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Dissecting the Black Box: A Knowledge Management System for Transferring Levels of Technical Knowledge

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ABSTRACT

Knowledge sharing is critical in activities such as product development, where multiple individuals make decisions outside their area of expertise with far reaching consequences. Despite its importance, the construct "shared knowledge" is rarely quantified. This research is unique as it pioneers a method for measuring knowledge transfer directly in terms of knowledge levels—in essence opening the "black box" of knowledge. The methods were developed as part of a comparative case study of product development projects in a manufacturing firm. Evidence of knowledge transfer has been gathered via focused interviews with knowledge recipients and codified along knowledge dimensions of depth, scope and action. Based on observations derived from this data, key aspects of a new type of knowledge management system are outlined.

Keywords

Knowledge Management, Knowledge Management Systems, Knowledge Transfer

INTRODUCTION

Scholars of organizational research increasingly recognize knowledge as the most important asset a firm can own. Knowledge is cited as a reason why organizations are considered superior to other forms of industry arrangements, since organizations permit knowledge sharing across diverse groups of specialists (Grant, 1996; Nahapiet & Ghoshal, 1998; Kogut & Zander, 1992). Knowledge may also be central to an explanation of why there is heterogeneity across firms (Hoopes et al., 2003).

Perhaps in no other arena is the prominence of knowledge more evident than product development (PD). Product development is an appropriate area for study in Organizational Learning (OL) and Knowledge Management (KM), since it represents one of the few **formal** activities performed by the firm facilitating guided, purposeful learning across the entire organization. Hitt et al. (2000) state there are only two real types of organizational learning, both prominent in PD. *Acquisitive learning* is the acquiring and internalizing of external knowledge outside the firm's boundaries (the innovation or adoption stage of the PD process). *Experimental learning* is the result of active experimentation by members who acquire new knowledge distinctive to the organization (the development and transfer stage).

Activities such as PD are performed by highly specialized individuals whose expertise lies in different areas; yet, to be effective, these "knowledge workers" must become cognizant of process constraints outside their area of expertise. For example, a designer optimizing a database design must be cognizant of bandwidth limitations across a network and processing times for queries to be performed by users. Knowledge sharing becomes critical since it overcomes problems of incomplete and recursive information flows (Sanchez & Mahoney, 1996).

Investigating the transformation of specialized knowledge into shared knowledge is becoming crucial for researchers and practitioners. The desired effect of integrating practices, most notably patterns of shared knowledge, are considered to yield competitive advantage according to the resource-based view of the firm, since they cannot easily be purchased, transferred or developed (Hoopes et al., 2003).

Thus, opportunities abound for PD process improvements via more effective knowledge sharing with KM technologies. Gallupe (2001) describes how a knowledge management system (KMS), i.e. the integration of KM tools and technologies, can extend beyond traditional information systems by providing 'context' for the information presented. Bowman (2002) proposes two types of KMS models, both useful for PD. The network model, utilizing directories of expertise to connect knowledge owners with users, is probably most beneficial in early stages of innovation. The repository model, using IT to capture, organize, store and distribute organizational knowledge, is most likely beneficial in latter stages of knowledge transfer.

Historically, researchers have avoided direct measures of knowledge, mostly due to the amorphous nature of knowledge. The KMS research community would benefit from studies that treat shared knowledge as something more than just a "black box". To this end, this research has pioneered methods for measuring the extent of technical knowledge transfer across individuals **directly in terms of knowledge depth**. The methods have been refined during a comparative case study involving 4 PD projects within a manufacturing firm in the transportation industry.

The following research questions can be formed:

1. How can levels of shared knowledge be quantified? What levels of knowledge depth can be discerned?
2. What factors influence the formation of shared knowledge levels? In what ways can a KMS facilitate the formation of shared knowledge?

The primary contribution of this paper is the elaboration of a repository model-based KMS. This KMS should be capable of supporting the acquisition, capture, storage and dissemination of deep, scientific and actionable knowledge in PD. The key points of functionality for the system are based on observations made during the study of the PD projects. The next two sections review the underlying premise of this research, describing the problem domain in detail. The proposed KMS is then conceptualized representing one possible solution to the problem.

LITERATURE REVIEW

Product development is comprised of three basic stages. The first stage, conceptualization, has been the focus of innovation and adoption research. The final stage of full scale production has been studied by organizational learning curve (OLC). This research focuses on activities in the intermediate stages of development such as concept development work, feasibility testing, product design, component development and production ramp-up (Takeuchi & Nonaka, 1986; Terwiesch and Böhn, 2001).

In early stages of development, knowledge is acquired primarily through experimentation. Here, PD is commonly modeled as a form of technical problem solving. Experiments are conducted to determine an unknown solution space of process parameters which optimize or satisfy a set of processing objectives (Pisano, 1996; Von Hippel and Tyre, 1995). Learning, as acquisition of new knowledge, is achieved by experimentation (both physical and conceptual) providing continuous feedback on gaps in process performance.

Latter stages are characterized by a shift away from controlled, laboratory experimentation toward pilot and full-scale production. The learning burden shifts from R&D to production workers, who learn through "doing" or "using" activities. Although the significance of learning-by-doing has been well stated (Arrow, 1962), the process by which these gains are made is still quite unclear. Several authors have investigated the "doing" and "using" part of learning. For example, Von Hippel and Tyre (1995) explored how problems are diagnosed through using upon introduction of new equipment to the factory floor.

Although several models of organizational learning exist, the most appropriate model for these intermediate development stages is communication theory (Shannon & Weaver, 1949) which describes the transfer of knowledge from a source (R&D) to a recipient (production). Szulanski (2000) describes knowledge transfer as a process where the organization recreates a complex, causally ambiguous set of routines in a new setting. Szulanski's four stages of initiation, implementation, ramp-up and integration coincide with the stages of a typical product development cycle.

Constructing the Theoretical Framework

This research is based on an overarching framework shown in Figure 1 that outlines the relationship between shared knowledge and product development performance (PDP). The framework is an expansion of one originally proposed by Hoopes & Postrel (1999), who suggested integrative mechanisms such as cross-functional teams promote PDP success through 3 channels of cooperation, coordination and shared knowledge. The distinction between channels is important because each channel requires different managerial and technological directives for improvement.

Cooperation refers to how individuals balance their actions between a regard for their own personal interests and the interests of the firm. *Coordination* is concerned with how individuals and subunits synchronize their actions within a firm for proper allocation of scarce development resources. The focus of this paper is on *shared knowledge*, referring to facts, concepts and propositions which are understood simultaneously by multiple agents.

Several sources contributed to the framework and are briefly listed here. Measures of PD performance at the project level are expressed in terms of efficiency (the ratio of outputs obtained relative to the units of inputs or resources required to achieve those outputs), effectiveness (degree of goal attainment) and job satisfaction (the affective reaction or feeling of unit employees), based on the work of Gresov et al. (1989). These dimensions account for common PDP metrics as reported by Driva & Pawar (2000).

Organizational dimensions posited to influence the creation of shared knowledge are derived from past research in information processing theory and task contingency theory (e.g. Galbraith & Nathanson, 1978). Project/team level factors have been studied by several authors (e.g. Clark & Fujimoto, 1991; Szulanski, 1996; Thomke et al., 1998; Pisano, 1996).

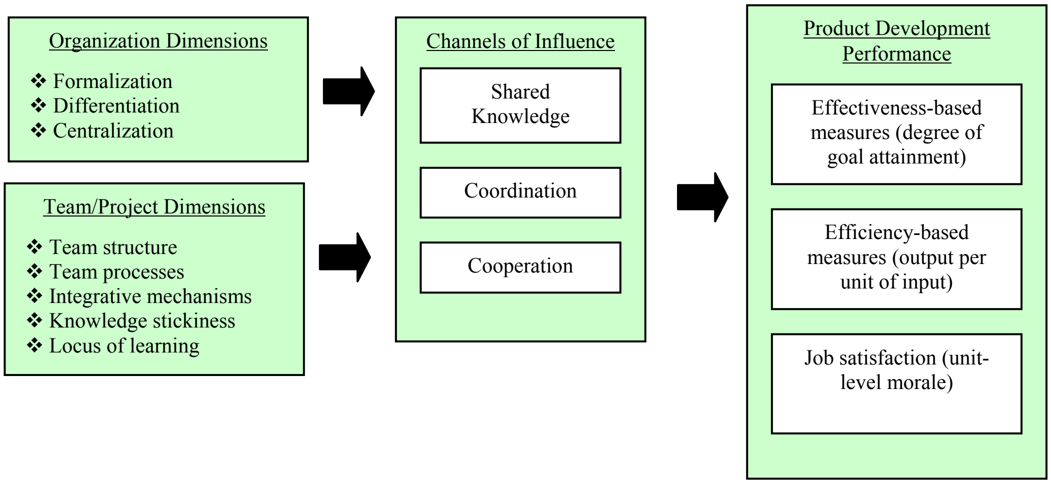

Figure 1. General Framework

To better understand the construct "shared knowledge", a method has been adapted from an existing scale of knowledge depth proposed by Böhn (1994). Böhn's scale identifies 8 levels of technological knowledge. Technological knowledge of process behavior is essentially the understanding of the effects of input variables on output. Mathematically, $Y = f(X)$, where an output vector, Y, is an array of several output variables associated with cost, dimensional requirements, material requirements, etc. Each output variable, y, is a function of an indeterminate vector of input variables, X.

Levels 1 and 8 of Böhn's scale represent unattainable extremes, where level 1 is absence of knowledge and 8 is complete knowledge. Intermediate levels 2 through 6 describe distinct stages of process knowledge acquisition. All stages are expressed in terms of the effects of one input variable, x_i, on a process output variable, y_i. Intermediate stages include awareness (level 2), measurement and control of the mean of x_i (levels 3 to 5), feedback control (level 6) and feedforward control (level 7).

Organizations traverse the typology (acquire knowledge) by conducting experiments to assess the effects of new input variables (perhaps thought to be inconsequential) on output. In this sense, learning is defined as the acquisition of technological knowledge. Böhn's highly differentiated levels add a level of distinction far more adaptable to the specifics of technological knowledge and informational derivatives.

RESEARCH DESIGN AND METHODS

To explore the role of shared knowledge in product development, a comparative case study was undertaken in a multidivisional, medium-sized manufacturing firm (between $100M and $500M in sales) headquartered in the Midwest part of the United States. The company has a separate R&D facility developing and testing new products for two recipient plants located within 60 miles of the R&D center. The case study approach follows similar studies, such as Hoopes and Postrel (1999) and Von Hippel and Tyre (1995).

Four development projects were studied. Project selection was conducted jointly with company executives. Projects were required to a) be completed within the past 2 years, b) contain a significant technological component, c) include members spanning at least 3 functional areas, and d) be representative of typical projects for the company. Projects were also confirmed by company executives to be approximately the same in terms of task complexity.

The study population included 23 participants familiar with the events surrounding the four projects. Of the 23 participants, extent of knowledge transfer was evaluated for 18 participants having decision-making authority for the processes under development. (Five participants were unit managers familiar with project events but not the processes and were thus excluded from knowledge assessment.)

Data Collection

Methods for data collection were followed based on guidelines provided in Burns and Acar (2001). Data was collected primarily through focused interviews. Focused interviews were initially developed in communications research and are appropriate when subjects are known to have been involved in an uncontrolled but observed social situation or psychological experiment (Merton et al. 1956).

Three forms of documentation served as interview guides. The first guide was a time-ordered matrix of events for each project, extracted by project files and a series of open-ended interviews with project managers.

The second interview guide, a knowledge "tree" diagram for each process, was instrumental in extracting evidence of subjects' depth of knowledge. Construction of the knowledge tree diagrams was performed with each process architect. First, process output variables were identified through blueprints, customer specifications and process routings. An architect could typically narrow down the list of critical output variables to less than a dozen. Next, for each output variable, the method of measurement, unit of measure and effective control limits were obtained. The architect was then asked to identify important input variables affecting each output variable. Finally, the architect was asked to rate the sensitivity of each input-output variable relationship. This process was repeated since some input variables were intermittent variables affected by other input variables. The line of questioning with the architect concluded until the input variable was considered primitive, i.e. controlled either by a machine setting available to the operator or a characteristic of an incoming raw material (controlled by a vendor external to the plant). A sample knowledge "tree" diagram is shown in Figure 2.

The third interview guide was a list of open-ended questions constructed and refined based on guidelines set forth by several authors (Glesne and Peshkin, 1992; Merton et al., 1956). The list of topics included subject background, communication modes used for knowledge transfers, assessment of subject's knowledge (based on the process knowledge tree) and influence of knowledge on performance. A complete list of questions can be found in Burns and Acar (2001).

Interviews lasted about 90 minutes per subject. All interviews were tape-recorded with subjects' permission. When probing for knowledge depth held by the subject, the knowledge tree diagram and interview questions were used as a guide for the interviewer (but not the subject). Whenever possible, a cued transition was made based on the subject's mention of quality or some other technical aspect of the project. The pattern of questions usually followed Böhn's classification of knowledge levels (How is y measured? Which input variables x do you think influences y the most? Why does x influence y? What, besides y, does x influence?, etc.) Several variables and relationships were explored with each subject. Probing questions were asked until either a "did not know/did not recall" response or evidence of a lengthy explanation had been collected.

Measuring Extent of Knowledge Sharing

The primary challenge of the study was the development of a method for quantifying knowledge held by study participants in as much detail as possible. Böhn's scale is useful for measuring technical knowledge about one *variable*, but not for quantifying knowledge held by *individuals*, whose knowledge spans many process variables and relationships.

A pioneering feature of this research is its ability to assess the extent of knowledge transfer directly, in terms of knowledge levels. After extensive analysis of the transcripts, 3 dimensions of knowledge were determined to be prominent: action, scope and depth. The **action** dimension measures the range of potential actions described by the subject in response to a variable being out of tolerance. Whereas action describes responses in terms of one "branch" of the knowledge tree, the **scope** dimension reflects the subject's understanding of a change in one variable on other "branches". The **depth** dimension underlies the knowledge tree itself, i.e. the degree to which science serves as a basis for the subject's understanding of the entire tree.

Appendix A displays a flowchart depicting the coding logic used for assessing recipient knowledge. Each interview transcript was segmented into passages, typically around 100 words in length. Passages containing potential evidence of process knowledge were selected (usually identified by mention of some process variable). Those passages were then analyzed for content and classified as casual observations or in-depth discussions (to avoid overfiltering). Casual observations occasionally contained evidence of process knowledge and were coded as useful or not useful.

In-depth discussions were classified as single- or multi-problem based on the number of problems mentioned by the subject. At times, subjects would mention a single problem which did not warrant extensive explanation (akin to simple cause-effect). At other times, the subject would describe a more sophisticated multi-faceted problem requiring more extensive explanation. If one were to only consider the number of in-depth discussions articulated per subject, viewing single problems in the same light as multi-faceted problems would be misleading. Multi-faceted problems required far greater understanding to articulate.

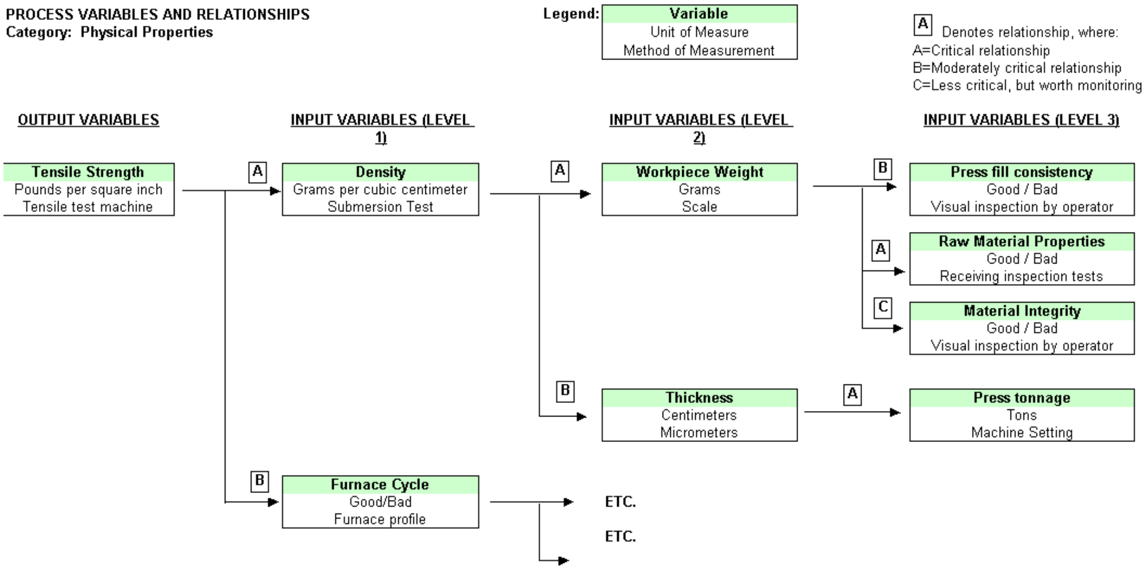

Figure 2. Sample Knowledge Tree Diagram

Each passage was coded in terms of the 3 dimensions of depth, scope and action. After extensive analysis of the transcripts, it was concluded that three basic levels could be discerned for each knowledge dimension: scientific/systematic (high), quasi-scientific (moderate) and direct (low).

For the **depth** dimension, these coding levels were termed script (low), analogy (quasi-scientific) and science (high). "Scripted" responses represented the lowest amount of evidence of knowledge and were usually recitation of the standard operating procedure (SOP). Probing usually led to the respondent saying "I do not know" or "I do not recall". "Science" responses showed evidence of the highest level of understanding, based on logical or scientific principles. "Analogy" responses were quasi-scientific—subjects could not describe process phenomenon in terms of science but were able to use an analogy or partial description of scientific principles.

Scope reflects the scope of process changes mentioned for one variable across other output variables and was coded as direct (low), partially systemic (quasi-scientific) or fully systemic (scientific). Passages were coded as "direct" when, upon mentioning a change in an input variable, respondents could only indicate the effect of the change in **one** output variable, even after probing. "Partially systemic" responses (quasi-scientific) included a description of the change on 2 output variables. "Fully systemic" responses (scientific) included the effects on 3 or more variables.

The **action** dimension characterizes the course of action proposed by the subject. Coding categorizes included direct (low), upstream (quasi-scientific) and systemic (scientific). "Direct" responses included only one possible action taken even after probing, e.g. a simple cause-effect description. "Upstream" responses showed knowledge of either feedforward or feedback control. "Systemic" responses included at least 3 possible actions that could be taken and reflected a more holistic understanding of the entire process.

On average, about 10 to 12 passages per subject were coded. The results of this coding scheme are presented in Appendix B, which shows the percentage of low, medium and high level responses in each dimension for subjects associated with each project. The numbers are normalized based on the total number of passages analyzed per subject. Process architects (the source) recorded countless passages of the highest form of knowledge (Depth=Science, Scope=Fully Systemic, Action=Systemic) and are shown first in the table, followed by recipients.

Appendix C shows 4 graphs of the coding results, one for each project. Darker shades imply deeper knowledge transfer. Each subject has 3 bars, one for each dimension. The bar graphs the percentage breakdown of low, medium and high results per dimension. As the graphs show, the method could discern the 3 levels of knowledge in each of the 3 knowledge dimensions; moreover, the method appeared repeatable across the 4 different projects which was encouraging.

CONCEPTUALIZING THE KNOWLEDGE MANAGEMENT SYSTEM FOR PRODUCT DEVELOPMENT

The structure of the Knowledge Management System (KMS) proposed here incorporates many of the features of a repository-based KMS as described by Bowman (2002). The KMS concept reflects the way knowledge was practically acquired, transferred and subsequently used during the course of the projects under study.

The user population for the KMS is described in terms of user roles (not job functions), since users may assume many roles during a project. Four roles in the PD process were identified. The primary knowledge source contributing to the knowledge repository is the process architect.[1] The architect was responsible for the myriad of decisions surrounding equipment selection, workstation methods and material flow. Working closely with the architect is an engineer, who adapts the experimental process under development to the production environment. Next, a technician is responsible for day-to-day issues such as scheduling workflow, ordering materials, assistance with setup and minor troubleshooting. At the end of the chain of knowledge transfer is the operator, responsible for day-to-day production, i.e. the yield of the process.

Features of the KMS

Without technology, it would be difficult to capture all the knowledge accumulated during the course of a typical product development project. The PD process, using modeling, experimentation, analysis, etc. is ripe with opportunities for acquiring knowledge from a variety of sources, but particularly the architect. In the four projects studied, however, knowledge was all too often discarded, ignored, lost, etc. One reason for this is the inherent difficulty in articulating and structuring deep, tacit knowledge held by the process architect. This "stickiness" impacts PD performance since it inhibits knowledge transfer to recipients.

It is for these reasons that technology, especially Internet-based technology with hyperlinking and multimedia capability, can facilitate effective knowledge management for the PD process. The KMS can be constructed using information technology in a fairly standard way to address many of the PD problems. A conceptual data model for the KMS is shown in Figure 3. The entities in the data model are based on the enabling of the following knowledge processes by the KMS. The data model and processes reflect the various ways the user population might use the system.

In terms of functionality, the KMS should enable the expected KM processes of acquisition, storage/structure, transfer, use and regeneration. Following communication theory, knowledge is acquired from a source (the process architect, primarily) and then transferred to recipients in production (the engineers, technicians and operators).

Acquisition. During stages of experimentation, the KMS should enable the architect to enter information about 1) experiments, 2) the variables to be explored in the experiments, 3) the variable relationships, and 4) the expected and actual results. Actual test results may include multimedia objects, including images, sound and video files. An important component here is the ability of the system to capture the architect's specialized, contextual *tacit* knowledge regarding the objectives of the experiment(s) being conducted.

Storage/Structure. Following the scheme set forth by Böhn (1994), technological knowledge of process behavior is structured using a recursive relationship of input and output variables. A particularly important attribute here is the

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[1] While it is possible for other roles to contribute knowledge to the system, this was not the typical case in the projects studied here.

relationship *sensitivity,* which creates a rank ordering of input variables to consider modifying when an output variable is out of tolerance.

The structure proposed here was used to construct the knowledge tree diagrams (e.g. Figure 2). Feedback at the firm indicated the knowledge tree diagram would be particularly useful for framing the boundaries of process knowledge.

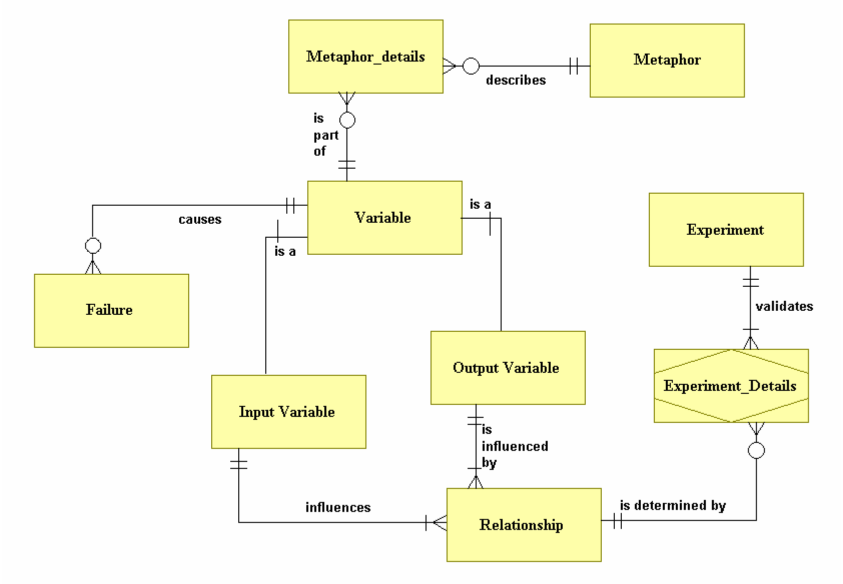

Figure 3. Data Model for KMS

Transfer/dissemination. The system should enable transfer of the three levels described previously, direct, quasi-scientific and scientific. Direct knowledge can be transferred via standard operating procedures (SOPs) and the knowledge tree diagram. Operators commented that understanding the practical limits of their knowledge would assist in the decision of when to call for support when problems arose.

Interview data indicated that subjects who did not possess sufficient scientific knowledge to absorb the vast array of process variables and relationships would inevitably resort to analogies and metaphors for understanding. Given this case, the system would improve performance by formally articulating these devices.

Scientific knowledge frequently requires tacit to tacit knowledge exchanges. The KMS can facilitate this, although the cumbersome nature of the exchange may limit the system's effectiveness. Video, for example, may be an efficient form of capturing architect knowledge. In cases such as this, the telephone may be a better and more obvious choice.

Regeneration. Over time, the production process accumulates statistical process control data. If the KMS can capture and store this data, the use of knowledge discovery techniques such as data mining can be performed to unearth knowledge "chunks" about new, undiscovered relationships between variables. Patterns observed in production can also lead to *awareness* of new variables (Böhn's knowledge level 1).

SUMMARY

The contribution of this paper was the description of a new type of system capable of managing knowledge during the life cycle of a process after conceptualization. Learning as acquisition and transfer of knowledge is pervasive in product development. Yet, much knowledge gets discarded along the way. The system described here uses information technology to develop one possible solution to the problem. The features of this system stem from observations about the formation of shared knowledge in a typical product development environment.

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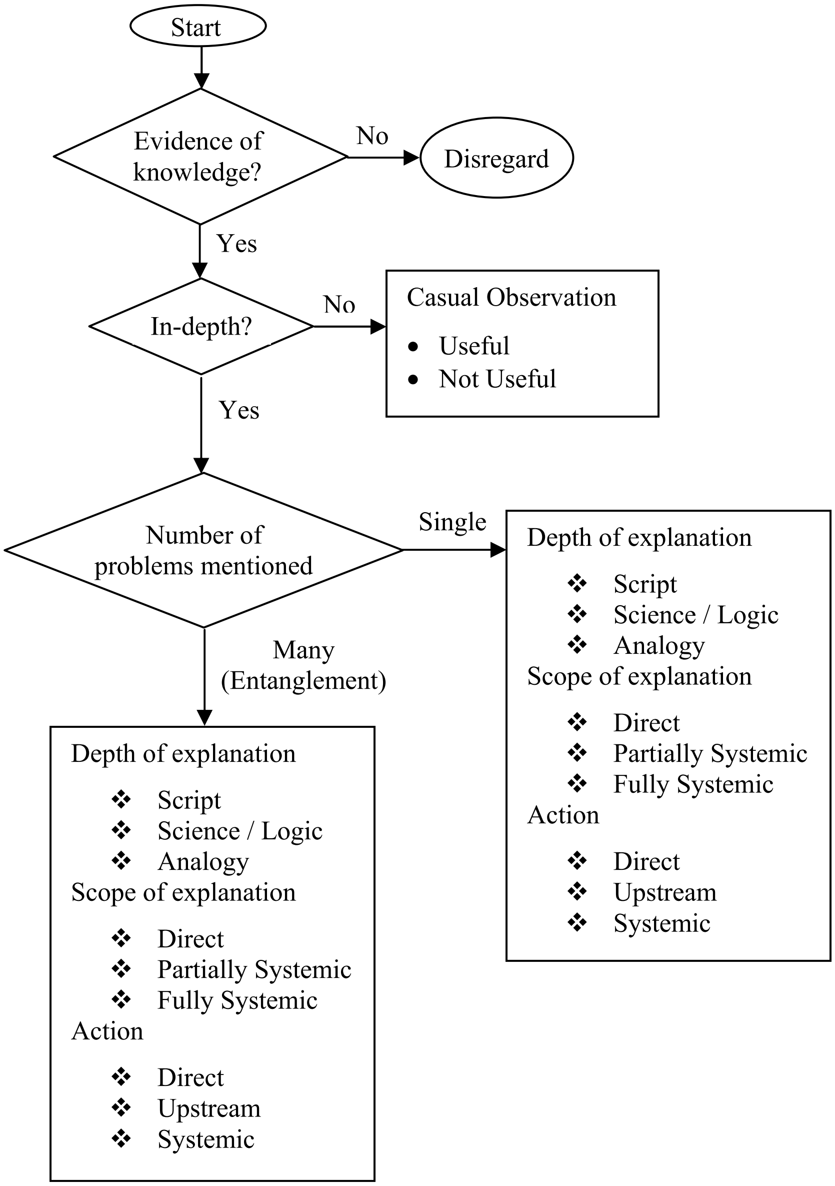
APPENDIX A. FLOWCHART FOR KNOWLEDGE ASSESSMENT CODING.



APPENDIX B. KNOWLEDGE CODING RESULTS (% RESPONSES, NORMALIZED BY TOTAL NUMBER OF PASSAGES)

Legend:

Depth: 1=Script, 2=Analogy, 3=Science;
Scope: 1=Direct, 2=Partially Systemic, 3=Fully Systemic;
Action: 1=Direct, 2=Upstream, 3=Systemic

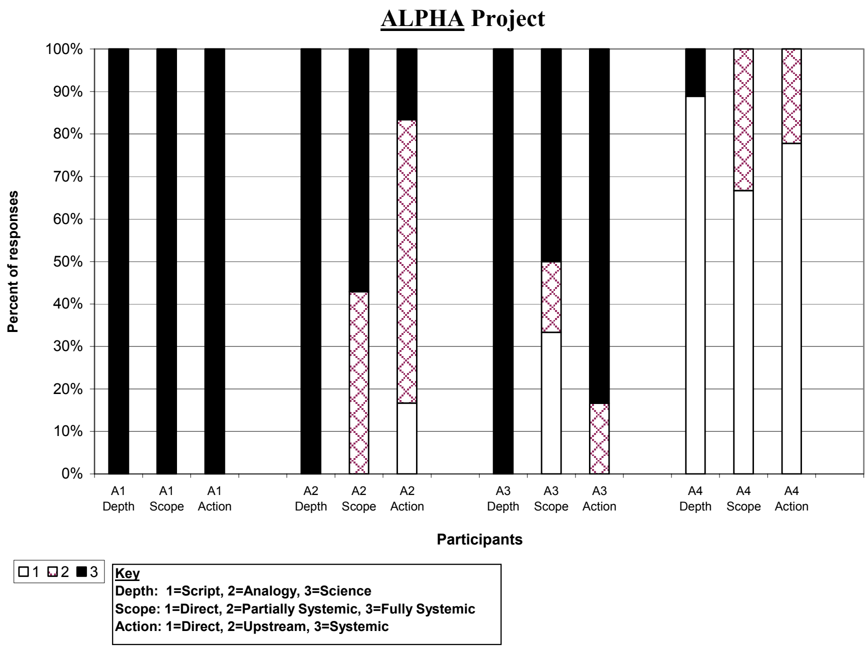
Alpha Project **Subjects →**		**A1 Depth**	**A1 Scope**	**A1 Action**	**A2 Depth**	**A2 Scope**	**A2 Action**	**A3 Depth**	**A3 Scope**	**A3 Action**	**A4 Depth**	**A4 Scope**	**A4 Action**
1	(Low)	0	0	0	0	0	14	0	33	0	89	67	78
2	(Medium)	0	0	0	0	43	57	0	17	17	0	33	22
3	(High)	100	100	100	100	57	29	100	50	83	11	0	0

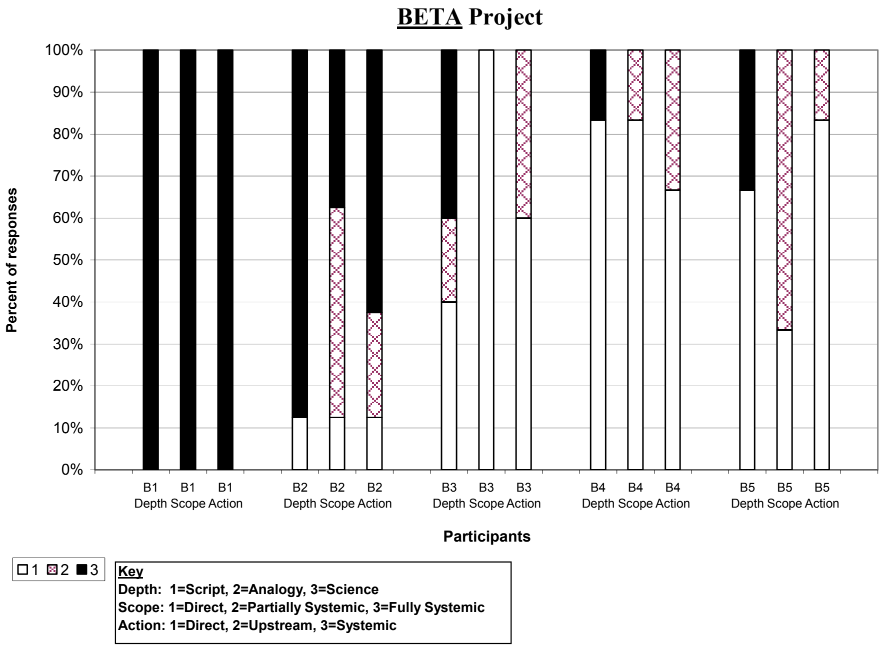
Beta Project **Subjects →**		**B1 Depth**	**B1 Scope**	**B1 Action**	**B2 Depth**	**B2 Scope**	**B2 Action**	**B3 Depth**	**B3 Scope**	**B3 Action**	**B4 Depth**	**B4 Scope**	**B4 Action**	**B5 Depth**	**B5 Scope**	**B5 Action**
1	(Low)	0	0	0	13	13	13	40	100	60	83	83	67	67	33	83
2	(Medium)	0	0	0	0	50	25	20	0	40	0	17	33	0	67	17
3	(High)	100	100	100	88	38	63	40	0	0	17	0	0	33	0	0

Delta Project **Subjects →**		**D1 Depth**	**D1 Scope**	**D1 Action**	**D2 Depth**	**D2 Scope**	**D2 Action**	**D3 Depth**	**D3 Scope**	**D3 Action**	**D4 Depth**	**D4 Scope**	**D4 Action**	**D5 Depth**	**D5 Scope**	**D5 Action**
1	(Low)	0	0	0	0	13	38	25	0	25	50	25	50	50	17	33
2	(Medium)	0	0	0	0	38	13	0	50	25	25	75	50	0	50	33
3	(High)	100	100	100	100	50	50	75	50	50	25	0	0	50	33	33

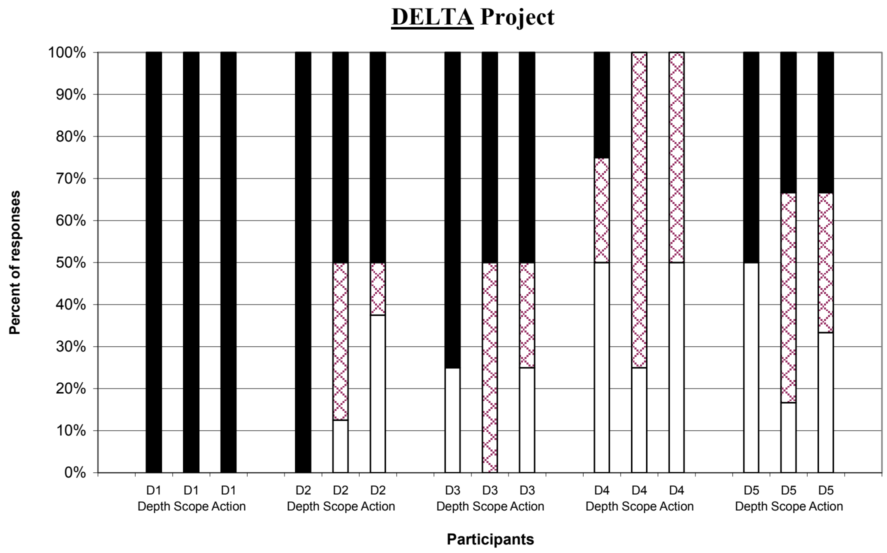
Gamma Project **Subjects →**		**G1 Depth**	**G1 Scope**	**G1 Action**	**G2 Depth**	**G2 Scope**	**G2 Action**	**G3 Depth**	**G3 Scope**	**G3 Action**	**G4 Depth**	**G4 Scope**	**G4 Action**
1	(Low)	0	0	0	38	38	75	100	83	83	80	80	80
2	(Medium)	0	0	0	0	50	0	0	17	17	20	20	20
3	(High)	100	100	100	63	13	25	0	0	0	0	0	0

APPENDIX C. GRAPHS OF KNOWLEDGE CODING RESULTS.



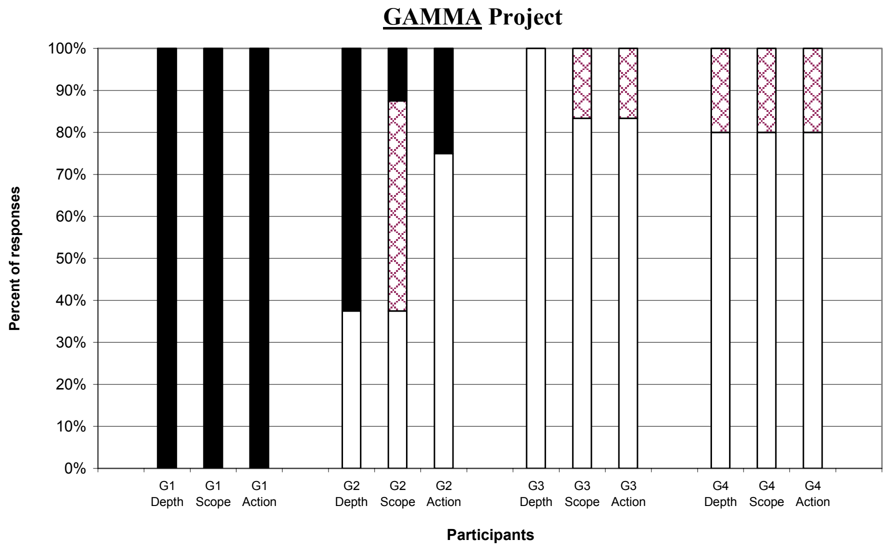


APPENDIX C. GRAPHS OF KNOWLEDGE CODING RESULTS (CONT.).



□1 ▨2 ■3

Key
Depth: 1=Script, 2=Analogy, 3=Science
Scope: 1=Direct, 2=Partially Systemic, 3=Fully Systemic
Action: 1=Direct, 2=Upstream, 3=Systemic



□1 ▨2 ■3

Key
Depth: 1=Script, 2=Analogy, 3=Science
Scope: 1=Direct, 2=Partially Systemic, 3=Fully Systemic
Action: 1=Direct, 2=Upstream, 3=Systemic