Knowledge Mapping: A Multipurpose Task Analysis Tool

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Abstract. A tool was developed to increase the objectivity and accuracy of task difficulty ratings for job design. The tool, knowledge mapping, involves identifying specific types of prerequisite knowledge for a given task and then assessing the difficulty of each type. The tool was applied in a semiconductor manufacturing environment and yielded valuable information not only for job design, but also for determining priorities for the development of training and establishing job levels for compensation purposes.

Much attention has been given to the myriad of task analysis tools and techniques available to educators and trainers. Some attention is given to integrating task analysis and instructional design (Carlisle, 1983; Reigeluth, 1983), but the majority of the efforts seem focused on distinguishing between the different task analysis techniques and providing some guidance as to how to choose the right technique for a specific application (Andrews & Goodson, 1980; Foshay, 1983; Jonesson & Hannum, 1986; Kennedy, Esque, & Novak, 1983).

One major distinction in determining how task analysis should be approached is whether the application is for industry or education. Kennedy, Esque, and Novak (1983), from a review of ten different methods, concluded that the most salient difference between approaches was whether the application was for industry or education. Jonesson and Hannum (1986) used the same distinction as the primary decision point in their algorithm for selecting the appropriate task analysis methodology for specific applications.

Differences in the desired outcomes of learning are often cited as the primary reason for differences between how task analysis is approached in industry and education. For example, due to its emphasis on cost effectiveness, industry is more interested in transferring procedural knowledge to quickly impact directly observable behaviors. On the other hand, education is more concerned with transferring nonprocedural knowledge for application to a broader range of situations over a broader time period (Jonesson & Hannum, 1986; Kennedy, Esque, & Novak, 1983). Desired outcomes of learning certainly impact one's approach to task analysis; however, another major difference is that industry often uses task analysis to determine much more than the knowledge and skills required to perform a specific task.

Information from task analysis is applicable for several aspects of human resource management in industry, including job design, employee selection, and training those selected to do a job. The task information required for these applications often requires an approach to task analysis which is very

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different from an approach directed solely at learning outcomes.

One major difference between different industrial approaches to task analysis is the kind of information collected about each task over and above how the task is performed and what knowledge and skills are required to perform it. Morsch and Archer (1967) list fourteen examples of what they call secondary rating factors in the task analysis process, including task criticality, task difficulty, satisfaction in performing the task, and supervision required while performing the task. Information from one or more of these task rating factors is typically used to make decisions about specific aspects of human resource management.

This article describes an approach to task analysis in which one of these secondary rating factors, task difficulty, was the primary source of information for making job design, selection, and training decisions in a semiconductor manufacturing setting. The key to this approach is a technique for deriving task difficulty information called knowledge mapping. Knowledge mapping was designed to improve the objectivity and the accuracy of task difficulty ratings for determining who is capable of performing what task and what training will be required. Although the technique was developed for a very specific application, it can be used to solve problems common to human resource management in any organization. Hence, it should be applicable in part or whole to many industrial settings.

The technique of knowledge mapping is described and examples of the tools that must be developed to implement it are provided. Lessons learned from the first application of the technique are cited, along with some discussion about the utility of the technique in general. First however, a description is given of the specific application for which this technique was developed. This should help any potential users of the technique to determine how and when it may be applied.

Throughout this article, many abstract terms such as content area, type of knowledge, and level of difficulty have been operationally defined in relation to each other for the purpose of describing the knowledge mapping process. The definitions are included (sometimes informally) to describe points that are useful in learning to apply the technique. They should not be interpreted as an attempt to structure the concepts of knowledge, but merely as a framework for understanding and using a practical tool.

Description of the Application

The knowledge mapping technique was designed and applied as part of an effort to merge three different classes of jobs in a semiconductor manufacturing environment into one class or family with progressively complex levels. More specifically, the functions of operating equipment, maintaining equipment, and monitoring a production process were combined. In this application, the knowledge requirements for all tasks required to sustain a specific type of equipment were determined and documented on several key types of equipment, applicable across six different manufacturing plants. The total effort directly impacted about 1,000 employees.

The data derived from knowledge mapping, along with task frequency and task duration data, were the primary sources of information used by subject matter experts (SMEs) and management to derive the task list for a single enhanced job from three previous jobs for each type of equipment. The same task data base is currently being used to develop training curricula and to define selection and training development requirements for the resulting enhanced jobs. Because of the scale of the effort, a computer program was developed to assist in collecting, storing, and sorting the data.

Why Knowledge Mapping?

Although the decision to take a task-based approach to the job design process was made early on, the knowledge mapping tool emerged late in the planning process as a proposed solution to three distinct problems. The first problem was the scale of the effort. By far the most time consuming component of data collection would be prerequisite analysis, that is, identifying actual prerequisite knowledge and skills in objective form. With the analysis covering seven types of equipment, each requiring between one and two hundred discrete tasks, an exhaustive prerequisite analysis was out of the question. The problem was how to collect just enough information on each task to ensure that redundant training requirements across tasks would be easily recognizable so that tasks could be prioritized for further analysis.

The second problem had to do with making sound job design decisions. Job design is the process of making the decisions that determine (a) what tasks are performed by the workforce, (b) what tasks are to be clustered into what jobs, and (c) how the jobs are to be linked together (Davis & Wacker, 1982). An important objective of clustering tasks into jobs is that all the tasks in one job be of a similar level of difficulty. Otherwise, a choice must be made between selecting someone who is either under or over qualified for parts of the job. Both have significant cost and worker morale disadvantages.

The problem is that it is difficult to get unbiased data about the difficulty of a task. The traditional approach to collecting data on task difficulty (as well as most other secondary task rating factors) is relatively subjective. Typically, a generic 5- or 7-point scale is provided, and SMEs are asked to choose a single rating for each task (Morsh & Archer, 1967). Even when SMEs do not know how the data is to be used, they are inclined to inflate the importance and hence the difficulty of their job. This phenomenon becomes even worse when SMEs perceive a threat that their job is being designed out of existence, regardless of whether or not that is an objective of the analysis.

The third problem, like the first, concerns obtaining information about identifying and prioritizing training requirements, but also has implications for selecting candidates for a job. Although industry is more interested in procedural knowledge for changing directly observable behaviors, there are many tasks in an industrial setting that require the mastery of non-procedural knowledge. In Gagné's terminology, procedural knowledge would be the application of discrimination, concrete concepts, and rules to learning the step-by-step instructions for performing a procedure. Nonprocedural knowledge, on the other hand, includes the remaining intellectual skills (defined concepts and higher order rules) and would typically require the use of cognitive strategies for applying that knowledge to making decisions, developing motor skills, or solving unique problems. Gagné defines each of these intellectual skills in *The Conditions of Learning* (1977). Their use is applied here to provide an operational distinction between the terms procedural and non-procedural knowledge, not necessarily in the context of Gagné's taxonomy.

The distinction as to whether a task requires procedural knowledge, non-procedural knowledge, or both provides a framework for determining the type and amount of knowledge and skills required to perform the task. This information is the basis for determining whether or not to train a given population or to select a population with the appropriate educational background. It also makes it possible to identify standardized instructional approaches for each anticipated type of training, which means training development can be prioritized and parceled out early in the process without the risk of designing incompatible materials or developing them for the wrong audience. The problem, then, is how to determine the basic types and amount of knowledge and skills required to perform specific tasks even before the content of the training—specific prerequisite knowledge and skills—is known.

The Knowledge Mapping Technique

Knowledge mapping involves identifying for a given task specific types of prerequisite knowledge and cognitive skills within defined content areas, and then assessing the difficulty of each type of knowledge and skill. The only difference between a type of knowledge or skill and a content area is level of specificity. Content areas represent a very broad subject matter; types of knowledge and skills represent a more specific subject matter within a content area. The defined content areas must encompass all expected types of knowledge for the specific application. Figure 1 shows the nine content areas used to analyze semiconductor manufacturing tasks. Ideally, all types of knowledge required to operate, maintain, or monitor the processing of semiconductor manufacturing equipment could be categorized within one of these nine content areas.

Figure 1. Content Areas for Semiconductor Manufacturing

- Technologies/Disciplines
- Equipment Assemblies
- Generic Process Knowledge
- Specific Process Knowledge
- Quantitative Skills
- Tools/Materials Knowledge
- Computer Skills
- Safety Knowledge
- Problem Solving Skills

Three different levels of task difficulty were defined based on their usefulness in determining who can be effectively trained for what job and what general form of training (from a limited number of selected forms) can be applied to the task. For this reason, the levels do not, and were not intended to, fit precisely into the existing task, knowledge, or learning taxonomies (e.g. Bloom et al., 1956; Gagné, 1972, 1977; Reigeluth, 1979). Figure 2 shows the generic levels of task difficulty.

The definitions are considered generic because they are modified in actual use for each specific content area. The modification is intended to help the SME make the transition from distinguishing between levels of difficulty across tasks to distinguishing between levels of difficulty for types of knowledge required to perform a task. Because of this, the specific definitions within a content area typically do not include the goal of the task (follow step-by-step directions, perform motor

Figure 2. Generic Levels of Task Difficulty

Level A	Tasks that require the performer to make discriminations and/or recall only concrete concepts and simple rules to understand and follow step-by-step directions.
Level B	Tasks that require the performer to use limited knowledge of a related set of defined concepts and principles from one or more technologies (e.g., electronics, mechanics, optics, gas dynamics, etc.) to correctly perform motor skills or to make decisions.
Level C	Tasks that require the performer to understand the underlying concepts and principles from one or more technologies and have the ability to apply that knowledge to solve unique problems.

skills, make decisions, solve unique problems) as stated in the generic definitions. Figure 3 shows how the generic levels of task difficulty have been modified for three of the nine content areas for semiconductor manufacturing. These specific content area definitions are referred to as knowledge-level definitions.

Figure 4 shows the knowledge mapping information for one sample task. This same information is collected for each discrete task in the job being analyzed. Note that the nine numbered subsections are the determined content areas shown in Figure 1. Although these content areas are broad, they are application specific.

Listed below each content area are the types of knowledge within that content area required to perform the task as solicited from the SME. (Areas 5, 7, and 8 differ in this respect because the nature of these content areas does not require listing types of knowledge.) Each of these types of knowledge have then been rated by the SME as A, B, or C, based on the level of difficulty of the type of knowledge required to perform the task. The ratings A, B, and C correspond to the knowledge level definitions (see Figure 3). The highest difficulty rating for any one type of knowledge required for a task is the difficulty rating for that task (difficulty ranking is ascending from A to C). The task in Figure 4 would be designated as a B-level difficulty task. The end result of the knowledge mapping process is a matrix showing the difficulty level of each task, broken down by content area and type of knowledge (see Figure 5).

Figure 3. Knowledge Level Definitions for Three of the Nine Content Areas

Equipment Assemblies

Level A State the function and location of the assembly and its key parts. Describe the general sequence of events for how the assembly/part works.

Level B Use limited knowledge of one or more technologies (e.g., electronics, mechanics, pneumatics, optics, vacuum, etc.) to describe why this specific assembly functions the way it does in a given situation.

Level C Use broad-based knowledge of one or more technologies to describe why this general type of assembly generally functions the way it does.

Computer/Programming Skills

Level A Using existing software and input/output methods for query/command functions (this includes inputting parameter changes).

Level B Use and interpret provided diagnostic software.

Level C Use appropriate computer languages to perform maintenance programming (this includes any alterations to actual programs).

Generic Process Knowledge

Level A State the process sequence of events in a given functional area and describe generally how the product is altered by the process (i.e., lithography, dopant deposition, etch, implantation, etc.). Recognize that the appropriate physical changes have occurred on the wafer at a given step.

Level B Apply limited knowledge of physics/chemistry to explain how the process variables (i.e., temperature, time, focus, exposure, etc.) affect specific process parameters (i.e., oxide thickness, CDs, etc.) at a single process step (as in a single step on a runcard). Identify variation in specific process parameters on the device.

Level C Apply broad-based knowledge of physics/chemistry to explain how variation in the process parameters at one process step will affect specific process parameters at future process steps.

Using the Knowledge Mapping Data Base

Together with frequency and duration data for each task, the knowledge mapping data provides enough information for the SMEs and management to make informed job design decisions. The task difficulty ratings for each task provide information about who is and who is not qualified to perform that task. They also provide information about the amount of training required over and above a person's existing knowledge. For example, one can conclude that a task of A-level complexity could be taught with a minimal amount of instruction to almost anyone who has at least a secondary education. Tasks of B-level complexity can also be taught to almost anyone with a secondary education; however, the amount of training required to learn the task will vary with each individual's background. Each individual may have a different amount of knowledge of the specific set of related concepts and principles needed to perform the task. (This is a given for this particular application because worker populations already exist for each of the three separate functions.) Although this information alone does not prescribe who is capable of performing a task or how much training any one individual would need, it provides a framework for getting that information through interviews (to record past experience) or through testing.

Tasks of C-level complexity provide more straightforward information for the job design process. A task of C-level complexity can only be taught to a person with specific postsecondary education or an equivalent amount of on-the-job experience. In other words, because the task requires knowledge of underlying principles in one or more disciplines, the job requirements typically can be defined in terms of educational background.

All of this information is useful for designing new jobs that are cost-effective in that they are made up of tasks

Figure 4. Completed Data Collection Sheet

TASK: Check Overlay

1. Equipment Assemblies

	A	B	C
Front Control Panel	✓		
Mask Transport System	✓		
Wafer Handling System	✓		

2. Technology/Discipline

	A	B	C
Optics	✓		
Pneumatics	✓		
Mechanics	✓		

3. Tools/Materials Knowledge

	A	B	C
Overlay Test Set	✓		
Microscope	✓		

4. Generic Process Knowledge (Process Parameters)

	A	B	C
Critical Dimensions		✓	

5. Specific Process Knowledge: (circle one) . . . . (A) B C N/A

6. Safety Knowledge:

	A	B	
UV Light Exposure	✓		

7. Computer Skills: (circle one) . . . . (A) B C N/A

8. Troubleshooting Skills: (circle one) . . . . A B C (N/A)

9. Quantitative Skills:

	A	B	C
Solve Simple Equations	✓		

Figure 5. Partial Knowledge Mapping Data Base for a Diffusion Furnace

CONTENT AREAS:	EQUIPMENT ASSEMBLIES				TOOLS/MATERIALS				TECHNOLOGIES/DISCIPLINES				ETC.
TYPES OF KNOWLEDGE: / TASKS	BOATLOADER DRIVE	CANTILEVER/PADDLE	OVERTEMP SYSTEM	. . . .	QUARTZWARE	CLEANING MATERIALS	HANDTOOLS	. . . .	DIGITAL ELECTRONICS	PNEUMATICS	VACUUM	. . . .	. . . . . .
COLD START UP	A								A				
CLEAN LUBE BOATLOADER	A	A				A							
VERIFY MFC FAILURE						A			A	A			
CHANGE QUARTZ TUBE		B			B								
TROUBLESHOOT CONTAMINATION						A				A	B		
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with similar knowledge requirements. In addition, the same information can be used to estimate how much training specific populations or individuals require in order to perform the job. This is valuable for determining which existing population is best suited to learn and perform the newly designed job(s).

Why take the time and effort to ensure that task complexity ratings are tied to a common set of definitions? Job design and selection decisions are only as good as the data from which they were derived. Defining difficulty at a subtask level (i.e., each type of knowledge within each content area) and then converting it to a single rating for each task has several advantages over rating difficulty just at the task level. The knowledge mapping technique forces the SME to think about all aspects of the job tasks, and hence reduces the probability that any prerequisites to performing the tasks will fail to be considered. One type of prerequisite knowledge could be the difference between whether a task is of A, B, or C level of difficulty. Even more important, rating difficulty at a subtask level makes it much easier for the experienced interviewer to probe the SMEs on their responses, even when the interviewer is relatively naive about how the task is performed. This process is demonstrated later in this article.

Once the job design has been completed and the target population has been selected, knowledge mapping information provides a structure for establishing training development priorities before an in-depth prerequisite analysis has been conducted. The first step of establishing training development priorities is to sequence the tasks for training. The knowledge mapping data, which lists the types of required knowledge for each task along with an understanding of when each task is performed, provides a basis for clustering tasks by how and when they will be trained. Once a sequence of training has been developed, the order in which the identified units of training will be developed needs to be prioritized based upon the sequence of training, what training already exists, and what skills and knowledge the target population for the specific job already possesses.

After determining the order in which training will be developed, the knowledge mapping data can be used to parcel out development responsibilities to several parties. Tasks that require similar areas of knowledge can be grouped for development by the same individuals or teams so that training for the same knowledge and skills is not developed twice. For example, the knowledge map for semiconductor manufacturing jobs reveals several tasks requiring prerequisite knowledge of basic photolithography principles. Having identified this before beginning training development, a single effort can be mounted to develop or acquire instruction on basic photolithography designed specifically to prepare the learner to perform a certain set of tasks. In addition, the generic difficulty levels can be used to categorize types of training development so that all development going on in parallel will yield similar products for similar applications. For example, methods and formats for developing procedural versus non-procedural training can be determined before training development begins. The A, B, and C knowledge level definitions from the knowledge mapping data can be used to identify whether knowledge is procedural or non-procedural and to prescribe the method and format of the training materials. This standardization strategy can also be used for involving SMEs without training development skills in the process. Once the methods and format for training have been determined, tools for soliciting from SMEs the right information in the right form can greatly increase the efficiency of a large-scale development effort.

A final use of the knowledge mapping data, unanticipated in the initial application, is establishing the comparable worth of the newly designed jobs. The task difficulty ratings provide a quantifiable measure of job difficulty that can be used for equalizing compensation with other jobs, as long as the other jobs have also been knowledge mapped. For example, a job made up of 20% A-level and 80% B-level tasks can be quantified as more difficult than a job made up of 80% A-level and 20% B-level tasks. Job difficulty is, of course, not the only factor in assessing the comparable worth of jobs. However, when difficulty is defined based upon the prerequisite education and training required, it is a major determinant. This was especially valuable in the initial application where new, enhanced jobs were derived from three existing jobs, all of which were documented through knowledge mapping.

Developing Knowledge Level Definitions

Before knowledge mapping data can be collected, the primary tool for knowledge mapping must be developed: knowledge level definitions. There are two major steps to developing knowledge level definitions for the analysis of specific tasks or jobs. The first step is to identify discrete content areas appropriate to the tasks or jobs. Once these have been defined, the second step is to translate the generic levels of task difficulty (see Figure 2) into three area specific definitions for each defined content area (see Figure 3). The area-specific knowledge level definitions should reflect a hierarchy of difficulty parallel to the generic levels of task difficulty. Each step is described below.

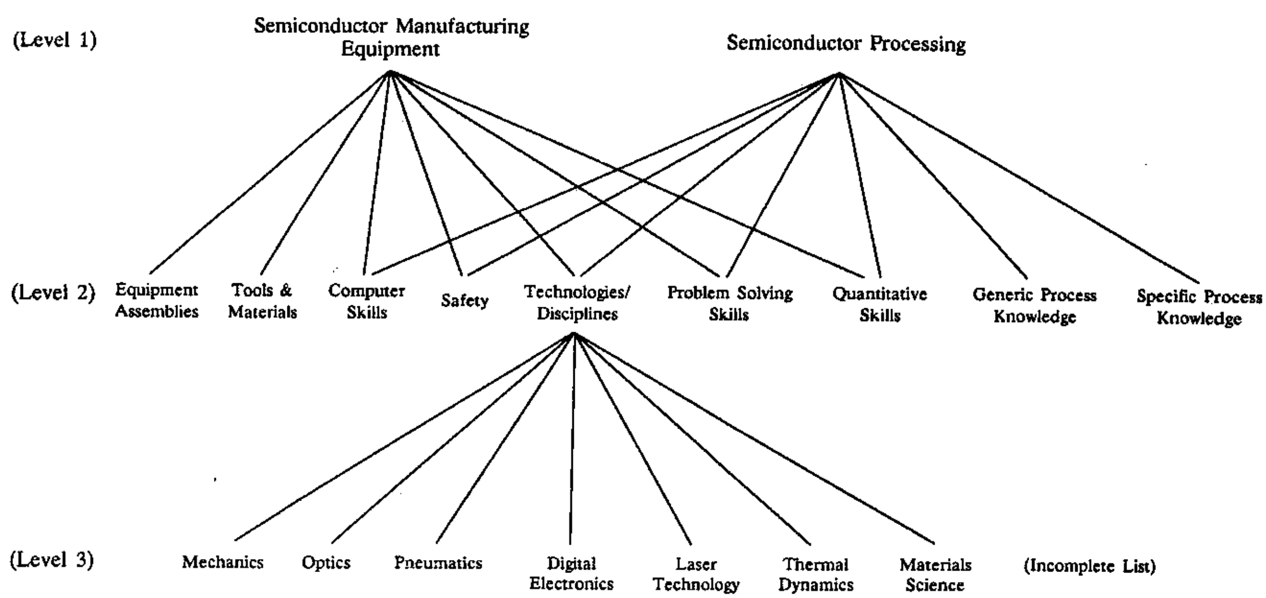
Identifying Content Areas

Knowledge mapping requires identifying discrete content areas associated with the job(s) being analyzed. Different jobs require knowledge of different content areas. Content areas can be defined at various levels of specificity. For example, knowledge of physics is a content area, so is knowledge of photolithography, and so is knowledge of the semiconductor applications of photolithography. Of course, for knowledge mapping to be a practical tool, content areas need to be defined at a similar level of specificity. The level of specificity also needs to be a relatively global one. Otherwise, the length of time to analyze any one task would be prohibitive.

In order to attain an appropriate level of specificity, global content areas must first be identified for the job(s). These global areas then need to be broken into more specific areas until the level is reached where it is easy to list specific types of knowledge within the defined content areas. A type of knowledge would be a more specific subject matter within a content area. Within the content area of quantitative skills types of knowledge would include knowledge of simple math, algebra, and statistics. The process is best understood by looking at an example.

Figure 6 shows the breakdown of semiconductor manufacturing knowledge into three increasingly more specific levels of content areas. The first level represents the two major content areas that make up knowledge of semiconductor manufacturing. Semi-

Figure 6. Defining Content Areas



conductor equipment refers to all the knowledge and skills required to operate and properly maintain and troubleshoot semiconductor manufacturing equipment. Semiconductor Processing refers to all the knowledge and skills required to characterize, monitor, maintain, and improve a semiconductor manufacturing process. Level 2 breaks down the two major content areas to the next level of specificity. The third level is only partially broken out because the number of discrete content areas increases greatly from level 2 to level 3. In addition to the increase in the number of items, it is possible to look only at the items in level 3 and accurately conclude that they are types of Technologies/Disciplines. In contrast, it would not be accurate to conclude that the items breaking out of Semiconductor Equipment in level 2 are types of semiconductor equipment. These are both signs that the previous, most general level (level 2 in this case) is the appropriate level to use in developing knowledge level definitions.

It is important to note that within each level of specificity, the listed content areas are discrete or mutually exclusive of each other. If two content areas are found to overlap, either the areas need to be redefined or possibly a third area needs to be created. Significant overlaps between the content areas can result in the collection of redundant data.

The process of defining content areas requires SME assistance unless the person developing the definitions is familiar with the job(s). At the very least, SMEs should check the defined content areas after a first draft has been developed. If the number of content areas exceeds ten, they are probably at too specific a level or the job(s) being analyzed may not be practically analyzed through knowledge mapping.

Developing Knowledge Level Definitions for Each Content Area

This is by far the most difficult aspect of preparing to conduct knowledge mapping. There were no set procedures identified for accomplishing this step during the initial application of knowledge mapping; however, a general description of how the definitions were derived will provide a starting point for future users of the knowledge mapping technique.

The difficulty in achieving good knowledge level definitions lies in the fact that developing the definitions requires a thorough understanding of both the generic levels of task difficulty and the specific subject matter. Because the individuals with the deepest understanding of the generic levels of task difficulty (instructional designers) are typically a different population from those who have the deepest understanding of the specific subject matter (SMEs), the challenge is having individuals from each of these populations work together to achieve knowledge level definitions with which they are both comfortable.

In the initial application, the process began by identifying individuals with knowledge of instructional design and experience in applying that knowledge to the given content areas (i.e., equipment assemblies, process knowledge, computer skills, etc.). When these individuals had developed first-draft knowledge level definitions, they were reviewed by SMEs. After the SMEs gave their suggestions and all involved parties were comfortable with the revised definitions, the definitions were tried out with a sample of SMEs from the population that would be used in the actual knowledge mapping interviews.

Like specifying the content areas, the development of knowledge level definitions is an iterative process. Changes to the initial agreed-upon definitions were made through several tryouts of the definitions until the decision was made to "freeze" the definitions for the initial application and record any potential improvements for use in future applications. One general strategy for improvement that came up several times during the first application and will no doubt be used in future applications involved providing specific examples for each knowledge level definition. This strategy is discussed later.

Collecting Knowledge Mapping Data

The knowledge level definitions are used in an interview setting after a list of job tasks has been developed. Carlisle (1986), Kennedy, *et al.* (1983), Andrews and Goodson (1980), and many others provide descriptions and bibliographies of documented techniques for generating task lists. Whatever techniques are used to generate the preliminary task list, it should be checked by SMEs before beginning the knowledge mapping interviews. The objective of a knowledge mapping data-collection interview is to identify for each task the types of knowledge required to perform the task and the level of difficulty of each. However, before the interview can be conducted, the interviewer needs to do some preparation beyond development of the definitions.

Preparing for the Interview

The interviewer needs to take three things into the knowledge map data collection interview: a copy of the knowledge level definitions, a data collection sheet for each task, and a predetermined list of types of knowledge for certain content areas. The definitions should be in a form useful to the SMEs who will be interviewed, and should be clearly organized (by content area) and concisely written. The data collection sheet should list each content area along with space to write in or check off specific types of knowledge. Adjacent to each type of knowledge should be a space to designate the level of difficulty (A, B, or C; see Figure 4).

Finally, to ensure that types of knowledge are kept at a consistent level of specificity across interviews, a list of likely types of knowledge should be generated for the appropriate content areas. This can be done in the initial interviews for generating task lists by explaining to the SMEs what "types of knowledge" are, and then having them generate as exhaustive a list as they can for the given content area. For example, referring back to Figure 6, an experienced semiconductor operator should be able to list types of equipment assemblies (e.g., control panel, wafer handling assembly, mask transport system) at a consistent level of specificity. Other SMEs may generate new types of knowledge within the same content area during the knowledge map data collection, but they are more likely to stay at the same level of specificity if examples are provided.

With all of the tools in place, the interviewer can further prepare by getting a general idea of the job(s) they intend to analyze. This can usually be achieved adequately by informally observing someone performing the job(s) and asking a few questions. The goal is to pick up enough terminology to talk about the job intelligently and also be able to visualize the SME's description of how certain tasks are generally accomplished.

Conducting the Interview

The SME should first be briefed on the purpose of the interview and how it will be conducted. Then, for each content area (for example, Power Systems Components or Quantitative Skills from Figure 6), the SME should be asked if that content area is in any way required for performing the specific task. If the answer for that content area is yes, the next question should be "what types of knowledge within the content area are required to perform this specific task?" The SME should be shown the predetermined list of types of knowledge to make sure the appropriate level of specificity is adhered to. However, responses should not be limited to the predetermined list.

When all appropriate types of knowledge have been listed, the SME should be asked, for each specific type of knowledge, "what level of this type of knowledge is required to do this specific task?" The SME should use the definitions to determine the level of knowledge required. To ensure that the SME is adhering to the definitions, the interviewer should probe to make sure the correct level has been identified. Figure 7 provides an example dialogue between the interviewer and the SME for one type of knowledge within one content area for one task. Note how the interviewer probes to verify that the SME is sticking to the definitions. The probing is only necessary on a periodic basis after the interviewer knows that the definitions are being adhered to consistently.

Figure 7. Excerpt from a Knowledge Mapping Data Collection Interview

Interviewer: The next task is cleaning the etcher chamber. Using our provided listing, what etcher assemblies do you need knowledge of to clean the etcher chamber?

Interviewee: Oh let's see . . . you would need knowledge about the interlock mechanism and quite a bit of knowledge about the etcher chamber itself.

Interviewer: Think about performing the task. Are there any others that we've left off the list?

Interviewee: Well, you need to know about O-rings, but I guess that would be considered a part of the chamber which we already listed.

Interviewer: OK, now for the chamber. What level of knowledge would you need to have about the chamber to safely and consistently perform this task? Look at the knowledge definitions under "Equipment Assemblies."

Interviewee: (Looks at definitions.) I'd say level B.

Interviewer: What technologies or disciplines do you need to understand about the chamber to clean it effectively and safely?

Interviewee: Well, basically you need to understand how the chamber physically works, which requires knowledge of several basic principles of vacuum technology. Without this knowledge, chances are you will cause the chamber to leak when it's back in operation.

Interviewer: Could the knowledge required be documented in the form of a series of procedures?

Interviewee: Not really. You tend to have to make decisions that require background knowledge.

Interviewer: OK, that certainly falls within level B. Now, what level of knowledge do you need about the interlock mechanism to clean the etcher chamber effectively and safely?

Interviewee: Oh, I'd say level C on that one.

Interviewer: OK, why is it that you need such in-depth knowledge of the interlock mechanism?

Interviewee: Because if you fail to seal the interlock correctly, you could have a potentially dangerous mix of gases during operation.

Interviewer: You definitely don't want to do that, but unless you need in-depth knowledge of the interlock mechanism to avoid making a mistake, we probably need to address the danger in the "Safety Knowledge" section.

Interviewee: I guess that's true. You don't really need to know much more than a couple of hydraulics principles to successfully perform this specific task, so I guess that makes it level B.

Interviewer: I agree. OK, if that's all the etcher assemblies involved in this task, let's move on to the next content area.

Lessons Learned

In its first application, knowledge mapping has shown its value by adding objectivity to SME ratings of task complexity, creating a time saving structure for training development and delivery, and providing a quantitative basis for compensation analysis. It is anticipated that the tool can be used more efficiently in the future based on lessons learned from this initial application.

Developing the Definitions

One comment which was repeated several times by SMEs participating in knowledge mapping interviews was that the definitions would be easier to understand if specific examples were given for each definition in each content area. This advice was followed in a second application of knowledge mapping that focused on nonroutine tasks that fall into the same three semiconductor manufacturing functions as the initial application (operations, equipment, and process). Figure 8 shows the examples provided for the different definitions within one content area.

Although each is based on one specific piece of equipment, the examples typically focus on subject matter and terminology that is common to many different kinds of equipment. Since the inclusion of these examples, many participating SMEs have commented that the examples do indeed help distinguish between levels. The participating analysts also are in agreement that the examples make it easier to explain to the SMEs the differences between the generic levels of task difficulty; A, B, and C.

Before Beginning the Interview Process

Once a set of clearly and concisely written knowledge level definitions with well thought out examples is created, the key to using the definitions effectively is for all users of the definitions (analysts) to interpret them consistently. The best way to achieve this goal is to limit the users of the tool to as small a group as possible, preferably the same group that developed the definitions. This will not always be practical, especially for larger scale applications. The alternative is to provide training for the users. Several observations about the preparatory training were made during the initial application.

One mistake to avoid is combining the knowledge mapping training with other information and training. In the initial application, travel cost was the impetus for packing too much training into one day. The savings, however, ended up being used to evaluate and coach the users later at their respective sites. The ideal objective of the training would be to achieve a significant interrater reliability. However, even if this goal is not attempted (as it was not in the initial application), plenty of time needs to be allowed to go over the definitions and ensure that everyone interprets them the same. Once this has been achieved, it is critical to provide practice and coaching on conducting the interview. If a realistic simulation of a knowledge mapping interview cannot be carried out in the classroom, each interviewer should be supervised and coached during their first interview.

One positive interviewer attribute, which is very difficult to train, is recognizing when the SME is no longer attending to the interview questions. This is often a risk with SMEs who catch on quickly and do not seem to need reminders about accurately using the definitions. Unless each consecutive task is very different in nature, it is easy for fast learners to start answering the questions in patterns based on key verbs in the task statement. It is important that the interviewer recognize when this is happening and do something to force the SME out of patterned responses. It often helps to try to mix up the tasks so that you do not analyze too many similar ones in a row.

Another factor for successful application of knowledge mapping is gaining access to the appropriate SMEs. It is very important that the SME used to provide knowledge map data on a group of tasks be very knowledgeable on how those tasks should be performed. This person should also be very knowledgeable about what someone needs to know to perform the task correctly, which is what the knowledge mapping tools are designed to find out.

The most appropriate SME for the knowledge map data collection interview may well be someone other than the SMEs used to derive the task list. Although the people who actually perform the job can best describe what tasks they perform, in many cases they are not necessarily the most knowledgeable about why tasks are done in a specific way. As a general example, where technicians are assisting en-

Figure 8. Knowledge Level Definitions and Specific Examples.

Equipment Assemblies

A. State the function and location of the assembly and its key parts. Describe the general sequence of events for how the assembly/part works.

Example: To clean the boatloader, you need to have the following knowledges about the boatloader assembly: state key parts and where they are located, and describe the sequence of how the boatloader operates because you need to partially operate the boatloader while you clean it.

B. Use limited knowledge of one or more technologies (e.g., electronics, mechanics, pneumatics, optics, vacuum, etc.) to describe why this specific assembly functions the way it does in a given situation.

Example: To adjust paddle soft placement speed, you need to have the following knowledges about the paddle: Explain how the vacuum system makes the paddle move in order to determine what kind of vacuum system adjustment would cause the paddle to sit further forward or backward.

C. Use broad-based knowledge of one or more technologies to describe why this general type of assembly generally functions the way it does.

Example: To calibrate any MFC in the Fab, you need the following knowledge about the MFC: broad-based knowledge of electronics and gas flow dynamics in order to explain how MFC's become out of calibration.

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gineers in an industrial setting, the technicians can probably provide a more accurate description of their job, but the engineers probably have more knowledge about why specific tasks are done in specific ways.

It is a good idea to knowledge map the first few tasks with two or three different SMEs and resolve any discrepancies that occur due to the knowledge level definitions or interviewer interpretation. When an acceptable level of cross-validation is apparent, it will be adequate to knowledge map the rest of the tasks in the same area of expertise with one SME. Hence, in setting up an SME base, it is important to identify the one SME who is most knowledgeable about how the tasks should be performed for each job or area of expertise.

The resulting data base is only as useful as the SME is knowledgeable. The most knowledgeable SMEs are also the most valuable on the job (assuming an industrial application), so it is often difficult to get management to release them. The alternative, however, is to risk either ending up with an inaccurate data base or performing time consuming interviews on the same tasks more than once. Even if getting the most knowledgeable SMEs extends the project timeline, it is worth the wait.

Successfully Conducting Knowledge Mapping Interviews

Like any other interview situation, there is a limit to how long the interview can be conducted productively before either the analyst, the SME, or both become fatigued. Because the analysis of each type of knowledge can potentially alter the difficulty level for the whole task, it is critical that the interview be terminated before either party becomes fatigued and therefore careless.

In the initial application, all interviews were scheduled for a two-hour duration, allowing for 20 minutes of explanation, 90 minutes of productive knowledge mapping, and 10 minutes to spare. It turned out that productive knowledge mapping could be sustained for no more than 60–75 minutes. For this reason, the ideal duration for an entire knowledge mapping interview seems to be about 90 minutes.

Finally, the most common mistake made by interviewers was to forget to specify early in the interview the conditions and criteria for performing the task. In other words, instead of asking, "what level of this type of knowledge do you need to perform the task under ideal conditions (no system failures) without risk to yourself, the product, or the equipment?" the interviewer would ask "what level of this type of knowledge do you need to perform the task?" Without the specific conditions and criteria, the SMEs are likely to overestimate the knowledge required because they often have more knowledge than is required to perform the task under ideal conditions. Conditions and criteria for performing the task could be different for separate applications, but it must be determined initially and communicated consistently to participating SMEs.

Discussion

Several benefits of using the knowledge mapping technique to accomplish various aspects of human resource management—job design, training curriculum design, and establishing job levels for compensation—have been presented. However, conclusions about the global value of knowledge mapping cannot be drawn from observations of the initial application of the technique. This is because, first, the technique was designed for and around this initial application, and second, no systematic, data-based assessment of the intervention has been conducted. At this point, the best indication of the tool's utility is simply that management has chosen to expand the use of the tool beyond the initial tryout described in this application. In the absence of data-based conclusions about the technique, some hypothetical pros and cons of knowledge mapping are presented.

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There were two primary reservations about the knowledge mapping tool which were discussed at some length both before and during the initial application. The primary problem, as perceived by many people associated with the project, was that the cost in SME and analyst time of developing the tools and collecting the data would outweigh the anticipated benefits of the technique. The second major reservation about the technique, prior to its use, was whether a measure of task difficulty based solely on knowledge and cognitive skills, without incorporating motor skills, would be adequate for making critical job design decisions.

The costs versus benefits concern was a demonstration of a classic conflict in for-profit organizational settings: how to balance up-front data collection and analysis against trial-and-error, "experienced-based" decision making. More specifically, there was a strong contention that a team of expert performers representing each of the three job functions being analyzed should be put into the work environment with the objective of determining how to optimize the efficiency of human resources in sustaining the specified operations. Proponents of the knowledge mapping technique maintained that the real cost of this alternative method could very likely be as great or greater than the cost of knowledge mapping, depending, of course, on the abilities of the individuals on any one team. It was finally decided to use knowledge mapping in the initial set of applications because the alternative method would not yield the level of documentation required to develop training. Again, the fact that the use of knowledge mapping has extended beyond the initial application is the only indication that the technique is cost effective.

The second reservation, whether task complexity could be adequately measured based solely on knowledge rather than observable skills, was not openly discussed but was very much a concern of the designer of the technique. After all, the vast majority of the tasks in question manifested at least partially in the form of observable behaviors. The decision to focus strictly on knowledge and cognitive skills in assessing task complexity was based on two assumptions. First, the assessment of skills in addition to the knowledge required to perform a task significantly increases the cost of data collection and analysis. Second, assessment of skills is much more subjective than assessment of knowledge, and would therefore require a technique much more rigid than interviewing.

One informal observation of the result of the knowledge mapping technique is that knowledge difficulty seems to be an adequate indicator of who is capable of doing what. There were very few cases where a task designated as appropriate for a specific employee population was found in practice to be inappropriate due to the difficulty of the motor skills required. (Some tasks were reallocated due to safety considerations, even though safety was included as one of the nine major areas of knowledge.) One interpretation is that even though a job is behaviorally oriented, the actual limits to performance often are not knowing what to do and when to do it. Based on this line of reasoning, it would be expected that in a situation where tasks are clearly dependent on motor skills, the knowledge mapping technique is not likely to be as useful.

In summary, knowledge mapping was designed to improve the objectivity and accuracy of task difficulty ratings for determining who is capable of performing what tasks and what training is required. In this particular application, the contribution made by knowledge mapping to job design, training curriculum development, and determining the relative worth of tasks and jobs warranted future use of the technique for similar applications. However, having been developed in an industrial setting, the methodology was applied at a very formative stage and without quantitative evaluation. It is hoped that by sharing our experience in this article, the methodology will be further analyzed and developed both as a practical tool and in the context of existing models of learning and performance.

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