PAPERS

Knowledge Maturity as a Means to Support Decision Making During Product-Service Systems Development Projects in the Aerospace Sector

Christian Johansson, *Division of Functional Product Development, Luleå University of Technology, Luleå, Sweden*
Ben Hicks, *Department of Mechanical Engineering, University of Bath, Bath, United Kingdom*
Andreas C. Larsson, *Department of Design Sciences, Lund University, Lund, Sweden*
Marco Bertoni, *Division of Functional Product Development, Luleå University of Technology, Luleå, Sweden*

ABSTRACT

Streamlining new product development forces companies to make decisions on preliminary information. This article considers this challenge within the context of project management in the aerospace sector and, in particular, for the development of product-service systems. The concept of knowledge maturity is explored as a means to provide practical decision support, which increases decision makers' awareness of the knowledge base and supports cross-boundary discussions on the perceived maturity of available knowledge, thereby identifying and mitigating limitations. Requirements are elicited from previous research on knowledge maturity in the aerospace industry, and a knowledge maturity model is developed through five industry-based workshops.

KEYWORDS: knowledge management; new product development; stage-gate; aerospace; product-service system

Project Management Journal

Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pmj.20218

INTRODUCTION

To stay ahead of the competition in an increasingly global marketplace, product-developing companies need to improve continuously both what they offer to the market and the processes by which they produce such offers. Since the research and development (R&D) process requires capital investment, which cannot be returned until the products reach the market, one priority is to make the product-development process more effective and efficient, to reduce lead-time and cost without sacrificing quality. For new product-development projects, this means that the decision-making process, typically structured according to a stage-gate (Cooper, 2001, 2008) format, with stages and gates, where information and knowledge are prepared in the stages for decisions to be taken in the gates, needs to be rendered more effective. From a project management perspective, a key challenge is how to make the right decisions in light of uncertainty, and thus how to make correct judgments about preliminary information, or even about established knowledge that may or may not be relevant for a particular context. Although there will always be a major element of risk, ambiguity, and uncertainty in any design activity, a radically transformed business context is emerging that changes the game of project management and requires project managers to improve their abilities to assess the level of maturity of the information and knowledge at their disposal.

For many capital-intensive products, such as aerospace products, the breakeven point when product sales generate enough profit to cover the initial product-development investment, can lie several years into the life cycle of the product (Buxton, Farr, & MacCarthy, 2006). A key challenge when shortening development cycles is that the same number of decisions needs to be made, only in a much shorter time frame—without decreasing quality. Alternative viewpoints on how to meet this challenge include being able to make the right decision directly to avoid costly iterations, or to fail early and often to succeed sooner (Kelley, 2001; Schrage, 2000; Thomke, 2001). Regardless of the view taken, the continuous streamlining of product-development processes forces companies to make decisions based on a higher degree than before on preliminary information and assumptions rather than on established facts. While acknowledging that product development and innovation will always be an exploratory activity laden with ambiguity and uncertainty (Bucciarelli, 1994; Stacey & Eckert, 2003), it has become more important than ever to efficiently and explicitly identify and understand such ambiguities and uncertainties during the development process (Stacey & Eckert, 2003). In the context of the aerospace sector, both given the rigorous regulatory frameworks related to aerospace safety (i.e., Federal Aviation Administration [FAA] regulations, etc.) and the long life cycles of the products, it is imperative to come to grips with these uncertainties and ambiguities and make sure that any decisions are made with confidence that the information is accurate and mature. The sources of uncertainty can be many, including considerations related to technology (i.e., will it perform as expected?), production (i.e., can it be effectively produced?), user needs (i.e., do the customers perceive it as valuable?), and market conditions (i.e., is the market large enough to justify the investment?) (Thomke, 2003). Aside from uncertainties that the development teams are aware of but might not have answers to, there are also implicit assumptions and ingrained views that might pose significant risks if not attended to carefully. For example, Thomke (1998, 2001) reported on how the car manufacturer BMW's engineers assumed that the stronger the area next to the base of a car's pillars (the structures connecting the roof to the chassis), the better the car would perform in the event of a crash. However, they later determined that strengthening that particular area would actually decrease the crashworthiness of the vehicle, and that the safer option was to weaken, not strengthen, the area.

Product-Service Systems

In the context of product-service systems (PSSs; Mont, 2002) and total offers (Alonso-Rasgado, Thompson, & Elfström, 2004), being an integration of hardware and service developed simultaneously in an integrated approach (Tukker & Tischner, 2004), many diverse knowledge areas (e.g., engineering design, manufacturing, business development, etc.) need to be more closely integrated. As a consequence, no one team or individual can integrate such knowledge, and the integrated development teams (Ulrich & Eppinger, 2008) are heavily dependent upon developing and maintaining a shared understanding. In addition, the total offer concept means that the manufacturer is the owner (compared to the customer with a traditional product) for the full duration of the PSS life cycle (Tukker & Tischner, 2004) from the first idea to when it is recycled, and the customers buy the function that the product-service system provides when they require it. Therefore, all the risk related to maintenance and availability of the "product" lies with the manufacturer (Alonso-Rasgado et al., 2004) adding an incentive for developers and providers to explore ways of designing the product as efficiently as possible from a life-cycle perspective (Williams, 2006), to maximize the profit and value that can be drawn from it.

As part of a PSS, the hardware goes from being a value-adding artifact to something that primarily incurs cost and expenditure for the manufacturer (Williams, 2007). To manage this, the manufacturer and its partners need to bring as much "downstream" knowledge (i.e., knowledge about the latter phases of a future product's life cycle) as possible to the early phases of product development. For instance, such downstream knowledge could relate to in-use behavior, expected maintenance cycles, or recycling considerations. What are the weaknesses in the knowledge base when taking a full life-cycle perspective? What do they not know well enough to make confident decisions about life-cycle parameters? What are their assumptions, and under which circumstances can those assumptions be trusted? These aspects are filled with inherent uncertainty and ambiguity, as knowing about this is largely about knowing what is unknown. Key questions include the following: How many people actually know the unknown parameters and values related to the decision to be made, and how can they advance their understanding before making a decision?

A major concern in PSS development is that such development efforts normally begin with relatively little shared understanding with respect to the many disciplines and functions involved in the development process. While "traditional" product development is also highly integrated and cross-functional, the total life-cycle perspective and the integration of hardware and services inherent in product-service system development further intensifies the challenge of bridging a wide diversity of data and knowledge coming from all parts of the value chain (Nergård et al., 2006).

In the process of developing a product or service, it is considered most advantageous to make changes in the early stages, when relatively little capital is committed. However, the "design process paradox" by Ullman (2003) highlights that "the more you learn the less freedom you have to use what you know" (p. 18). This means that development teams are in the unfortunate situation of having limited knowledge in the early stages, when they have good opportunities to influence the design. When they have established a more developed knowledge base in the later stages, the major decisions have already been made, capital has already been committed, and it is therefore more costly and time-consuming to make changes. With assumptions and uncertainties abounding about the status of technical and process knowledge, regarding where to go next and why, companies need to deploy several complementary (Mankins, 1998, 2002) strategies and approaches to deal with such uncertainties.

There is a range of strategies and approaches in companies aimed at supporting decision making on the development of new technologies—for example, technology readiness level (TRL) (Mankins, 1995). However, while these approaches can also be suitable in a PSS context, the complexity of the total offers implies that companies not only need to assess the readiness of technological components, but also need to develop a shared understanding from a wide set of disciplinary concerns and perspectives. How each piece of information or knowledge contributes to the knowledge base used to make decisions must also be assessed. Furthermore, there is a need to provide decision makers with a deeper understanding of the status of the knowledge base, to help them deal with the uncertainty and ambiguity of the decision base, thus providing increased confidence for decision makers.

This article explores practical decision support for PSS development aiming to increase decision makers' awareness and understanding regarding the status of the knowledge base they draw upon when making decisions. In particular, cross-boundary discussions focused on the perceived maturity of available knowledge assets (i.e., knowledge providing potential value to the result) need to be supported, ensuring that any potential risks related to limitations in the knowledge base are identified and mitigated. The purpose of this article is to revisit previous exploratory and descriptive research on knowledge maturity and to propose a framework for how stakeholders in the stage-gate process can use the concept of knowledge maturity to more effectively deal with uncertainty and ambiguity in the stage-gate process.

Research Approach

This article builds on previous work on knowledge maturity as a decision support for stage-gate processes that have mainly been undertaken as explorative and descriptive research efforts (Ericson, Bergström, Johansson, & Larsson, 2007; Johansson, 2009; Johansson, Larsson, Larrson, & Isaksson, 2008; Johansson, Parida, & Larsson, 2009), exploring the problem area and providing a description of the challenge. In contrast to these previous studies, this article offers a prescriptive perspective, with an attempt to devise a support tool for the situation discovered in the previous phases. Based on the analysis of the problem situation and other developments in the area (e.g., TRL, etc.), and by attending to the quality and maturity of knowledge, it reports on the development of a set of knowledge maturity scales to support decision making in stage-gate processes. The aim is to increase the confidence for decision makers working in the stage-gate process, since they will be provided with a better understanding of the strengths and weaknesses of the knowledge base by which they make decisions.

Motivation

The main motivation for the development of the knowledge maturity scales comes from the increasing need for aerospace industries to make the product-development process more efficient by saving cost and time. This was also the main target of Value Improvement through a Virtual Aeronautical Collaborative Enterprise (VIVACE; 2007), an integrated project within the European Union's sixth framework program (FP6). The VIVACE goals stem from the Advisory Council for Aeronautics Research in Europe (ACARE; 2009) targets outlined in the strategic research agenda (SRA; ACARE, 2002) and developed under the initiative of the European Commission (EC). The ACARE group consists of members from the EC, EU member states, and aerospace stakeholders (i.e., airlines, manufacturers, academia, etc.), with the aim to develop the SRA, which is intended to guide development efforts in the aerospace domain to create a competitive industrial sector in the European Union, able to compete on equal terms mainly with their American counterpart.

Specifically, the targets of VIVACE (2007) were to achieve cost and lead-time savings both in development of aircraft (5% cost and lead-time reduction) and aero engine (30% lead-time reduction and 50% cost reduction) development. These targets were to be achieved through deployment of numerous advanced capabilities to deal with challenges and problems elicited in the partner companies' processes during the project. One of those capabilities was "knowledge-enabled engineering" being able to provide the engineers working in the processes with the right knowledge, at the right time. One of the challenges elicited was the "7 Day Proposal" use case (originally reported in a VIVACE technical report by Bovik [2006]) as part of the extended jet engine enterprise scenario work package, forecasting future business scenarios and business models.

The 7 Day Proposal

The main purpose of the 7 Day Proposal was to develop a customized value proposal for a PSS in a virtual enterprise within seven days, thus managing a wide range of aspects in a very short time frame, while still minimizing or at least having a good awareness of the ambiguities and uncertainties in the decision material produced for the gates. As a reference, the current nominal period for such an activity is somewhere from six weeks to many months, with peaks of several years.

Shortening this phase would allow companies to anticipate competitors in the market as well as reduce the time between proposal and sale, thus speeding up the return on investment timetable and increasing competitiveness in the global marketplace. One of the main drivers behind aiming for the kind of extensive reduction in lead-time that the 7 Day Proposal represents was to force radical changes to how things are done in practice. With a seven-day time frame, it is virtually impossible to do things the same way as before. For instance, the virtual enterprise partners have to be better prepared managing ambiguity and uncertainty in the decision base by

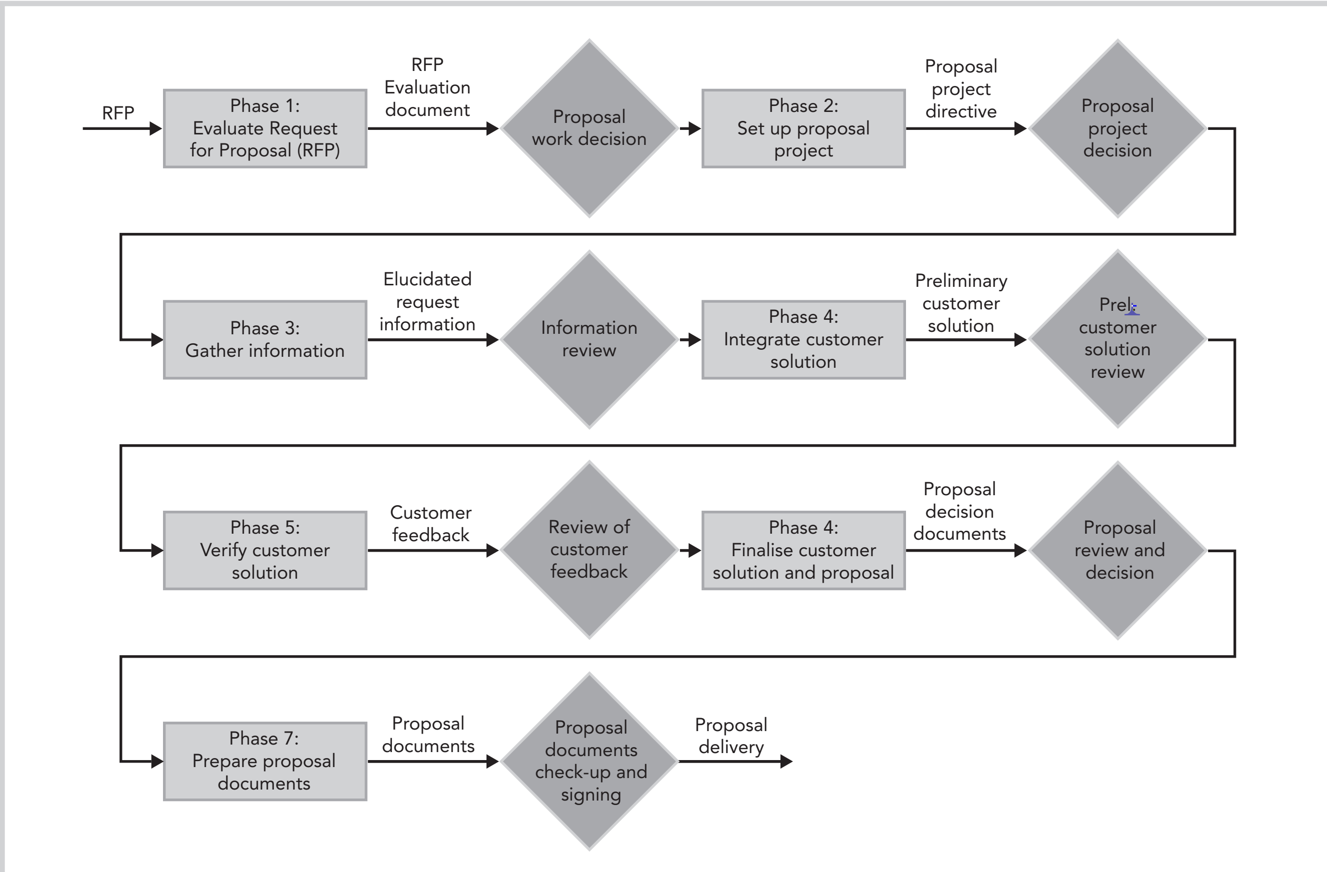

Figure 1: 7 Day Proposal process with stage and gate structure (adapted from Bovik, 2006).

making decisions on immature and sometimes unproven information and knowledge, but still maintaining confidence or at least understanding the level of confidence in the decision base and the decisions that need to be made.

The core of the 7 Day Proposal work was a definition of the process to develop a proposal in a stage-gate format (Figure 1), as well as a set of definitions of support tools and methods (i.e., advanced capabilities) needed to support the development.

Knowledge Support for the 7 Day Proposal

The knowledge maturity concept was perceived as an advanced capability to support the knowledge-intensive 7 Day Proposal process, where PSS necessitates sharing of large quantities of data and information between partners. In addition, it must efficiently deal with ambiguity and uncertainty due to the limited amount of time available to both identify relevant knowledge assets and to assess their maturity and readiness with respect to the needs and objectives identified in the 7 Day Proposal process.

The development of the framework is underpinned by the needs of the "7 Day Proposal process," as well as data collected in previous exploratory and descriptive studies (Ericson et al., 2007; Johansson, 2009; Johansson et al., 2008, 2009), where a synthesis of this data has formed an input to a set of requirements for knowledge maturity assessment.

To elicit the needs of the 7 Day Proposal, a research effort preceded the development of the knowledge maturity scale, where 18 months were spent in the VIVACE project with partners from Europe's aerospace industry with original equipment manufacturers (OEMs), tier 1 suppliers, and risk- and revenue-sharing partners, as well as research institutions taking part. This was then refined through a series of workshops with one of the partner companies, where knowledge support for the 7 Day Proposal process was identified as one of the key enablers. The process involved five workshops (see Table 1) with up to eight participants loosely following a future workshop approach (Kensing & Madsen, 1991). The participants were involved with three steps: (1) criticizing and problematizing the current situation, (2) wishing for a future scenario that solved the current problem, and (3) assisting in the development of the future solution. Here the focus was to elicit the participants' expertise of their work contexts to develop general knowledge maturity scales as well as to learn of their contexts to determine the utopian situation for them in a

Workshop No.	No. of Participants	Company(s)	Input	Focus	Output
Workshop 1 W1	5	Aerospace company 1	Knowledge maturity idea	Critique of current situation; early ideas and requirements for tool support	Early outline of ideas, scale, problems
Workshop 2 W2	6	Aerospace company 1	Draft scale	First draft of scale presented; outline of dimension areas completed	Developed scale, dimensions
Workshop 3 W3	7	Aerospace company 1	Redeveloped maturity scales, suggestions for dimension definitions	Development and refining of knowledge maturity scales; development of contextual scales	Refined definitions of criteria, draft sugges-tions of contextual maturity definitions
Workshop 4 W4	8	Aerospace company 1	Final scales	Dissemination; final revisions to the tool	Slight revisions to the final scales
Workshop 5 W5	5	VIVACE partners	Final scales	Dissemination; reactions and reflections on the support tool	

Table 1: Methodology for development of the knowledge maturity scale.

decision-making situation, and conversely what is the worst situation they can think of. This served as input to the knowledge maturity scales, together with established theories from related developments found in literature. The focus of each workshop and the outputs are described in Table 1.

The Role of Knowledge Maturity in Stage-Gate Decision Making

As previously discussed, this article addresses the need to support the decision-making process in PSS projects. In particular, it provides an understanding of the maturity of information and knowledge in cases where these can be both in limited supply and of varying quality (Zhao, Tang, Darlington, Austin, & Culley, 2008) and of a limited degree of completeness, trustworthiness, or accuracy (Darlington, Culley, Zhao, Austin, & Tang, 2009). To handle the paradox of doing more with less, decision makers need to improve their understanding of the "fitness for purpose" of a piece of information or knowledge, to make sure that the decision-making process is guided by well-founded ideas, principles, theories, insights, and so on. In this context, "better decisions" do not automatically result in "better results." However, it is a way of ensuring that decisions are taken with appropriate consideration of the maturity or readiness in relation to the decision-making objectives—that is, companies can choose to move forward with "known risk" as the result of a voluntary, conscious choice, rather than moving forward with unknown risk through an implicit, unconscious choice. In many situations, the end result of a conscious decision and an unconscious decision might be identical, but when it comes to successfully capturing and tracing decision rationale throughout a project, such an assessment can be of crucial importance (Bracewell, Ahmed, & Wallace, 2004; McAlpine, Hicks, Huet, & Culley, 2006). To contextualize the importance of assessing knowledge maturity in product-development projects further, the subsequent sections will highlight key aspects related to the role of knowledge maturity in stage-gate decision-making processes.

Decision Making

Mintzberg, Raisinghani, and Théorêt (1976) defined a decision as a specific commitment to action. Further, they defined the decision process as the "set of actions and dynamic factors that begins with the identification of a stimulus for action and ends with the specific commitment to actions" (p. 246). These authors developed a three-step model for decision making consisting of the stages of identification, development, and selection. The identification phase consists of decision recognition and diagnosis. The development phase is about both searching for existing solutions and designing customized solutions. Finally, the selection phase has three substeps—screen, evaluation choice, and authorization—to narrow down the alternatives, evaluate the final ones, select, and then make sure that the decision is supported by management. This model is an example of rational decision making. Rational decision making is related to rational choice theory (Scott, 2000), which is based on the idea that all action is rational and that actors calculate the costs and benefits of everything they do beforehand. Rational decision making is based on four aspects (March, 1999): knowledge of alternatives, knowledge of consequences of alternative actions, consistent preference ordering, and a decision rule by which to select a single alternative of action. Similarly, according to Simon (1979), rational decision making:

> . . . calls for knowledge of all the alternatives that are open to choice. It calls for complete knowledge of, or ability to compute, the consequences that will follow on each of the alternatives. It calls for certainty in the decision maker's present and future evaluation of these consequences. It calls for the ability to compare consequences, no matter how diverse and heterogeneous, in terms of some consistent measure of utility. (p. 500)

However, rational decision making is a rare occurrence (Simon, 1979). According to Eisenhardt (1990), it is more important to move fast and keep pace in projects than to carefully analyze all aspects. She said, "A slow strategy is as ineffective as the wrong strategy" (Eisenhardt, 1990, p. 53), since the fast-paced business climate would mean missed opportunities. In their review on strategic decision making, Eisenhardt and Zbaracki (1992) found that people are rational, but only in a bounded way, and further stated that "these traditional paradigms rest on tired debates about single goals and perfect rationality, and on unrealistic assumptions about how people think, behave, and feel" (p. 18).

Many problems in product development are intrinsically "wicked" (Rittel & Webber, 1973, p. 155) or "ill-defined" (Cross, 1982, p. 224), because it is virtually impossible to know everything about all alternatives: "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 & Webber, 1973, p. 163). Making a decision is often about settling for what is good enough rather than waiting for the optimal solution to emerge. This means that the decision makers need to approach the situation knowing whether or not the decision is based on flawed information (e.g., placeholder values [Flanagan, Eckert, & Clarkson, 2007]), uncertain information about competitors, assumptions, or missing information (Rosenzweig, 2007), coming back to the limited degree of completeness, trustworthiness, or accuracy (Darlington et al., 2009). Raising the awareness of what such flaws entail is a first step on the way to a solution to this issue.

Simon (1979) discussed bounded rationality, which arises when not all alternatives are known, when external factors cannot be managed, or when consequences cannot be calculated; it is essentially when decision making is not fully rational. *Satisficing*, a portmanteau of *satisfying* and *sufficing*, is an important word in this context, because it describes the selection of something that is good enough (Simon, 1979). Eisenhardt and Zbaracki (1992) found that it is not a question of either being rational or boundedly rational, but that most decision makers are rational in some ways but not in others. In the field of project management, decision making in the context of uncertainty is a major issue (Kerzner, 2009), and this article does not imply that making a decision in an uncertain situation should be considered "irrational." Rather, the point is to support decision makers in the process of challenging assumptions, evaluate cause-and-effect relationships, and assess the accuracy, quality, stability, completeness, and relevance of the information and knowledge at hand, rather than merely assuming these characteristics.

Stage-Gate®

Stage-gate, developed by Cooper (2001), is a process that facilitates projects from idea to launch of a product. The process can be seen as a set of information-gathering activities or phases (Cooper, 2008), with evaluation and decision points at intervals between the phases. The overall process map is shown in Figure 2.

The key components of the stage-gate process are the "stage," where activities take place, and the "gate," where information is assessed and decisions are made (Figure 3).

Each stage can be seen as an information- and knowledge-gathering activity that, after analysis and deliberation by the project team, produce deliverables as input to the gate (Cooper, 2008) (Figure 3). As identified in previous research (Johansson, 2009; Johansson et al., 2009), the deliverables brought to the gate meetings include summary documents, criteria documents, design rationale documents, technical reports, analysis results, and test reports, as well as the tacit knowledge of the people performing the work.

It is important to note here that even though the decision makers may have many complementary sources to use in the decision-making process, a crucial challenge is how to assess these knowledge sources and knowledge assets with respect to their fitness for purpose. What is the level of readiness of the presented information? Is it reflecting assumptions or verified facts? Is there anything missing? Is the information current or out of date? Are there specific knowledge assets that would need further development to contribute more clearly to the objective? Is there a need to prioritize refinement of some aspects over others? In addition, it is important 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 does the gut feeling of the participants contradict the formal data? In these situations, there is a degree of uncertainty that needs to be handled, perhaps not by directly focusing on reducing the uncertainty, but rather by assisting the decision makers in achieving a better understanding of what those uncertainties, ambiguities, and assumptions actually involve.

Within each stage, activities are normally undertaken in parallel. The

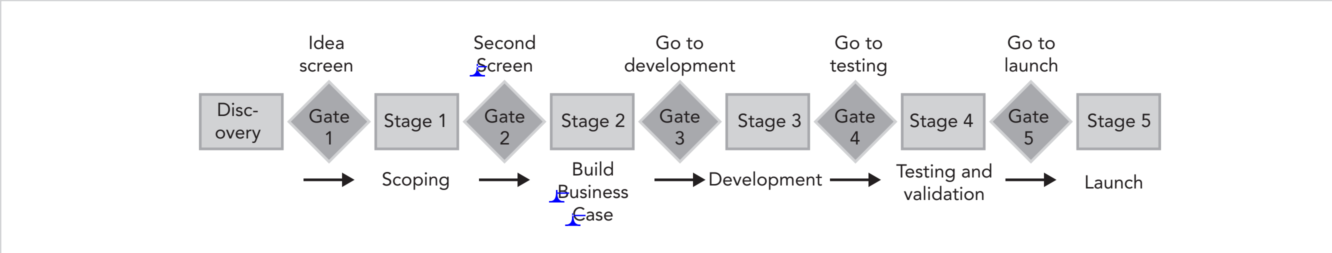

Figure 2: Stage-gate process overview (adapted from Cooper, 2008).

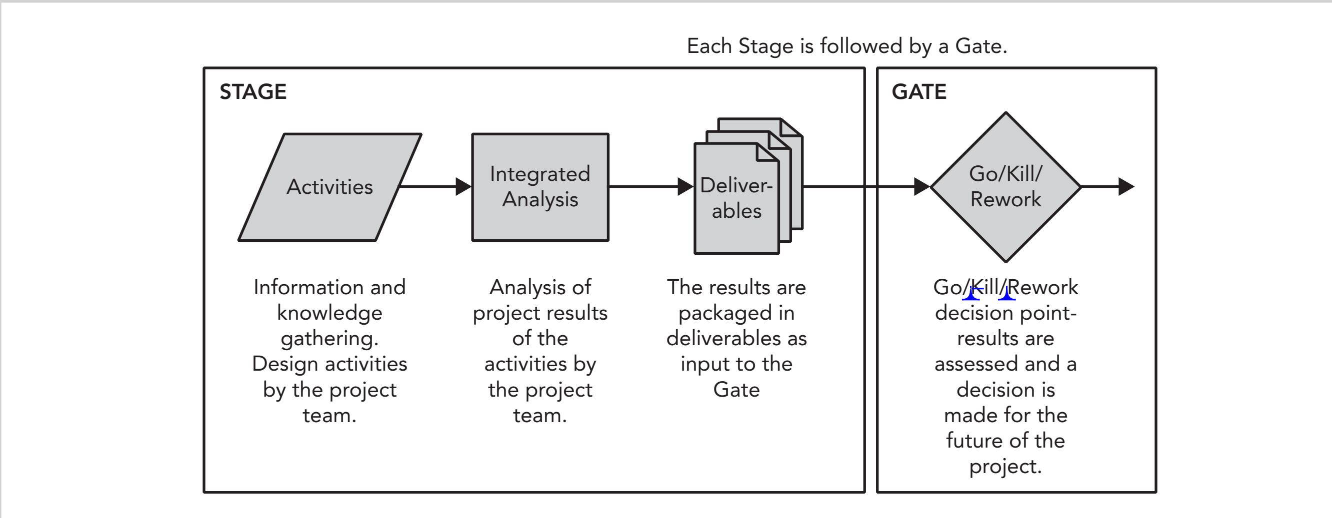

Figure 3: Stage-gate structure with a stage followed by a gate (adapted from Cooper, 2008).

role of the gate is to evaluate what was done in the previous stage and to decide the way forward, what should be done in the next stage, how that path forward should be undertaken, and the resources to be allocated for the next stage (Cooper, 2008). Reviewers evaluate the information, or the deliverables, developed during the stage. This information is matched against a number of criteria to make a decision. According to Cooper (2001), the reviewers have four options to choose from. The first option is "Go," when the project is in good health and can keep going into 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 further presents a major risk. The project is thus terminated. In the middle is the option either to "Hold" or to "Recycle"—that is, providing certain changes are made, the project can still go on—with or without a delay depending on the nature of the required changes.

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

From a project management perspective (Kerzner, 2009), the stage-gate model is a commonly used tool for portfolio management (Christiansen & Varnes, 2008; Cooper, Edgett, & Kleinschmidt, 1997a, 1997b, 1999, 2000; Project Management Institute, 2008). It compares projects to one another and decides on the continuation or stopping of projects and programs in a portfolio, by making sure not only that projects are done right, but also that the right projects are undertaken (Cooper et al., 2000). Cooper et al. (1997a, 1997b) saw the stage-gate model as a tool to maximize value of projects, finding the right balance between projects and to link the portfolio to the strategy of the business. However, in the context of this article, where development of aerospace products is governed by contracts among partners and where the dependencies between parallel projects are limited, the perspective of portfolio management is not as central to the managers at this particular level. Since the projects have been given the go-ahead with the signing of the contract, the gate meetings have a focal perspective on managing the project at hand.

Knowledge Maturity

Maturity is defined by Grebici, Goh, Zhao, Blanco, and McMahon (2007) as "a compromise between the target uncertainty and the expected uncertainty" (p. 282), denoting maturity as the *distance* between the level of completeness relative to what should be the level of completeness—that is, *as-is* status versus *to-be* status. Information maturity is thus the relative state of the development of a piece of information with respect to achieving a purpose, which implies that a piece of information may be mature for one purpose and immature for another. For example, a preliminary analysis result concerning the heat tolerance of an aero engine component may be good enough in the feasibility stage of designing the component, whereas the same numbers may be too inaccurate to be of value in the detail design stage. Bohn (1994) defined maturity of knowledge as "understanding the effects of the input variables on the output" (p. 63). He further stated that:

> The manager's or process engineer's goal is to manipulate the raw materials, controls and environment to get output that is as good as possible. It is customary to treat the environmental variables as exogenous and uncontrollable. However, with enough knowledge, the environmental variables can be turned into control variables and, therefore, are not exogenous. (p. 63)

The knowledge maturity concept builds on the assertion that not everything can be known—some things are known, while other things are not. With the terminology used earlier, some variables are exogenous and uncontrollable, while others can be controlled. In PSS development, and in particular of the innovative kind, there are many environmental and contextual variables, with varying degrees of controllability. While it would not be feasible to create innovative PSS, and at the same time completely eliminate uncertainty and ambiguity, companies would most likely benefit from learning more about what exactly those uncertainties and ambiguities involve. The same amount of decisions have to be made earlier in the process, but information and knowledge that can help guide such decisions is often in limited supply or based on preliminary findings and even vague assumptions.

Knowledge maturity is based on other frameworks of maturity—that is, technology readiness level (Mankins, 1995) and capability maturity model (CMM) (e.g., Bower & Walker, 2007; Paulk, Curtis, Chrissis, & Weber, 1993)—to apply these ideas to a knowledge context. Johansson et al. (2008) build upon the concept of knowledge maturity to create a measure of maturity where the state of readiness of a knowledge asset is assessed using a narrative scale, highlighting how "fit for purpose" a piece of information or knowledge is with regard to the objectives brought forward in, for example, a stage-gate review meeting. The basic idea behind the knowledge maturity model is to represent information and knowledge over three dimensions: input, method (tool), and expertise (experience). This enables an assessment of the input data, the tool to refine or develop the input into an output, and the individuals contributing to the work. In addition, it allows teams to have a shared artifact around with which they can identify and discuss issues of concern, visualize the current status of the knowledge base, and negotiate a shared understanding of the advantages and drawbacks with the available knowledge base. In turn, this will enable them to take action on improving the knowledge assets that are not yet perceived to be fit for purpose. Teams can thus reason about their collective knowledge, or lack thereof, in a similar manner as they usually do with aspects related to technical performance (i.e., technology readiness; Hicks, Larsson, Culley, & Larsson, 2009; Mankins, 1995).

From a project management perspective, the two main constructs of maturity (Cooke-Davies, 2004) are the Project Management Institute's Organizational Project Management Maturity Model (*OPM3*®) and the U.K. Office of Government Commerce's Project Management Maturity Model (PMMM). Cooke-Davies (2004) found that maturity models make a contribution to project management by (1) broadening the discussion in the field, (2) recognizing that a maturity in project execution comes with incremental improvements (as has successfully been demonstrated in the case of the CMM), and (3) bringing core values from quality movements into project management. Further, maturity models provide a visibility feature to project management (Cooke-Davies, 2004) and increase the awareness of the role that competences play in projects (Jugdev & Thomas, 2002).

Requirements for Knowledge Maturity Assessment

When designing a supportive approach for assessing knowledge maturity within the context of decision making in the stage-gate process, a set of features and considerations can be elicited from previous work. These include dealing with a diverse set of product and service parameters (Ericson et al., 2007) and dealing with ambiguity and uncertainty, as well as being able to take conditional go decisions in the stage-gate process even though knowledge and information is immature or even incomplete (Johansson, 2009; Johansson et al., 2009). Also, the development of other maturity-based tools relating to, for instance, technology readiness levels (Hicks et al., 2009; Johansson et al., 2008), need to be taken into consideration. When dealing with the design of product-service systems, while being under pressure to keep up with tight

Requirement	Knowledge maturity needs to . . .
Boundary negotiation	. . . support establishment and negotiation of boundaries, challenging perceptions of knowledge base.
Tacit knowledge sharing	. . . assess expertise and experienced people, point towards experienced people.
Learning	. . . support exploration of what-if scenarios and feedback implications of actions taken to improve knowledge base.
Visualization	. . . support visualization of current level of maturity relative to required level as well as support visualization of different alternatives relative to each other, acting as a discussion trigger on knowledge level and future activities.
Traceability	. . . trace individual factors of the decision base, and to *see* the relations and dependencies between PSS components and thus the impacts of actions being taken.
Prioritization	. . . support prioritization of some areas over others and give feedback of impact of actions on the total maturity of the PSS based on relative importance.
Pragmatic decision making	. . . support elaboration on risk of taking *go* decisions on loose decision bases, that is, differentiating between *no-go* and *conditional-go* decisions based on the quality of the knowledge base.

Table 2: Summary of the knowledge maturity requirements.

schedules in a highly distributed and diverse virtual enterprise, we identified seven fundamental requirements related to knowledge maturity assessment. The requirements are summarized in Table 2.

Support for Boundary Negotiation

The stage-gate process was found to fill a role of establishing as well as negotiating the boundaries that relate to people's potentially different perceptions of the available knowledge, thus facilitating collaboration and knowledge sharing (Johansson, 2009). Using the stage-gate as a boundary object, they can challenge each other's perception of the knowledge base and synthesize what they know, thus creating new knowledge.

The knowledge maturity approach needs to support this boundary-negotiating activity and enable the collective shaping of knowledge, allowing team members to share and challenge each other's perceptions of the maturity of the proposed decision base.

Support for Tacit Knowledge Sharing

Making decisions related to total offers and PSS (Ericson et al., 2007) means that the decision makers must take account of numerous aspects that they have limited knowledge about, and which they would have difficulties turning into a formal (explicit) (Polanyi, 1967) basis for decisions for the purpose of a gate review meeting. In the early stages of product-development projects, the relative importance of gut feeling, or intuition, was seen as having a greater influence on decision making (Ericson et al., 2007), because more formal decision materials, such as blueprints, virtual models, and bills of material, are often not developed at this stage (Ericson et al., 2007). Therefore, decision makers can be forced to rely on guesses based on a designer's experience of the way it usually is or what is acceptable. Additionally, also later on in projects tacit knowledge and gut feeling play an important role in complementing the formal decision material (Johansson et al., 2009). Recognizing that such gut feeling or intuition might be a result of years of experience, sometimes it is very hard to judge the level of maturity and quality of such emotionally laden knowledge since it is based on personal assumptions and experience more often than established facts. Here, it could be important to gather the "right" people for the task. These are the people who are experienced and recognized in the company for being knowledgeable to influence, and perhaps validate, the decisions that need to be taken so that they can be carried out in the company with increased confidence. A knowledge maturity framework therefore needs to support this aspect and both point toward the people who are knowledgeable as well as be able to assess the expertise and experience that underpins the decision material. It should be noted that another, complementary role of the knowledge maturity framework would be to challenge ingrained assumptions and rule-of-thumb perspectives at decision points.

Support for Learning

As seen with early development of PSS, the early phases, which require a lot of downstream knowledge about the PSS's life-cycle phases (i.e., use, maintenance, recycling, etc.), are characterized by uncertainty and ambiguity, making decision making challenging (Ericson et al., 2007). Based on Mintzberg and Westley's (2001) "thinking first," "seeing first," and "doing first" dimensions to decision making, the seeing first approach involves aspects related to the insecure situation of innovative PSS development, which enables team members to co-create a shared picture that allows them to see everyone's concerns. This is particularly relevant in situations where differences in opinion need to be voiced to challenge premature consensus—that is, avoiding groupthink (Janis, 1972). A thinking first approach is strong when issues are clear and information is reliable, allowing them to carefully define a problem, analyze its cause, and design a solution. PSS development is normally not as straightforward, and it includes visioning, imagining, playing with ideas, or alternatives—learning about the various options to move forward and reasoning about the pros and cons of each possible decision. Within the knowledge maturity approach, there is a need to support the exploration of what-if scenarios, such as how the perceived risk and expected outcome is influenced by an influx of resources—for example, adding a certain competence to the team or starting a knowledge-gathering activity.

Support for Visualization

Closely related to the learning aspect is the requirement to visualize the status of knowledge maturity. Visualization also relates to the seeing first approach (Mintzberg & Westley, 2001), in that a team needs to see the influence that its individual and collective actions have on the knowledge maturity and the project. Further, the visualization aspect is important when considering knowledge maturity as a boundary object—that is, the visualization of the criteria and the generic scale works as a catalyst for discussions around knowledge maturity and ambiguity issues, explicating any gaps in the knowledge base and facilitating knowledge sharing and creation to manage those perceived weaknesses (and take advantage of the strengths). A knowledge maturity support needs to provide visualization of the level of maturity relative to the required level at any time of the development activity. Further, impacts of changes (e.g., influx of resources, etc.) should also be visualized as part of a learning-focused approach.

Support for Traceability

In the context of PSS, where the value, performance, and life-cycle impact of such systems (or functions) are related to a wide range of cross-disciplinary, cross-enterprise issues, it is important to trace all the factors that compose the total offer, enabling stakeholders to track and address the relations and dependencies between different areas of the PSS. Using the TRL scale developed by NASA as a reference, the problem in a PSS perspective is not merely related to the aggregation of the different technical considerations into an overall metric—that is, deciding whether individual technologies are ready for integration into a system or subsystem. Here, the focus is shifted from merely aggregating different issues and topics into a whole toward supporting the individual traceability of all the aspects that influence the design of a total offer.

Support for Prioritization

For decision making, there is a need to prioritize certain factors and decisions. Consequently, it is more important to have a solid knowledge base in certain areas than others. For instance, in the context of aerospace, the most important areas are the ones that have an impact on flight safety and certifications and tests of the products by aerospace authorities, such as the FAA in the United States. In these cases, a pragmatic decision or adjusting the gate criteria slightly is impossible, because the product will still not be allowed to fly in the end. This has to be reflected in the maturity scales, highlighting the relative higher importance of these areas. Therefore, there is a need to provide a weighting or a prioritization mechanism to reflect the impact of the more important areas and parts in the whole.

Support for Pragmatic Decision Making

There is a need to differentiate between the strict *no-go* decisions (i.e., when to flag red and possibly terminate the project) and the more pragmatic decision situation (i.e., when to flag yellow and continue on the condition that changes are made). Considering the complexity and scope of many development projects, particularly those in the PSS domain, obtaining a green flag across all criteria, and thus a completely rational decision, would be an unlikely and utopian situation. It is important to highlight where the decisions are characterized by extensive bounded rationality. Furthermore, with so many decisions to be made, work will not stop completely in search of answers to problems raised at the gate reviews. Therefore, it becomes a matter of moving forward with manageable and known risk.

Development of a Knowledge Maturity Scale for the Aerospace Industry

From a decision-making perspective, shortening lead-time in the offer development phase in the 7 Day Proposal means that decisions need to be taken with shorter intervals as well as based on incomplete information since they will not have the time to either perform thorough analysis tasks or to wait for final results from ongoing technology/knowledge-development projects. However, the need to ground the decisions on a confident knowledge base is as strong as before, or perhaps even stronger due to the life cycle and ownership concerns that force companies to make a long-term commitment to deliver, without having the time or resources to analyze the consequences of such a commitment carefully. Dealing efficiently with ambiguity and uncertainty in the knowledge base, especially when the most important parameters are not even known to the decision maker (i.e., unawareness [Modica & Rustichini, 1994]), is a crucial success factor in this challenging context.

This argument shows strong similarities with the knowledge maturity concept in the stage-gate product-development process. In both situations, highlighting the uncertainties and the ambiguities in the knowledge base is a main concern. In a stage-gate decision as well as during the quick decision iterations in the 7 Day Proposal case, it becomes crucial to provide improved confidence for decision makers at the decision point. When the decision base is too poor, decision makers need to choose to either move on in spite of their poor understanding, thus accepting the risks and dealing with the issues, or, if necessary, choose to take corrective action immediately.

What became evident from the early development steps (workshops W1 and W2) was the need to assess a decision base over multiple dimensions, since many different, and sometimes contradicting, parameters could influence the quality of the knowledge used at the decision point. These parameters were synthesized into three main dimensions, thought of as having significant influence on the quality of the knowledge base. The three dimensions considered were *input*, *method/–tool*, and *experience/expertise*. The main rationale for this selection relates to the need to break down the knowledge/information carrier instead of just looking at it as is and trying to assess it, which would require a very high degree of abstraction—that is, analyzing the face value of the information. By dividing the focus into three dimensions, there is a way of getting behind the face value of the information, which makes it easier to digest the knowledge and reach adequate conclusions about its maturity as well as understanding the reasons why the knowledge elements look the way they do at the decision point. This essentially describes the underlying process resulting in the knowledge base used at the gate review.

Input

The input dimension plays an important role for the achievement of the output—that is, what is introduced into an activity strongly influences what results the team extracts from it, regardless of how the team can efficiently perform at the decision point. Therefore, having indicators that help indicate the level to which people may trust the material entering in the design activity is highly beneficial to understand the expected level of quality of the final output—that is, correctness of the decision taken regarding the design solutions proposed at the gate.

Method

The means with which the input is formalized is an interesting aspect to consider when analyzing the decision material. Some methods provide more confidence than others do. For instance, a full-scale prototype test might give the decision makers more confidence than a hand-based calculation of an idealized model, which is a lot cheaper. Different methods provide different confidence, and this is assumed to have an influence on the confidence of the decision base. Since investing in a prototype test would not be appropriate in some situations, a cheaper and less refined approach might be better suited. It is about finding an appropriate match for the case and knowing which is good enough for the confidence level needed at the specific time in the decision-making process.

Experience

The experience and expertise dimension of the decision base considers the people performing the work. Having an expert on board will add confidence in the material, especially in the early stages where facts are scarce and where the gut feeling and intuition related to experienced and knowledgeable people will be a strong influence, as discovered in Johansson et al. (2009).

It should be noted that there is interplay between the three dimensions. For instance, a less-refined method can be weighed up by having an expert contribute to the work, which means that if the expert says things are acceptable, the work can still move on to the next phase with the less-refined method applied to the material.

The Knowledge Maturity Scale

Initially, a base scale was developed (workshops W2 and W3) to serve as a reference for decision makers. The strength of this is that any team and any development project will have the same base knowledge maturity scale that they start out from. The generic scale was developed through consideration of TRL (Mankins, 1995) and the CMM (Paulk et al., 1993). These were chosen because they are the two main maturity constructs in use in industrial settings and since they deal with both the artifact (TRL) and the development process (CMM). This is useful when assessing the knowledge maturity of a decision base, since the decision base and its knowledge maturity will be reflected in both the process to develop it as well as its contents being an artifact. Table 3 depicts the generic narrative scale developed for the knowledge maturity concept, as developed in Johansson et al. (2008). It should be pointed out that the "dubious" and "good" levels (2 and 4) have been left out from definition in terms of criteria. The reason for this is that it was considered as sufficient at the early stage in the process to define the three levels "inferior," "acceptable," and "excellent." The two other levels can be used as intermediary levels for when an agreement might be difficult to reach among the stakeholders. Part of future development efforts of knowledge maturity, once testing of the concept can be accomplished and more learning can be achieved, is to develop definitions for these additional levels.

From the generic base scale, three dimensions related to input, method, and experience/expertise were developed (workshops W3 and W4; see Table 4), with the rationale for them described earlier. As with the generic base scale, this also provides a common reference point for the team, knowing that the levels are based on a structured thinking—that is, a level "5" essentially means the same to everyone. Having these predefined base scales enforces its usefulness as a

5	Excellent	The content and rationale is tested and proven. It reflects a known confidence regarding, for instance, risks. The procedure to produce the content and rationale reflects an approach where verified methods are used and where workers continually reflect and improve. Lessons learned are recorded.
4	Good	
3	Acceptable	The content and rationale is more standardized and defined (i.e., documented and formalized). There is a greater extent of detailing and definition (compared to previous level). The procedure to produce the content and rationale is more stable (compared to previous levels) with an element of standardization and repeatability.
2	Dubious	
1	Inferior	Content and rationale is characterized by instability (e.g., poor/no understanding of knowledge base). The procedure to produce the content and rationale is dependent on individuals, and formalized methods are nonexistent.

Table 3: Generic narrative scale for knowledge maturity (adapted from Johansson et al., 2008).

		Input	Method	Experience
5	Excellent	Input is detailed and verified.	Tested, standardized, and verified methods that are under continuous review and development.	Long-verified experience and expertise within area of concern.
4	Good			
3	Acceptable	Input is available in detailed form but is not verified.	Standardized and tested methods have been used.	Proven experience and competence within area of concern.
2	Dubious			
1	Inferior	Risk of incorrect input data.	Untried methods have been used (ad hoc).	The person doing the work is inexperienced (first-time).

Table 4: Generic knowledge maturity scales for input, method, and experience.

boundary object, where a major benefit with the maturity approach is not primarily the exactness of the assessment or having an exact measurement. Rather, the main benefit is that the stakeholders have a common denominator to debate, and they have something related to knowledge, learning, and uncertainty to debate. When opinions among stakeholders differ, their individual perceptions of the maturity levels can highlight this, triggering a discussion relating to the stakeholders' perception of the project.

Knowledge Maturity Scales for the Aerospace Sector

While the more generic scales are useful, it is of further benefit, and might be crucial, for the development team to adapt the knowledge maturity criteria to the specific context of the task in focus. Essentially, they create their own scales, in their own natural language, as they are accustomed to, from the generic definitions. Having scales adapted to the specific context makes it easier to assess what actions need to be taken—that is, which methods are specifically mature in the working context, which competences are needed, and what input data, with which quality, are needed. This process requires input from experts accustomed to working in the specific context, to contribute and assess what constitutes appropriate definitions for the specific knowledge maturity levels. Additionally, the assistance of a person acquainted with the knowledge maturity definitions and the rationale behind these definitions is needed to assist the experts in the definition work. There also needs to be a

		Input	Method	Experience/Expertise
5	Excellent	Very good quality of input data with assessment by customer as well as several independent sources.	Developed support system for risk assessment regarding future volume and prices.	Long-verified experience and expertise within the area of concern
4	Good			
3	Acceptable	Market survey based solely on data from customers.	Systematic modus operandi with qualitative risk assessment regarding prices and volume.	Proven experience and competence within the area of concern.
2	Dubious			
1	Inferior	Data from customer and independent sources is missing.	No evaluation of external data.	The person doing the work is inexperienced (first-time).

Table 5: Contextualized scale for market assessment, as developed by workshop participants.

validation process with independent people coming in as reviewers of the scale definitions being developed, to make sure that the definitions are kept at the right level and that the scales are not altered too much, rendering them ineffective. Further, as part of this, there is a need for an iteration process with the steering group, certifying that the scales are suitable as acceptance criteria in the following gate. This is especially important in the cases where the decision component represents a high risk for the company, or where it is "mission critical" that the decision is accurate—that is, that confidence mirrors a truly correct decision.

Table 5 shows an example of a contextualized scale for a market assessment, which was created by the participants in a series of VIVACE workshops (workshops W3, W4, and W5). Based on the generic definitions from Table 4 and with the help of several people related to business development in general, as well as one person working with market assessment in particular, the participants who used the researcher to relate the knowledge maturity definitions discussed and related prior cases of market assessment to arrive at the definitions described in Table 5. In this process, the industry participants, being experts on how they work, ubiquitously referred to previous projects as examples, making sense of the challenges with defining the scale. The main challenge in this phase is to relate to the best and worst cases imagined, not the best and worst cases experienced. For example, the fifth level is supposed to represent an optimal state, potentially making it difficult and rare to reach unless extraordinary resources and effort are devoted to it. Therefore, there is a need to be aware of this while defining the scales, so that they do not choose levels they know that they will reach, thus justifying those actions.

Since this practice adds overhead to the team's workload, not all areas are likely to go through this process. Some areas may be considered as insignificant, and thus the base scale will be sufficient. The contextualized scales will naturally be useful beyond the first project, by reusing the definitions in future projects faced with similar development efforts in other projects that are similar in the project portfolio of a company. The reuse of adapted TRL scales in the same company shows this value, for example, reusing the TRL definitions adapted for manufacturing (i.e., manufacturing readiness level). A structure for storing past definitions and a process for reusing them is needed, making sure that the "chain of evidence" is kept, verifying them before reuse, and ensuring that errors are not propagated.

As the scales have been adapted to the working contexts, the next stage is to apply them in the projects and at the gates. The definitions can be useful both for the teams doing the work, being able to assess "on the fly" what the level of confidence is, and naturally for the decision makers at the gates. It is, therefore, recommendable to agree on the scale and the required level of maturity before the work phase, so that the team can know the boundaries and expectations. As with the current, performance-related criteria, the team and the steering group need to agree at the first gate what the level of expectation is for the following gate, and so on for the following gates. This also applies to the knowledge maturity scale. This clarifies the expectations for the next gate and reduces the risk that the scale will be used incorrectly, setting targets that would be below what is customary. Once at the gate and when evaluating the previous phase and about to make a decision, it is useful for all stakeholders, regardless of if they are project leaders or if they are decision makers from the steering group, to assess the project results from a knowledge maturity perspective based on their perception of the results. Thereafter, they have a useful tool for comparing and discussing the confidence in the decision being taken by focusing naturally on the weak areas and on the ones where the stakeholders' assessments reflect a difference in perception. This is where the ambiguity and uncertainty is most likely to be found, and it is here that any decisions on corrective efforts should start.

Case to Illustrate the Knowledge Maturity Scale

The following example illustrates the application of the knowledge maturity scale, demonstrating how the scale is intended to assist in a decision on the market assessment in an offer-development process, such as the 7 Day Proposal process described earlier.

Initially, the team and the steering group needed to create the contextualized scale from the base scale, with the application of expertise regarding cost calculations.

In the first gate, the scale is completed and approved by the steering group as having levels that adequately represent the levels of knowledge in the case at hand. Thereafter, acceptance criteria for the following gate are set by the stakeholders and are communicated to and agreed upon by the team. In this example, an input of level 4, a method of level 4, and an expertise of level 3 are needed to pass the gate.

At this point, the work in the stage starts. The acceptance criteria will guide the team in the work in the stage, with regard to the fidelity of the input, methods, and expertise that is needed for the activity. For instance, setting an expertise level equal to 3 means that the team can still manage a solid level for the decision without necessarily involving top expertise in the company.

As the team prepares for the gate, they analyze the work conducted during the stage and compose the results into deliverables. At this point, they analyze the results relative to what is needed—that is, what numbers the market assessment activity can produce in terms of possible market size. At the same time, the knowledge maturity scales assist in assessing the level of trust in the numbers. This is where the scales are most useful to the development team, triggering discussion about the level of confidence in the material that will be brought to the gate. The team knows that the knowledge maturity scales work as a guide throughout the stage and when they prepare the deliverables. In addition, they know that this will be evaluated by the management team at the gate. After some deliberations in the project team, a shared understanding is reached regarding the results, and they prepare for the gate review.

Eventually, the understanding of the level of completeness is brought to the gate meeting as part of the deliverables, and the steering group performs the same assessment. Thereafter the results are discussed, mainly focusing on areas that are perceived as too weak and/or areas where the perception between stakeholders differs, trying to find ways to help the project move forward, either by clarifying the perception or, if necessary, by devising actions and milestones where the project needs to be brought up to the right standards. As part of the development team's discussion around knowledge maturity during the stage, they will propose actions to the management team in areas where they feel that the maturity level is too low, and where improvements are needed.

Having knowledge as an additional assessment dimension means that they have a more nuanced base to reason about, where of course adequate results and an adequate knowledge level are the ultimate goal. If either of them is too low, the team needs to assess whether improvements are necessary, and what improvements are needed and how quickly they need to catch up. Essentially, this type of coordinative artifact (Schmidt & Wagner, 2002) or boundary object (Star & Griesemer, 1989) plays the role of highlighting the knowledge base and triggering communication between stakeholders, which is a major benefit with the knowledge maturity scale.

Discussion

The work presented in this article is based on a conceptual framework developed in close collaboration with aerospace industry partners. Taking into account the extraordinary challenges related to the 7 Day Proposal, companies in this industry need to develop methods and approaches that are better suited for cross-disciplinary decision making in a virtual enterprise context. However, it should be acknowledged that the knowledge maturity work presented here also builds on a number of assumptions when it comes to forecasting the needs that are experienced and expressed within today's industry context. These are envisioned to arise in a not-too-distant future in light of an increasing interest in product-service system provisions and radically shorter proposal and development phases. Thus, the future workshop approach, outlined in the Research Approach section, has been useful in the investigation of both the limitations of the current stage-gate practices, and in the exploration of perceived opportunities to improve those practices with an increased focus on the assessment of the knowledge base used in stage-gate meetings.

The knowledge maturity concept puts knowledge in focus, supporting an increased awareness of assumptions (Lewis, Mahatham, & Wrage, 2004), uncertainties, and ambiguities from the sometimes distinct perspectives of the stakeholders in the stage-gate process. By highlighting the assumptions and uncertainties and facilitating a discussion on the uncertainties that are worthwhile to assess immediately and those to postpone, the framework provides the decision makers with a means to increase the confidence about the decisions they make. Here, making a confident decision does not imply that all issues have been attended to, but rather that the issues are raised. This increases the possibility to identify and mitigate risks by using the collective reasoning ability of the team, as opposed to basing decisions on what can often be ill-founded assumptions or uncertain results. As emphasized by Eisenhardt (1990), speed matters, reflecting the importance of not delaying decisions.

The knowledge maturity approach offers support with this aspect. Again, the objective is not to eliminate uncertainties or assumptions but to make decision makers aware that they exist, so they can more confidently start attending to them.

The knowledge maturity concept aims to avoid wasting time because the knowledge foundation is too weak. Gaining insights related to the status of the knowledge base early in the process means that mitigating actions could be applied before arriving at a point in the process where it is too late to act. Related to knowledge maturity is a concept briefly described as knowledge readiness level (KRL; Chiaramonte & Joshi, 2004), which highlights the need to assess the knowledge available to the team. In some cases, all that is needed is to make sure that the right people meet and collaborate and share what they know. At the other end of the spectrum, a fundamental research initiative is needed, and Chiaramonte and Joshi (2004) argued that "the cost of the 'answer' is related to the KRL. Low KRL's are relatively inexpensive, while high KRL's require substantial research funding" (p. 36).

One of the crucial aspects related to the acceptance of this kind of method in industry is how to balance its usefulness with the level of overhead required on the part of its users. There are plenty of methods for project management in general, and risk management in particular, and the extra workload on the part of the user is an important barrier toward broad acceptance. A perceived benefit with the proposed approach is that teams do not need to prepare for a knowledge maturity assessment in advance; it simply offers an opportunity to discuss, create awareness, and shape shared understanding of the status of the information and knowledge assets under review. Triggering a discussion is the main intention with the approach. Therefore, one could argue that there needs to be little precision involved in calibrating the method. It could serve as a checklist, or guideline, that can be attended to rather quickly in gate review meetings. If major issues should happen to arise because of the discussion, the issues need to be acknowledged and mitigation actions registered. If no issues should arise, the team can move on to other agenda items without paying more attention to the method. Thus, the ambition is that the method should be "lightweight" enough to be perceived as a useful contribution at a low overhead cost, in terms of resources and time.

Table 6 elaborates on how knowledge maturity supports the seven requirements that were presented earlier in the article, explaining the scale's role of meeting the requirements and supporting the stakeholders in attending to ambiguities and uncertainties in the gates as well as making decisions on knowledge that potentially is flawed.

Given the range of requirements, it is not possible to address all the dimensions

Requirement	How?	Description of Knowledge Maturity Support
Boundary negotiation	Knowledge maturity scale (boundary object)	Acting as a facilitator in discussion and knowledge sharing, being a conversational piece that triggers knowledge creation and elicitation, rather than a container of knowledge. Providing a common reference point to assess the knowledge base and discuss differences in perceptions of knowledge assets.
Tacit knowledge sharing	Knowledge maturity scale (boundary object)	Representing tacit knowledge and expertise and thus triggering discussions that can exchange tacit knowledge.
Learning	Computer-based support tool	Visualizing knowledge maturity to provide feedback and learning about impacts and effects of specific decisions and changes.
Visualization	Computer-based support tool	Relating current level of maturity to required level of maturity.
Traceability	Computer-based support tool, mash-ups	A computer-based support tool to the knowledge maturity scale would allow the stakeholders to trace individual components in the whole PSS.
Prioritization	Rating and weighting functionality	Different aspects of a knowledge asset (i.e., input, method, and experience/expertise) as well as different knowledge elements can be given preference depending on importance to decisions.
Pragmatic decision making	Knowledge maturity scale	Knowing the status of knowledge base relative to required status provides added confidence; that is, stakeholders know when and where the decision base is immature, and what has to be recovered before future decision points.

Table 6: How the knowledge maturity tool supports the seven requirements.

through a single tool. Therefore, in the fullness of time a suite of complementary tools are likely to be needed. From Table 6, it is apparent that there is a need to supplement the knowledge maturity scale with additional developments to support decision making in gates when developing a product-service system. More specifically, there is a need for a computer-based support tool to integrate and trace the vast amounts of information in the components of a PSS. Additionally, a mechanism for rating and weighting the decision components based on their importance and impact to the development of the PSS also needs development to support the stakeholders both in managing acceptance criteria and in devising and prioritizing actions. Notwithstanding this, the fundamental scales developed and the process of their application provides varied levels of support for the seven requirements. It should be stressed that, as indicated earlier, the main benefit of this approach is adding a dimension to the discussions that shape the rationale for decision making in the stage-gate process, and the computer-based tool will act as a support for this discussion with its visualization functionalities.

It is important to stress here that the scope of application of the knowledge maturity scales is mainly within development projects in the aerospace industry. The top level of such a project—that is, focusing on the airplane or aero engine as a product—is less applicable from a portfolio management perspective since the diversity is limited and contracts between stakeholders are driving decisions. However, on a sublevel, while deciding on different options for components and concepts, this kind of an approach can provide valuable support in contributing to the discussion with a knowledge perspective, which provides the stakeholders with “knowledge glasses” for the decisions that they need to make. Further, as mentioned earlier, the fact that the scales and their application in projects can be stored for use in future, similar projects further strengthens their applicability in this perspective. The knowledge maturity scales provide possibilities to tap into the knowledge base of previous projects.

Conclusions

The purpose of this article is to revisit previous exploratory and descriptive research on knowledge maturity and to propose a practical decision support to increase decision makers’ awareness and understanding of the status of the knowledge base they draw upon when making decisions.

Previous studies have observed the decision-making dynamics at the gates in an aerospace company, thus discussing how such activity could possibly be supported from a knowledge perspective, as opposed to the traditional performance-based approach. Furthermore, the analysis has outlined the need for methods and tools able to support cross-boundary discussions at the gate, to ensure that any potential risks related to limitations in the knowledge base could be identified and mitigated when making a decision.

Thus, this article presents a framework built upon the knowledge maturity concept. This framework is based on seven requirements for knowledge maturity: support for boundary negotiation, tacit knowledge sharing, learning, visualization, traceability, prioritization, and pragmatic decision making. Further, three main dimensions have been proposed to assess the maturity of the knowledge at the decision gate: input, method, and experience/expertise. Moving from these dimensions, generic as well as contextualized knowledge maturity scales have been created. The knowledge maturity scales are intended as hands-on tools that prescribe stakeholders how to work with issues related to knowledge, assumptions, ambiguities, and uncertainties. To exemplify their use, the tools have been applied to a case study in an aeronautical industry, with the purpose to assess the role of the knowledge maturity scales as a support for decisions in a gate.

The approach presented in this article offers a way of boosting decision makers’ confidence in situations where information and knowledge about alternatives is in limited supply. Assumptions, ambiguities, and uncertainties are inherent features in product development. The knowledge maturity concept may therefore represent a valuable approach for companies to take decisions that are more conscious at the gates, ensuring that implicit assumptions, ingrained views, and provisional results are not mistaken for verified facts. Creating an increased awareness of the status of information and knowledge assets could allow companies to move forward with known risk, rather than making decisions based on an unclear rationale.

The use of the knowledge maturity decision support does not ensure that all issues concerning assumptions, uncertainty, and ambiguity can be resolved. However, it represents a way to ensure that such issues are at least discussed in the cross-disciplinary gate review meetings. By doing so, the possibility to identify and mitigate risks through the collective reasoning ability of the team may be significantly increased.

Suggestions for Future Research

The next step in this work is to test this tool in a number of industrial settings to evaluate its benefits and generality, and also to iterate and improve the tool further.

Additionally, the suggested approach in this article is envisioned to have an influence on the processes in place in companies and on the people encountering the approach in the stage-gate process. Once implemented, there is a need to evaluate the real-life implications of the approach in relation to what was there before. What kinds of improvements could be seen? Are there any negative findings, such as overload for the people in the process? These are a few items that need to be evaluated.

In Table 6, a set of further developments to complement the knowledge maturity concept has been outlined. A computer-based support tool and a rating and weighting functionality needs to be developed to realize the potential of the knowledge maturity concept.

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Christian Johansson is a researcher in functional product development at the Luleå University of Technology in Sweden. His main research interests include knowledge management, product development, and support for decision making. The focus of the current research is related to the use of knowledge management in stage-gate-governed product development to support decision making. The main area of application for his research is within the European aerospace industry. He is active in the European Commission–funded research project CRESCENDO, as well as Swedish research projects.

Ben Hicks is director of the Innovative Design and Manufacturing Research Centre at the University of Bath. Since joining the university, he has held a variety of positions within the Department of Mechanical Engineering. He is involved in the teaching and supervision of undergraduate and postgraduate courses in design, computing, and computer-aided design. He has led a large number of research projects and has authored/co-authored more than 100 publications and articles. His research interests include design methods, machine and manufacturing systems improvement, and information management.

Andreas C. Larsson is an associate professor in the Department of Design Sciences at Lund University, where he is heading the Innovation Engineering Group. His research agenda aims to create a rich blend of needs-motivated activities dealing with, among other things, cross-functional knowledge sharing, local and distributed teamwork, and participatory innovation. These interests can be summarized in the overarching aim to support product-developing individuals, teams, and organizations in effectively and efficiently co-creating and sharing ideas and knowledge across a wide range of boundaries (i.e., teams, organizations, cultures, languages, time zones, etc.) in the pursuit of innovation.

Marco Bertoni is an assistant professor in the Functional Product Development Division at the Luleå University of Technology in Sweden. He is building his competence in the knowledge engineering domain, with a focus on knowledge sharing in product development. The focus of the current research is on the use of "lightweight" knowledge-sharing methods and tools (Engineering 2.0) to support decision making in cross-functional teams.