal with and make trade-offs wherever there are gaps in the decision base. The knowledge base is flawed, consisting of placeholder values [Flanagan et al. (2007)], uncertain information about competitors [Rosenzweig (2007)], and assumptions [ibid.], and it is missing information [ibid.], demonstrating that a detailed understanding of the ambiguities and uncertainties is lacking. This can potentially negatively influence decision making because the company finds itself in a position of *satisficing* (i.e., satisfying and sufficing at the same time) [Simon (1955; 1979)] when making decisions, thus reducing the decision makers' confidence. Since product development activities in the aerospace industry are growing in complexity and scope [Flanagan et al. (2007); Acha et al. (2007)], such development activities will always include aspects of ambiguity and uncertainty. However, there is a need to deal more confidently with situations in which not all the knowledge is in place, given that decisions still need to be made in the gates. Therefore, the first step is to better understand this aspect of the process, and the purpose of this paper is to investigate how decision-making practices in the gated process relate to ambiguity and uncertainty.

2. Methodology

This paper is based on an in-depth study conducted primarily at an aerospace manufacturer reviewing current decision-making practices from the perspectives of the main stakeholders in the stage-gate process (e.g., management group, project leader). The study involved respondents from these areas, thus allowing for an investigation from different angles and enabling the researcher to strengthen the analysis by considering several perspectives. The conclusions drawn originate mainly from the data gathered from nine key respondents with different backgrounds, skills, and experiences in product development at the aerospace company, called Company A. What they have in common is that the stage-gate process affects them all (albeit from different perspectives) and that they have extensive experience working with the stage-gate model in several product-development projects. Both the company names and identities of respondents have been changed to retain anonymity.

Company A is an enterprise that develops and produces parts of entire aeronautical systems. Their closest partners and customers are aeronautical systems original equipment manufacturers (OEMs). Their development is organized in larger stages: a *predevelopment phase* delivers technologies mature enough to move into *product development*, which involves the final maturation into a *finished product*. This study mainly targets product development, which is organized around an adapted version of the stage-gate process to suit the industrial group of which Company A is part. Activities are performed in parallel in different functional areas and reported to the management team, whose members evaluate the project in gate meetings. Sometimes these mirror those of their customers and partners [Johansson (2009)]. Evaluation targets both technical performance, on one hand, and business aspects and scheduling, on the other, and assessments can be divided into several sessions owing to the complexity of technical evaluation **[Johansson (2009)]**. Company A has about 3,000 employees and an approximate turnover of €700 million; it is active in numerous civil and military aviation programmes.

A second company in the aerospace industry was considered in order to provide a complementary perspective to that of Company A, highlighting the role of the aerospace context. Company B also develops and produces parts of entire aeronautical systems, focusing on components different from those Company A works on. Like Company A's, Company B's closest partners and customers are aeronautical systems OEMs. Company B has about 12,000 employees and an approximate turnover of €3 billion and is also active in numerous civil and military aviation programmes. Company B contributed limited information to this study from a structured interview study, mainly verifying data from Company A. Both Company A and Company B are active in the European aerospace industry but often operate with partners to complete projects on a global scale.

Product development usually lasts for several years owing to the products' inherent complexity and the extensive need for testing and certification as required by aviation authorities' regulations. In addition, long-range planning for the development of key technologies takes place following the technology readiness levels [Mankins (1995)] for systematically increasing the technology's maturity.

The aforementioned complexity of aerospace manufacturing requires that companies collaborate closely. Thus, in some programmes Company A and Company B may be collaborators, whereas in other cases they may be competitors for the same market opportunity (albeit in different consortia). This, however, is not a focus or a unit of analysis in the present study.

Acknowledging the reduced possibilities for cross-case analysis and generalization, I examined only one company because this allowed the data collection and analysis to focus on a deeper understanding of the stage-gate process in that company. The main goal of this investigation was to understand the respondents' perceptions of the stage-gate process, as well as their perceptions of how they deal with knowledge-related aspects—assumptions, ambiguity, and uncertainty.

The respondents were approached for the study with the help of a gatekeeper [Neyland (2008)] who was acquainted with suitable respondents who had adequate experience at the case company.

Regarding data collection, the main modes were semi structured interviews and workshops for group discussion [Yin (2003); Fontana and Frey (1994)]. The strength of these approaches is that they allow respondents to talk freely based on their experience, sometimes diverging to touch upon supplementary topics and areas. This conversation needs to be facilitated by the researcher, who has an analytical lens and who should moderate the discussion in the desired direction while not limiting opportunities to discuss topics that were not anticipated ahead of time [Fontana and Frey (1994)]. In the workshops, findings from previous studies were used to drive discussions. All interviews and workshops were recorded and transcribed to ensure consistency in the analysis phase and to ensure that the "chain of evidence" [Yin (2003)] remained intact.

A structured questionnaire with open-ended questions was then used to supplement the data collected in the interviews and to fill in some apparently lacking details in the initial analysis. Data were collected from Company B using a similarly structured questionnaire (sent to several aerospace manufacturing companies, but only Company B responded to the questionnaire) comprising open-ended questions in order to supplement the data collected from Company A; the intent was to confirm common patterns and uncover possible anomalies in Company A that could not be regarded as generally applicable to the aerospace industry. The focus was on topics such as generic stage-gate issues, decision making, roles, communication, and knowledge-related concerns. In either case, the response rate was low, with only one response from each from Company A and Company B respectively.

In analysis, the transcripts were iterated with the respondents, allowing them to verify and complement their statements; this ensured that the researcher had captured their views correctly, thus increasing the construct validity [Yin (2003)]. As a basis for the analysis, the analytical lens *quality and completeness of knowledge* was used. On reflection, this essentially comprised an antonym for *ambiguity* and *uncertainty*. Although the respondents do not talk in explicit terms of knowledge, the researcher can relate the discussed issues to knowledge considerations. Sometimes what the respondents did not say was as important as what they did say.

All transcripts were thoroughly analysed, and interesting areas and quotes received more attention, focusing the analysis on knowledge-related aspects of the stage-gate process, on how the respondents deal with ambiguity and uncertainty, and on a perceived lack of knowledge in the stage-gate process.

Furthermore, theoretical constructs—such as boundary objects [Star and Griesemer (1989)] and bounded rationality [Simon (1979)]—played an important role in making sense [Yin (2003)] of the stage-gate model's role and the role of information and knowledge, especially since much of the interest focused on what was not there and on what perhaps should have been there. According to Yin [2003], this aspect is important for validity, particularly when single-case studies have been applied.

3. Theory

With the aim of investigating the ways that decision-making practices in the gated process relate to ambiguity and uncertainty, this paper addresses the relevant theoretical area of the stage-gate process, which many companies use to manage product development and to facilitate decision making. In essence, much of the work involves managing and reducing uncertainty and ambiguity in an orderly fashion, through a formalized and managed process. Finally, decision making is an important part in this—particularly decision making at large and in situations where all the facts may not be on the table.

3.1. *Stage-Gate model*

The stage-gate model, developed by Cooper [2001], is a process that facilitates projects from idea to product launch. It is based on a phased review process [Cooper (2001); (2008)] implemented at NASA called phased project planning [Engwall (2003)] and first used in the 1960s to manage development projects by dividing long processes into distinct stages and incorporating a reporting session at the end of each stage. The phased process was implemented to control the projects and to allow the option of either cancelling or reprioritizing projects while they are running [Engwall (2003)].

The process can be seen as a set of information-gathering activities [Cooper (2008)] combined with evaluation and decision-making points at intervals in between. The overall process map is shown in Fig. 1.

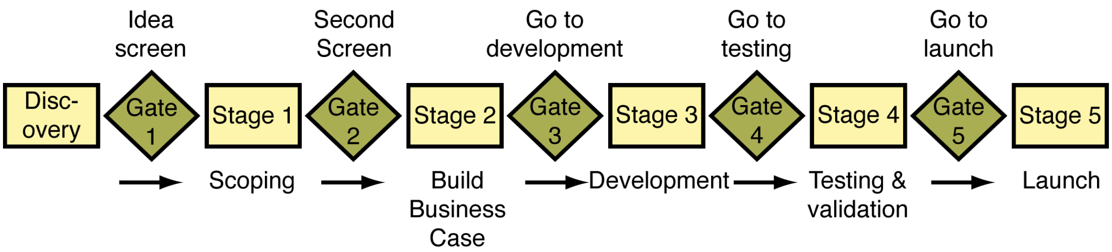

Fig. 1. Stage-gate process overview (adapted from [Cooper (2008)].

The key components of the stage-gate process are the *stage*, at which point activities take place, and the *gate*, at which point information is assessed and decisions are made (see Fig. 2).

In line with principles of concurrent engineering (e.g., [Prasad (1996)]), each stage can be seen as comprising of a number of parallel information- and knowledge-gathering development activities that, after analysis and deliberation by the project team, produce deliverables as input to the gate [Cooper (2008); see Fig. 2].

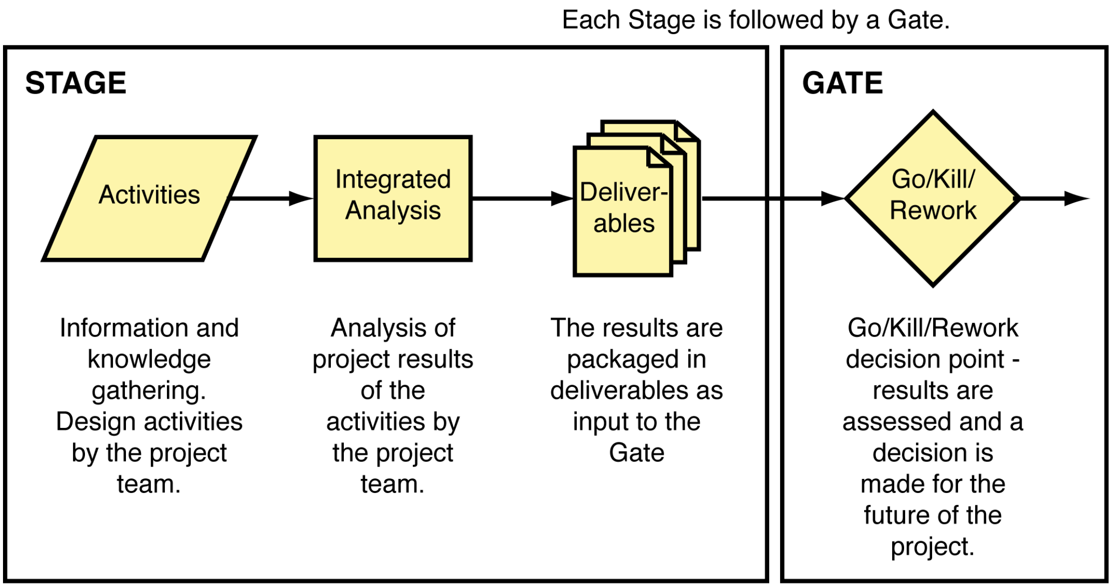

Fig. 2. Stage-gate process: each stage is followed by a gate (adapted from [Cooper (2008)]).

The knowledge elements and information carriers used in the gate meeting include the following:

- Project assurance plan (PAP): This document is structured as a representation of the main criteria document that summarizes the project and explains the gate criteria. It is the main document used at the gate review.
- Design justification files: These documents collect rationale on solutions and about why the product looks the way it does.

- General documents and technical reports: These are essentially technical reports and similar types of documents, the main points of which are included in the summary document.
- Test reports: The results of various physical tests, such as engine tests, are important ingredients in decisions made at the gate.
- Analysis results: Likewise, reports on different kinds of analysis, such as finite element (FE) analysis and computational fluid dynamics (CFD) analysis, provide an important basis for decisions.
- Tacit knowledge: The team creates tacit knowledge and builds an implicit understanding of the product. Implicit probing is performed at the gate reviews, where experts may need to complement written information.

Note that even though decision makers have many sources to use in the decision-making process, assessing these information and knowledge sources in terms of their fitness for purpose remains a crucial challenge. What is the level of readiness of the presented information? Does the information reflect assumptions or verified facts? What is missing? Which areas require more resources for further development? Is there a need to prioritize the development of some aspects over others?

In addition, it is interesting to assess how well these pieces of information and knowledge work in harmony with each other—that is, how does the tacit knowledge complement (or perhaps challenge) the formal documentation? Is there an alignment in the knowledge base, or do participants' gut feelings contradict the formal data? In these situations, a degree of ambiguity and uncertainty—in the form of assumptions, beliefs, guesses, and so on—needs to be handled, perhaps not by initially focusing directly on reducing the uncertainty but rather by assisting decision makers in better understanding what these ambiguities, uncertainties, and assumptions actually involve.

The role of the gate is to evaluate what has been done in the previous stage and to determine the way forward: what needs to be done next, how this path should be undertaken, and which resources need to be allocated for the subsequent stage [Cooper (2008)]. Reviewers evaluate the information, or the deliverables, that have been developed during the stage, matching it against a number of criteria in order to make a decision. According to Cooper [2001], the reviewers have four options. The first of these is "Go," when the project is healthy and can move on to the next stage. Resources are then allocated for continued work. The opposite of this is "Kill," when the work has not progressed as expected and moving forward presents a major risk;

the project is thus terminated. In the middle, are the options to "Hold" and to "Recycle"; in other words, provided certain changes are made, the project can continue—with or without a delay, depending on the adjustments required.

The main functionality of the stage-gate process is decision making [Christiansen and Varnes (2006)]. Christiansen and Varnes [2006] claim that decision making in the gate meeting prescribes the use of rational choice theory to facilitate arriving at the right decision—essentially, whether to go ahead with, rework, or terminate a project.

An earlier study [Johansson et al. (2009)] found that product development in the aerospace domain is often contract driven, meaning that contractual agreements are signed between the participating companies before any development work begins. This has an impact on the gate decisions because any delays (entailed by a hold or kill decision) would trigger penalties as stipulated in the contracts. Therefore, companies want to avoid these actions.

3.2. *Uncertainty and Ambiguity*

Part of designing is managing uncertain or missing information and knowledge, communicating incomplete designs when aspects are missing and information is approximate [Stacey and Eckert (2003)]. In the literature the concepts of uncertainty and ambiguity are often not differentiated but are rather used to describe the same things, even though in fact they represent different viewpoints [Schrader et al. (1993)]. Sometimes the two are even used interchangeably, without clear distinctions [Perminova et al. (2008)].

One way to distinguish between ambiguity and uncertainty is to use the uncertainty/ambiguity matrix (see Fig. 3). At low ambiguity and low uncertainty, the variables, as well as their values and relationships, are known. Uncertainty relates to the fact that one knows which variables are available but not the specific numbers for these variables. In decision theory, uncertainty is viewed as a characteristic of a situation in which a range of outcomes are known, but the probability distributions related to these are unknown [Schrader et al. (1993)]. The structure of the problem is available [Schrader et al. (1993)], meaning that the variables and their relationships are present; the primary issue is filling them with information. Schrader et al. [1993] considers uncertainty closely related to lack, or scarceness, of information. Carleton et al. [2008] characterize uncertainty as "known unknowns," meaning that the variables are identified, but the values and parameters are incomplete, insufficient, or imprecise. Ambiguity, on the other hand, is portrayed as "unknown unknowns": one does not know what to measure, let alone where to look for parameters. Ambiguity is viewed as a lack of clarity regarding relevant variables and their relationships [Martin and Meyerson (1988)]. Schrader et al. [1993] see ambiguity on two different levels (see Fig. 3): at the first level, relevant variables are given, and the main problem is determining how these relate. At the second level, both the variables and their relationship need to be determined. However, since the understanding of variables changes frequently depending on which ambiguity level is chosen [Schrader et al. (1993)], it is often difficult to distinguish between the two types of high ambiguity [Carleton et al. (2008)].

UNCERTAINTY REDUCTION

	Low uncertainty	High uncertainty
Low ambiguity	Model using - Variables known - Values known - Functional relationships known	Model using - Variables known - Values ***unknown*** - Functional relationships known
High ambiguity Ambiguity level 1	Model building - Variables known - Values known - Functional relationships ***unknown***	Model building - Variables known - Values ***unknown*** - Functional relationships ***unknown***
Ambiguity level 2		- Variables ***unknown*** - Functional relationships ***unknown***

AMBIGUITY REDUCTION

Fig. 3. Uncertainty/ambiguity matrix (adapted from Schrader et al. [1993]).

Carleton et al. [2008] also find that there is an order to the uncertainty/ambiguity matrix in terms of how to reduce these undesirable factors and bring clarity: problem solvers must make sense of the situation and reduce the ambiguity before they can approach the uncertainty dimension and fill out the values for the variables.

Closely related to uncertainty and ambiguity is the concept of environmental uncertainty [Milliken (1987)], which suggests that the source of uncertainty is in the organization's external environment. Milliken [1987] divides this concept into three distinct parts: state uncertainty, effect uncertainty, and response uncertainty. The main differences between them involve the information that is lacking. In state uncertainty, the organization's environment is unpredictable, whereas effect uncertainty involves a lack of information about the impact of events and changes. Response uncertainty can be defined as difficulty predicting the consequences of choices or decisions [Milliken (1987)]. Response uncertainty is closely related to decision theory in that this is the type of uncertainty decision makers are likely to experience [Milliken (1987)], for instance, in gate meetings.

Solving a problem essentially has to do with reducing uncertainty and ambiguity [Sutherland (1977)]. Reducing uncertainty, in turn, involves gathering information about variables that are known to the problem solvers, whereas reducing ambiguity is about “model building, negotiation, problem framing, evaluating and reframing, and model testing” [Schrader et al. (1993), p.78]. Schrader et al. [1993] argue that there are differences in the mental models used to approach the two concepts, thus offering a way to distinguish between them. In cases of uncertainty, the availability and precision of these models are greater, allowing decision makers to know better where to look for the missing information. However, in cases of ambiguity, problem solvers might feel that they do not have a “good grip on the problem” [Schrader et al. (1993)]; essentially in these cases, the mental models are not adequate to support the problem-solving process. Reducing uncertainty basically entails filling the mental model with information, whereas reducing ambiguity calls for coming to grips with the problem and finding or defining the problem’s mental model [Schrader et al. (1993)].

3.3. *Decision Making*

Design is closely related to decision making, since design can be seen as “the evolution of information punctuated by decision making” [Ullman (2001), p.3]. From this perspective, Ullman [2001] defines a decision as a commitment to resources regarding the future development effort. Similarly, Mintzberg et al. [1976] define a decision as a specific commitment to action.

Mintzberg et al. [1976] have developed a three-step model for decision making consisting of the phases identification, development, and selection. The *identification* phase comprises decision recognition and diagnosis. *Development* can be both searching for existing solutions and designing customized solutions. Finally, the *selection* phase involves narrowing down alternatives, evaluating the final options, selecting one, and ensuring that management supports the decision. This is an example of rational decision making.

Rational decision making is related to rational choice theory [Scott (2000)], which states that all action is rational and that people calculate the costs and benefits of everything they do before they do it. Rational decision making is based on four aspects [March (1999)]: (1) knowledge of alternatives, (2) knowledge of the consequences of alternative actions, (3) consistent preference ordering, and (4) a decision rule by which to select a single alternative for action.

However, rational decision making is rarely found in practice [Simon (1979)]. Many problems in product development are intrinsically "wicked" [Rittel and Webber (1973)] or "ill-defined" [Cross (1982)], given that it is difficult to know everything about every alternative: "there are no true or false answers. . . . solutions are expressed as 'good' or 'bad' or, more likely, as 'better or worse' or 'satisfying' or 'good enough'" [Rittel and Webber (1973), p.163]. Similarly, Ullman [2001] states that decision making has to do with managing data, models, and knowledge in order to reach a good decision but acknowledges that seldom is all the information available and that time and resources are usually scarce, thus weakening the decision base. There will always be factors that are impossible or uninteresting to control, and this produces uncertainty [Ullman (2001)]. According to Eisenhardt [1990], careful analysis and finding the optimum solution are often sacrificed for the sake of keeping pace. In their review on strategic decision making, Eisenhardt and Zbaracki [1992] find that people are rational, but in a bounded way: "these traditional paradigms rest on tired debates about single goals and perfect rationality, and on unrealistic assumptions about how people think, behave and feel" [Eisenhardt and Zbaracki (1992) p.18]. Bounded rationality [Simon (1979)] arises when not all the alternatives are known, when external factors cannot be managed, or when consequences cannot be calculated [Simon (1979)]. *Satisficing*—again, a combination of *satisfying* and *sufficing*—describes the selection of an option that is simply "good enough" [Simon (1979)]. Making a decision often amounts to settling for what is good enough; therefore, the decision maker needs to approach the situation knowing that the decision will be based on what could be flawed information. Adequate awareness of what such flaws entail is the first step toward solving this issue.

4. Results: Stage-Gate model in an Aerospace Context

The gates used at Company A are an adaptation of the group common development process (which covers a wider industrial spectrum than aerospace) to the industrial conditions applicable specifically to Company A (which works in the aerospace field). These gates are also to some extent aligned, where possible, with the ones the main partner companies use so as to avoid excessive redundancy in the collaborative development process. Key gate criteria are based on a predefined template covering all crucial areas of development, such as technical performance, budget, and scheduling. Formally the management team, along with the project leader, decides on the criteria and determines whether changes (i.e., the addition of complementary criteria or the removal of redundant criteria) are necessary. This is done on a gate-by-gate basis. Any changes to the criteria are preceded by the management team's careful consideration and involve a very formal process.

As mentioned earlier, product development in this industry is contract driven. One of the respondents said:

> "In our projects, we get an order from the customer over here [speaker pointed to a point early in the company's stage-gate process], so we have already sold what we are developing."

Consequently, the company has to ensure that when the order arrives and the contract is signed, it will be able to deliver what it has promised. Therefore, preliminary research and development (R&D) activities requiring comparatively few resources and typically targeting several development programmes are already in progress before the contracts are signed, in order to build competence and mitigate risk in the product-development phase.

Before the contract is committed to, a great deal of homework is done to assess the risks involved in signing it; as one of the respondents put it,

> "There is a breakpoint when you enter the contract. Before this breakpoint we do work to assess the risk that we take. Once the contract is signed and the project is launched, you have chosen to take a certain risk."

Once a project is in progress, Company A do not want to release the constraints in these contracts unless a substantial change occurs in the project's terms or unless there is a risk for flight safety. Inability to fulfil one's commitments is usually not an acceptable reason to break a contractual agreement. One of the respondents made clear that although internal issues may not yet be clear enough to allow the project to move forward, these seldom constitute a reason to delay entire programmes, which is the effect holding would have on the supply chain. A faltering decision-making process becomes an issue for the company as a whole because most projects are conducted in an interorganizational fashion, with firm contracts in place. If a project is not viable, a breach of contract will trigger penalties.

Therefore, projects are rarely disbanded, and decisions are made from a more pragmatic perspective in which the most important task for the decision maker is to help the team meet the gate criteria. In practice, stakeholders want to deal with issues, such as uncertainties, that arise at the gate *while* moving ahead with the broader project—opening the gate, instead of terminating or delaying an entire project. As one respondent put it:

> "To identify where the risk is and deal with that risk . . . is more rational than to say; 'Full stop; finish up before moving on.'"

What happens in reality is that weaker areas are flagged "yellow" in the gate documentation. Often project leaders can anticipate the outcome of the gates, since they know about gate criteria ahead of time (even though a formal decision is necessary given the industrial context); they can thus propose actions for completing the task at hand. Action and time plans are created for completing the work. This is done in conjunction with the next phase so as not to lose time. This dynamic aspect of the process means that in relation to external partners, projects never stand still. Deviations are managed internally through the regulation of effort and resources in the catch-up actions. As one respondent indicated,

> "From the beginning I think the idea was that we were supposed to take 'go/no-go' decisions. But in the end nobody really believed it, since projects were never stopped."

The stage-gate model's main benefit here is not the go/no-go decision logic (for although the no-go option is always possible, it is not probable); rather, the respondents see it as a valuable tool for keeping projects aligned with the plan. At the gate, people are required to present and defend their views and to answer for their choices by sharing information and knowledge with others. At the same time, they can challenge the perceptions of others and advance the project's knowledge base. One respondent said that this forces everyone to relate to the material:

> "This is the strength with the gated process. Allow things to mature for long enough, then bring it up and relate to it."

And from experience, the respondents see this as a function that is needed in the stage-gate process and the gate meeting. This collaborative aspect is something that they need to deal with:

> "Even though you think you have things under control, there are all sorts of things popping up that you have to relate to and deal with."

This is an essential factor in ensuring that the development project remains on track and does not ultimately end up behind schedule in a way that cannot be managed. As one respondent pointed out,

> "[The] gated process is so important to us, since we need to keep on track and not end up in a situation where we find out that the project is not profitable."

The threat of falling behind places the company under intense pressure from customers and partners; therefore, the highest priority is to stay on track and not slow the project down.

One respondent highlighted the importance of reflecting on each project participant's position in relation to the project's goals, adjusting actions and activities in accordance with these goals:

> "You reflect on where you are and what you're doing instead of just keeping on working and running your head against the wall."

In dealing with situations that involve various degrees of ambiguity and uncertain information, as well as with situations in which information and knowledge are lacking altogether, the gated process is an important tool for managing these challenges, even though making go/no-go decisions is not the main priority.

5. Discussion

This study shows that the tough decisions advocated in the stage-gate model are not made with substantial frequency and that the process, as well as the gate meeting, takes on a more communicative role. One could argue that this is a weakness and a risk of the stage-gate model. However, Company A is successful and takes part in most major current and future aircraft programmes; headed by both of today's major OEMs, the company provides value to its partners. To a certain degree, the nature of the industry, in its contract-driven product development, has made the management of uncertainties and ambiguities more important than ever because falling behind is simply not an option.

As Christiansen and Varnes [2006] highlight, the stage-gate model is supposed to focus on making rational decisions. However, the actions devised in Company A demonstrate that the practical instantiation of the gate obviously does not support the rational approach to decision making that Cooper [2008] advocates. This finding concurs with Simon's [1955; 1979] contention that rational decision making does not exist in practice. Christiansen and Varnes [2008] have identified a similar tendency, referring to a concept of appropriate decision making [March et al. (2001)]. This concept builds on the logic of appropriateness as opposed to the logic of consequence, which the rational paradigm of decision making advocates [Cyert and March (1992)].

The pragmatic approach that has been found in practice can be compared to "bounded rationality" [Simon (1955); (1979)]. In a state of bounded rationality, access to information is limited, basically rendering rational decision making untenable because it is not possible to evaluate all the alternatives [Simon (1979)]. Decision makers *satisfice* [Simon (1955)] decisions—that is, they make a trade-off between the optimal and the sufficient, being forced to select an option that is simply good enough. This model comes close to the way decision making is done at Company A, for in virtually any decision-making situation (though to varying degrees), decisions must be made, gates must be cleared, and the next stage must begin in order for the company to keep up with its partners.

Action plans are then devised to deal with elements that are considered "not good enough yet"; this is an area of concern because these decisions need to be made even though the team might not be entirely confident about the status of the knowledge on which they must base their decisions. This circumstance is also found in other companies [Christiansen and Varnes (2008)], which have reported that kill decisions are rare and that they make extensive use of what they call "conditional go" decisions.

Christiansen and Varnes [2008] also find that time is the most important criterion, more vital than any other, since falling behind is highly undesirable.

Although the numbers may be correct, the knowledge behind them is occasionally based on assumptions rather than on facts. Without knowing the real characteristics of the knowledge used at the gate, the decision makers are challenged to make decisions despite these uncertainties.

In this study, ambiguity and uncertainty are apparent both in the comments regarding the conditional go decisions and also in that respondents see the gate meeting as an important forum in which to highlight and bring up a given ambiguity or uncertainty. That potential surprises emerge at the gate is a sign either that adequate information is missing or that it has not been framed correctly [Schrader et al. (1993)]. The gate meeting then plays an integral part in reducing both ambiguity and uncertainty [Schrader et al. (1993)].

From the perspective of decision making, considered the main objective of the stage-gate model, a boundary object represents a way of dealing with ambiguity and uncertainty, of addressing the "wicked" [Rittel and Webber (1973)] and the "ill-defined" [Cross (1982)] nature of problems. It should be noted, however, that ambiguity is recognized as both a drawback and an opportunity for the design team [Stacey and Eckert (2003)], especially when making decisions at the gates. Knowing about ambiguities and uncertainties at the gate reviews provides awareness so that the team can manage and mitigate these ambiguities and uncertainties, allowing decision makers to be more confident in their choices. Here, the concept of "conscious uncertainty" [Modica and Rustichini (1994)] is interesting: a state of knowing that one does not know something (cf. known unknowns).

The stage-gate model resembles a boundary object [Star and Griesemer (1989)] that the team and other stakeholders can gather around, discuss, and use to deal with issues in the project; it assumes a role similar to that of a prototype or a model. The stage-gate model is a common denominator that the stakeholders can use to visualize progress and communicate the status of the project and to determine what is missing and what is needed. It synchronizes people's perceptions of the progress being made, bringing various actors onto the same page. Similarly, Engwall et al. [2005] conclude that the stage-gate model resembles a boundary object because it mainly supports coordination, communication, and sense giving [Engwall et al. (2005)].

From a knowledge perspective, boundary objects provide "a concrete means for individuals to specify and learn about their differences and dependencies across a given boundary" [Carlile (2002), p.452]. It provides a means through which people specify what they know and what they are unsure about [Carlile (2002); Browne and Zhang (1999)], communicating this to other team members. A closer look shows that the stage-gate model is intended to support knowledge creation through the intermediary states [Boujut and Blanco (2003)], from immature to mature knowledge, of the product. Similarly, Engwall [2003] highlights the need for supporting such a *knowledge journey* in the context of the stage-gate process, in which a pragmatic and less rigid instantiation of the gate better supports learning about the product.

However, again from a knowledge perspective, the concept of a stage-gate model as a boundary object can be taken a step further, facilitating negotiation between engineers and supporting learning about the product. For instance, a boundary object means different things to different people [Larsson (2003)]. Thus, the stage-gate model is closer to the concept of "boundary negotiating artefacts" [Lee (2007)], which deviates from the boundary object idea in that the artefacts are in a state of continuous change and reinterpretation, and the people dealing with them push and renegotiate the boundaries. Boundary negotiating artefacts support the team members in questioning the conception of a project and the knowledge they believe they possess. This kind of conflict is an important basis for new knowledge creation because people, through synthesizing their beliefs and questioning what they see, can create new knowledge. The stage-gate process, therefore, plays a more refined and a deeper role in the design activity and should be not be considered merely a means to support communication among team members. The boundary negotiating artefact [Lee (2007)] is not simply a physical exhibition of knowledge but rather a way of challenging and questioning what the members of the design team believe they already know.

The role of the stage-gate process has been found to facilitate communication and discussion among the team members who gather around it and relate their perceptions to it. Much of the work taking place in relation to the gates seems to involve both sensemaking [Weick (1995)] and reflection [Schön (1983); Weick (1995)]. For people with different perceptions of reality, the gate acts as a discussion trigger. This allows people to voice their opinions and discuss why their views differ, as well as to consider what they can learn from those differences.

As this study and its discussion show, in the words of Schön [1983], technical rationality is becoming more and more unrealistic for modern practitioners. Instead, decision makers need to be able to deal with messes—that is, ambiguity, uncertainty, and complexity—in a confident way. Modern engineering is not about solving problems alone, since those problems have in some cases not yet been defined. The first thing practitioners need to do is to determine the problem. This activity can be seen as a reflective conversation with the situation. In the case of the stage-gate model, the activity of bringing one's perception of the stage-gate process to the table could be seen in this light. To use Schön's [1983] terminology again, actors need to set the problem they will solve, not simply solve it. In this activity, experience is an important factor because practitioners will fall back on experience—previous examples, understandings, and actions—in order to reframe and define the problem [Schön (1995)].

The stage-gate model appears to play an important role in this context, facilitating communication about the status of a project and about areas in which more knowledge might be needed to facilitate a confident decision to move forward. The latter is crucial when managing projects with strict contractual obligations, as in aerospace product development, because not being able to move forward both creates negative repercussions for industrial partners and invokes penalties for the company. Companies need to see and know early in the development process whether they are on track and whether changes are needed.

This process of reflecting and making sense of the decision material needs to be supported in some way. The communicative and negotiatory dimension of the stage-gate process mentioned in this paper is often implicit and dependent on people's ability to reflect on the status and quality of the available knowledge elements. There needs to be a structured way of considering the knowledge dimension—that is, the amount of learning that has been achieved about the product and the environmental factors in connection with it. Engineers should employ a method that forces them to reflect on questions such as these: "What do we know about the product, process, market, and so on?" "What do we not know?" "What do we need to know?"

In project management literature, the main areas of project evaluation revolve around time, cost, and performance [Meredith and Mantel (2010)]. It should be noted here that this paper does not attempt to argue against these measures; however, as effective as they may be in terms of assessing progress, there exists a need for evaluation based on the knowledge that supports the project result. In this context, the stakeholders would benefit from further support for discussing the learning that takes place at the gate.

Further, even though evaluation and decision making are important for any project, this dimension should also support the engineers working on the project at each stage in developing the results that they will present at the gate. Having a tool that visualizes this aspect and thus provides a better understanding of the uncertainty and ambiguity that might arise would help engineers take corrective action as early as possible.

5.1. *Scenario to Illustrate the Application of Knowledge-Focused Evaluation Criteria*

The following fictitious example is intended to illustrate the way the stage-gate process could be supported with a more knowledge-focused approach.

Each stage, or work phase, is essentially a stage between two gates, both of which affect conditions for the work. In the first gate, which precedes the work phase in question, the stakeholders need to agree on and communicate the evaluation criteria for the next gate. The steering group approves criteria and acceptance levels, which represent the advancement of the gate in question.

When work in the stage of this stage-gate process starts, the acceptance criteria will guide the team through the stage, instructing team members as to which performance levels are required, as to the necessary level of quality in terms of information, and as to the methods and tools to be utilized. Explicit knowledge-related acceptance criteria will make this aspect clearer and more explicit for the team.

As the team prepares for the gate, they analyse their results from the work phase and create deliverables to be sent to the steering group as input for the gate meeting. At this point, they analyse their results relative to the expectations set by the acceptance criteria. Using knowledge-related acceptance criteria, team members can also focus and reflect on their learning from the work phase, as well as discuss their confidence in the results that they bring to the gate.

At the gate, the project leader and the team in collaboration discuss the progress not only from performance, time, and cost perspectives but also from a knowledge point of view. Weak areas and areas in which their perceptions differ are targeted for further elaboration. Regarding any weak areas, the project leader and the steering group can propose actions to be implemented that will raise the confidence level.

The knowledge-related dimension of the stage-gate process allows actors to develop a more nuanced perspective of both the work in the stage and the decisions that need to be made at the gate.

6. Conclusion and Managerial Implications

This paper has investigated the stage-gate process in an aerospace context, drawing mainly on interviews with stakeholders working with the stage-gate model, in order to reach a deeper understanding of how the process relates to ambiguity and uncertainty in the decision-making knowledge base.

The stage-gate model's role in practice has been found to differ from its theoretical role (e.g., [Cooper (2001); (2008)]). Instead of making kill decisions, actors normally flag the area in question and draw up an action plan. A major reason for this is that development is contract driven: contracts are signed before development begins.

Naturally, if the decision pertains to flight safety, in particular to certification issues, a decision would be taken not to proceed but to address the problem. It should be noted that this does not mean that these developers and engineers treat their tasks lightly; rather, it highlights a need for managing the development in a pragmatic manner. Actors attempt to identify any risks and deal with them while simultaneously moving the project forward.

This is one area in which the stage-gate model seems to be beneficial for Company A. It acts as a common denominator through which they can raise issues for discussion, communicate and visualize their progress, and make sense of the knowledge base in order to manage open issues.

In the analysis presented here, the role of the stage-gate process can be likened to that of a boundary negotiating artefact [Lee (2007)], facilitating communication, discussion, and knowledge sharing, as well as highlighting areas in which additional knowledge is needed so as to deal with ambiguities and uncertainties and to raise confidence in decisions. Team members bring their perceptions of the knowledge base to the table and defend their views against any challenges posed by others, thus negotiating the boundaries of people's perceptions of the knowledge base.

Based on this, three managerial issues can be highlighted:

(1) It is essential that managers be aware of the differing role of the stage-gate process and the sensemaking processes. It is important that they acknowledge this role and support this process in the best possible ways—for instance, by assembling the proper people to support this usage of the stage-gate model.
(2) Managers need to be aware that the knowledge base is often not ideal and should devise actions in order to seek complementary information, knowledge, and expertise. It is important that they shift their mindset from focusing on kill decisions to helping the project along by providing latitude for the management of ambiguity and uncertainty in what is effectively the project's learning process.
(3) Essentially, stakeholders in the gate meetings need to be able to reason about knowledge in a similar way, as they do with other evaluation criteria, such as performance, time, and cost considerations.

The processes taking place in the gates seem to be of an ad hoc nature and depend a great deal on the people who are working in the gate, as well as possibly on the culture of the company and its particular environment.

What is needed is a formalized framework that will support a more intentional focus on the knowledge base and thereby also on any ambiguities and uncertainties. It would be interesting to develop knowledge-related evaluation criteria that, with the proper support for visualization, could facilitate both the gate meeting discussions and the reflection that is needed during the work itself.

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