Hierarchical Task Analysis: Developments, Applications and Extensions.

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Hierarchical Task Analysis (HTA) is a core ergonomics approach with pedigree of over thirty years continuous use. At its heart, HTA is based upon a theory of performance and has only three governing principles. Originally developed as a means of determining training requirements, there was no way the initial pioneers of HTA could have foreseen the extent of its success. HTA has endured as a way of representing a system sub-goal hierarchy for extended analysis. It has been used for a range of applications, including interface design and evaluation, allocation of function, job aid design, error prediction, and workload assessment. Ergonomists are still developing new ways of using HTA which has assured the continued use of the approach for the foreseeable future.

1. Origins of Task Analysis

According to Kirwan & Ainsworth (1992), HTA is the "*best known task analysis technique*" (page 396). As such, it is probably a special case in the ergonomics repertoire of methods. Since the first paper written on the specification for the method in 1967 by Annett and Duncan, the past 37 years have seen many developments in ergonomics research and methods. Despite this, HTA has remained a central approach. It is fitting to review the current state of the art to help take stock of where HTA has come from, the contemporary issues, and the potential for the future.

The origins of all modern task analysis techniques can be traced back to the scientific management movement in the early 1900s (Annett & Stanton, 1998, 2000). The three figures that stand out from this time are Frank and Lillian Gilbreth and Frederick Taylor. The Gilbreths sought to discover more efficient ways to perform tasks. By the- way of a famous example of their work, Frank and Lillian Gilbreth observed that bricklayers tended to use different methods of working. With the aim of seeking the best way to perform the task, they developed innovative tools, job aids and work procedures. These innovations included: scaffolding that permitted quick adjustment, shelves for bricks and mortar, and methods for getting the bricks and mortar to the bricklayers by lower paid labourers. The net effect of these changes to the work meant that the laying of a brick had been reduced dramatically from approximately 18 movements by the bricklayer down to some 4 movements. The task was therefore performed much more efficiently. The principle underlying this work was to break down and study the individual elements of a task. The individual elements (called Therbligs - a reversal of Gilbreth - such as 'grasp' and 'assemble') were recorded against time, hence the phase 'time-and-motion' study (Gilbreth, 1911). Annett (2000) notes that whilst most of the therbligs refer to physical movement, there were some 'cognitive' therbligs, such as 'search, 'select', and 'find'. The scientific management community, with which Frederick Taylor's name is inextricably linked, sought to apply the rigour of scientific method in the analysis of work. At the heart of this approach was serious analytical critique of the details of methods for working: How was the work performed? What was needed to perform the work? Why was the work performed in this way? How could the working methods be improved? Modern task analysis methods have retained this general approach to task critique. Annett (1996) has certainly argued that HTA encourages the analyst to consider not only what should happen, but what does actually happen and how this can go wrong. He suggests that these questions will arise naturally as the analyst seeks to discover the indicators for success and failure of each of the sub-goals.

The scientific management approach has been criticised for failing to consider the psychological make-up of work (e.g., Hackman and Oldham, 1980). Accounts of efficiency drives and job simplification may lead one to suppose that it fails to take the effects on individual person into account. Certainly, Taylor's (1911) (in)famous book on 'The Principles of Scientific Management' does little to dispel this idea, which contains capatilistic political overtones and accounts on the laziness of the working classes. The Gilbreth's work however, seemed to be focused on the well-being of the person as well as the effectiveness of the work. This may well have been influenced by Lillian Gilbreth's profession as a psychologist. This latter approach is much closer to the heart of modern ergonomics. In the century that has passed since these original pioneers of task analysis, several important changes have taken place. Annett (2000 - CTA book) cites several influences that have contributed to early thinking in HTA. In the 1950s, Ergonomics was emerging as a distinct discipline, but drawing on contemporary trends in psychology and engineering. A few of these advances which have influenced the early development of HTA were identified by Annett (2000). The 1950s gave rise to new theories of human performance in systems and new ways of assessing human activities in system design. Whilst it is difficult to pinpoint all of the possible factors that could have led to the development of HTA, some of the main influences are likely to include: the break down of tasks into their elements, the questioning of human performance in systems, a need to understand both physical and cognitive activity, a desire to represent the analysis in a graphical manner, and a need for an underpinning theory of human behaviour. One of the most influential ideas for HTA was the identification of error varience in system performance from systems theory (Chapanis, 1951). Annett (2004) states that the top-down systems approach taken by HTA enables the analyst "to identify and deal first with factors generating the largest error variance." (p. 68-69). The error varience could be generated by either humans or machines, or an intereaction between human and machines.

Annett (2004) points out that the initial development effort in hierarchical task analysis was in response to the need for greater understanding of cognitive tasks. With greater degrees of automation in industrial work practices, the nature of worker tasks were changing in the 1960s. Annett argued that as these tasks involved significant cognitive components (such as monitoring, anticipating, predicting and decision making), a method of analysing and representing this form of work was required. Existing approaches tended to focus on observable aspects of performance, whereas hierarchical tasks analysis sought to represent system goals and plans. At the time of the late 1960s this was a radical departure from contemporary approaches. The 'cognitive' revolution had yet to happen in mainstream psychology and the 'behaviouristic' paradigm was dominant. At that time it was considered 'unscientific' to infer cognitive processes, and academic psychology focused principally on observable behaviour. Hierarchical tasks analysis however, offered a means of describing a system in terms of goals and sub-goals, with feedback loops in a nested hierarchy.

The influence of control theory of human behaviour as proposed by Miller et al (1960) can clearly be seen in HTA. Central to this theory are the twin ideas of a TOTE (Test – Operate – Test – Exit) unit and hierarchical levels of analysis. The classic example of a TOTE unit is the explanation of hammering a nail flush with a piece of wood. This is illustrated in figure one.

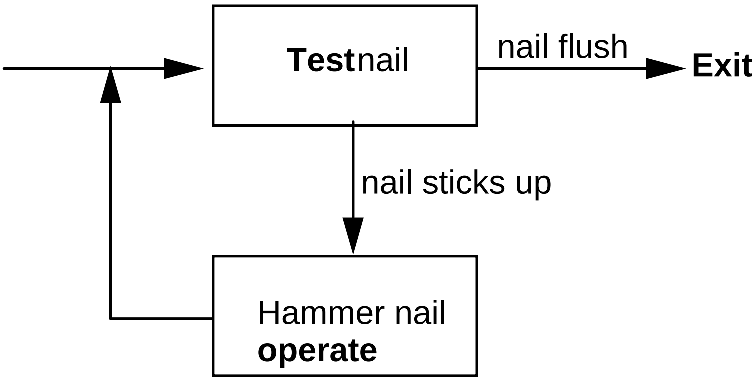

Figure one. A TOTE unit for making a nail flush with the surface.

The three units of analysis are a TEST (where the goal is to see if the nail is flush with the surface of the wood), if the nail is not flush then an OPERATION is performed (i.e., striking the nail with the hammer), then the TEST is performed again. If the nail is flush, then the operator can EXIT this activity. We can imagine a situation where the nail is already flush, so the analysis would comprise just the TEST and EXIT components, or other situations where multiple TESTS and OPERATIONS are performed prior to the EXIT. In TOTE terms these would be TE and TOTOTOTOTE respectively. The important aspects of the TOTE analysis are that it implies some level of information feedback, a system of control, and it offers hierarchical analysis of systems. Miller et al (1960) illustrated the hierarchical analysis, by showing how the operation in figure one could be further investigated, as illustrated in figure two.

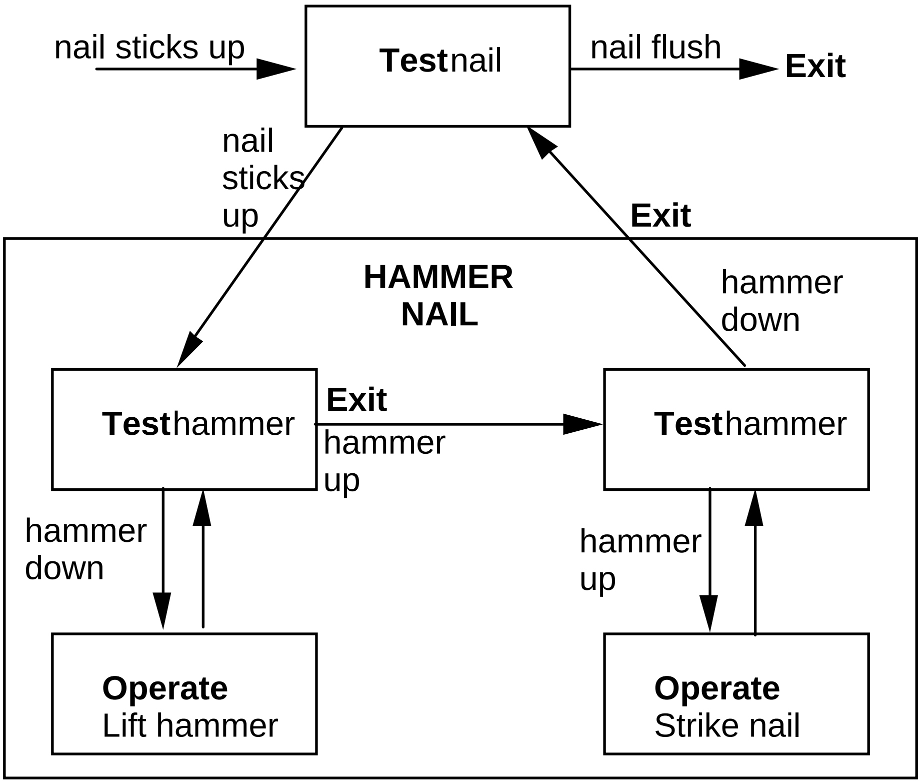

Figure two. The hierarchical plan with 'hammer nail' re-described.

Miller et al (1960) point out that the hammering of a nail only serves as an example and one might not attempt to analyse all tasks down to this level of detail. The analysis does show how it is possible to develop a more detailed system view of the control structures within a hierarchical analysis. Any system could, potentially, comprise of hierarchically arranged TOTE units. As Miller et al put it:

> "*Thus the compound of TOTE units unravels itself simply enough into a co-ordinated sequence of tests and actions, although the underlying structure that organises and co-ordinates the behaviour is itself hierarchical, not sequential.*" (Miller et al, 1960, p. 34)

The example in figure two shows how the operation of a hammer comprises a test of its position and then the operation of striking the nail. If the test of the hammer's position shows the hammer to be in the down position, then the operation of lifting the hammer is triggered. If the hammer is already in the up position, then this operation is omitted. There are many parallels with this form of analysis of control structures and the triggering of operations with the representations used in HTA. An illustration of the hammering task analysed by HTA is presented in figure three for comparison with the TOTE analysis in figure two.

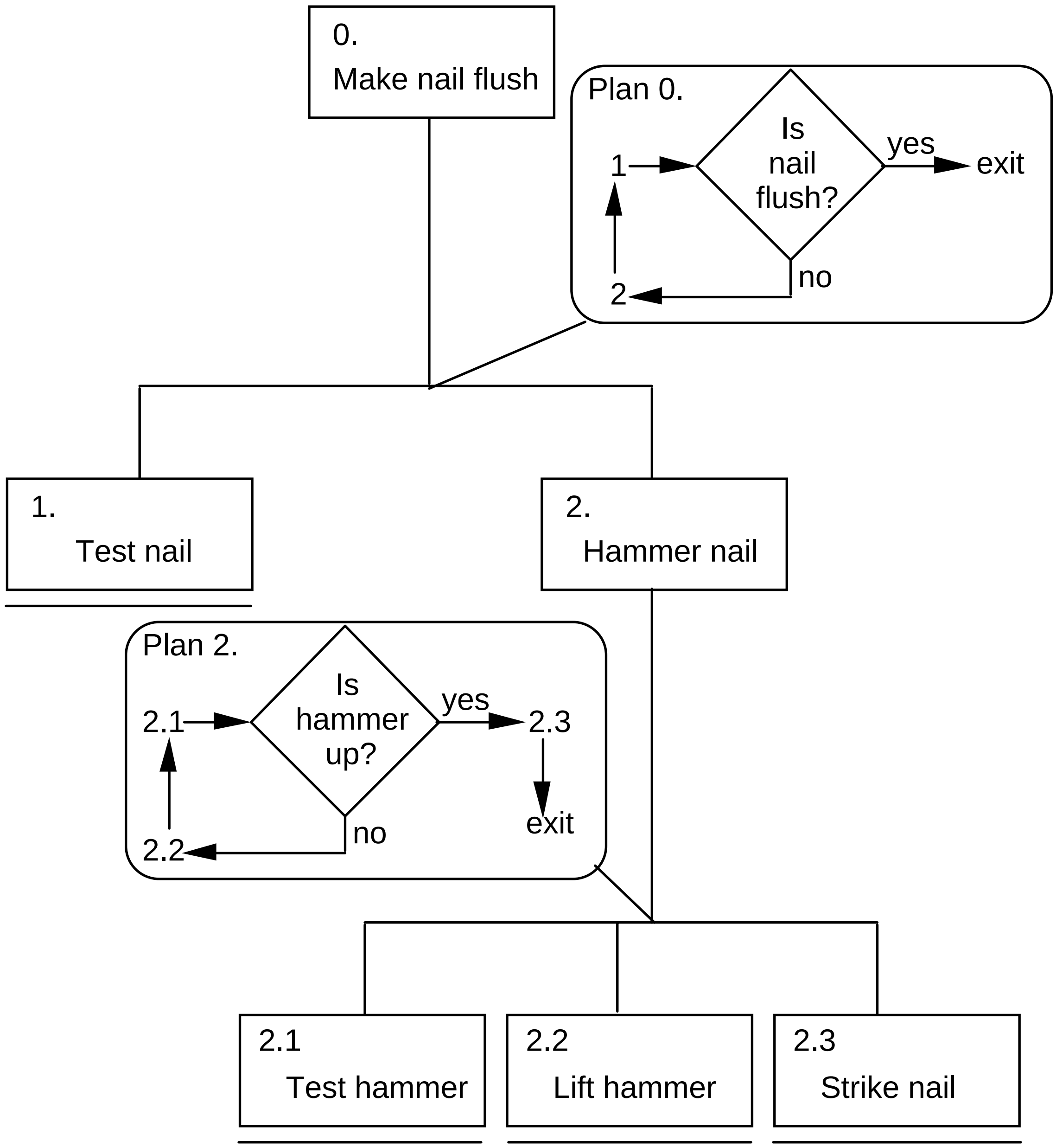

Figure three. HTA for goal of 'Make nail flush'.

As shown by comparison between figures two and three, the sub-goal and plans from HTA in figure two map onto the TOTE units in figure one. The hierarchical systems analysis and control structures, whilst represented differently, the two systems of analysis are comparable. A super-ordinate goal of "Make nail flush' has been added in the HTA, but this was implicit in the hierarchical plan shown in figure two. The plans in HTA act as the control structures that govern the sequence of the sub-goals. These are precisely the same control structures as those in the TOTE analysis. The two forms of analysis are highly compatible.

In one of the earliest papers leading up to the specification for HTA, Annett & Duncan (1967) show their concern with the adequacy of the description. The idea of a hierarchical description comprising subordinate operations is proposed with rules governing the level that this is taken to. They argued that some aspects of a task might be taken down several levels of re-description, whereas others will not. The decision to re-describe the task will depend upon estimates that the task can be performed adequately at that level of description. The authors proposed that this estimate was likely to include decisions about cost-critical aspects of the performance and difficulty of the task.

2. Development of Hierarchical Task Analysis

In the original paper laying out the approach for conducting HTA, Annett et al (1971) make it clear that the methodology is based upon a theory of human performance. They proposed three questions as a test for any task analysis method, namely: does it lead to any positive recommendations, does it apply to more than a limited range of tasks, and does it have any theoretical justifications? Perhaps part of the answer for the longevity of HTA is that the answer to each of these questions is positive. More modern methods might well fail some of these criteria. To paraphrase Annett et al's words, the theory is based on goal-directed behaviour comprising a sub-goal hierarchy linked by plans. Thus performance toward a goal can be described at multiple levels of analysis. The plans determine the conditions under which any sub-goals are triggered. The three main principles governing the analysis were stated as follows:

> "*1. At the highest level we choose to consider a task as consisting of an operation and the operation is defined in terms of its goal. The goal implies the objective of the system in some real terms of production units, quality or other criteria.*
>
> *2. The operation can be broken down into sub-operations each defined by a sub-goal again measured in real terms by its contribution to overall system output or goal, and therefore measurable in terms of performance standards and criteria.*
>
> *3. The important relationship between operations and sub-operations is really one of inclusion; it is a hierarchical relationship. Although tasks are often proceduralised, that is the sub-goals have to be attained in a sequence, this is by no means always the case.*" (Annett et al, 1971, page 4)

It is important to fully digest these three principles, which have remained unwavering throughout the past 32 years of HTA. In the first principle, HTA proposed as a means of describing a system in terms of its goals. Goals are expressed in terms of some objective criteria. The two important points here is that HTA is a goal-based analysis of a system and that a system analysis is presented in HTA. These points can escape analysts who think that they are only describing tasks carried out by people, whereas HTA is quite capable of producing a systems analysis. Therefore HTA can be used to describe both team work and non-human tasks performed by the system. HTA describes goals for tasks, such that each task is described in terms of its goals. 'Hierarchical Sub-Goal Analysis of Tasks' might be a better description of what HTA actually does.

In the second principle, HTA is proposed as a means of breaking down sub-operations in a hierarchy. The sub-operations are described in terms of sub-goals. This re-iterates the point above, that HTA is a description of a sub-goal hierarchy. Again the sub-goals are described in terms of measurable performance criteria. The final principle states that there is a hierarchical relationship between the goals and sub-goals and there are rules to guide the sequence that the sub-goals are attained. This means that in order to satisfy the goal in the hierarchy its immediate sub-goals have to be satisfied, and so on. The sequence with which each sub-goal is attained is guided by the rules that govern the relationship between the immediate super-ordinate goal and its sub-ordinates.

In their original paper, Annett et al (1971) present some industrial examples of HTA. The procedure described in the worked examples shows how the analyst works in a process of continual reiteration and refinement. To start with the goals are described in rough terms to produce an outline of the hierarchy. This allows further clarification and analysis. Progressive re-description of the sub-goal hierarchy could go on indefinitely, and Annett et al (1971) caution that knowing when to stop the analysis is "*one of the most difficult features of task analysis*" (Annett et al, 1971, page 6). The criterion for stopping the analysis was determined satisfying the probability of failure (P) multiplied (x) by the cost of failure (C) to an acceptable level, known as the PxC rule. Annett et al (1971) admit that it is not always easy to estimate these values and urge task analysts not to pursue re-description unless it is absolutely necessary.

The stopping rule is simple enough in its conception: if the probability of failure (P) times (x) the cost of failure (C) is acceptable then stop the task analysis. If P x C is unacceptable, then the analysis should continue. Under most situations, the probabilities and costs are not known and the analyst has to apply an approximation of this rule, although it may not be clear what they are basing this judgement on. Stammers & Astley (1987) point out that the stopping rule has remained a problem area for HTA. The P x C rule attempts provide an economy of description. The is no need to re-describe every sub-goal down to the most basic, elemental, level if failure to perform that sub-goal is inconsequential. Exactly when to stop the analysis has remained a problem for HTA (Stammers & Astley, 1987). Piso (1981) notes that the P x C criterion is complicated and time-consuming. His proposed solution to this problem is to continue the analysis until the sub-goal is clear to both the analyst and subject matter expert(s). Annett (2004 – personal communication) has pointed out that "it is important to think of the P x C criterion as a statement of principle rather than an exact calculation." The role of the P x C rule seems to be to save the analyst time in analysing tasks where the 'error variance' would be inconsequential, and to guide more exploration where the 'error variance' would be intolerable.

The original hierarchical number scheme for HTA required that every sub-goal was uniquely numbered with an integer in numerical sequence. Each sub-goal was further identified by stating its super-ordinate goal and its position under that sub-goal. This arrangement is illustrated in figure four. The overall goal of 'Operate radiator line' is numbered '1' as the super-ordinate goal. The immediate subordinate goal are numbered 2 to 7 (only 2 to 4 are shown in figure four). The sub-goal 'Operate control panel' has additional numbering of '1,1' to denote that it is the first sub-goal of super-ordinate goal 1. 'Control cross welder' is denoted 3/1,2 to show that its unique identifier is sub-goal 3, and that it is the second sub-goal of super-ordinate goal 1. Likewise, sub-goals 8, 9 and 10 show their relationship to their super-ordinate goal 3.

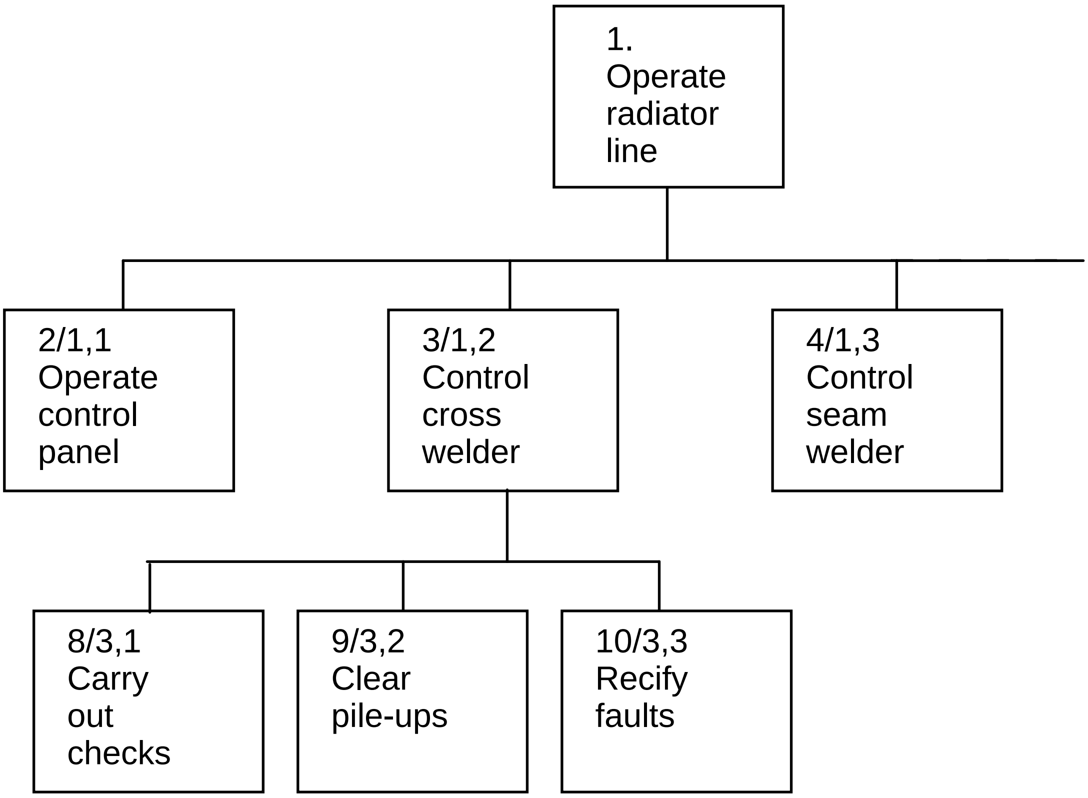

Figure four. Numerical hierarchy system specified for HTA.

As well as the hierarchical diagram, Annett et al (1971) specified the production of a table for representing task relevant information as illustrated in table one. The numbers in the left-hand column identify the goals in the hierarchical diagram (although this is a different task being analysed to that in figure four). The next column (Description of Operation and Training Notes) contains the goal name, an 'R' if it is to be re-described elsewhere in the table, and notes relevant to training performance, methods and constraints (as HTA was original devised to address training specification). The column titled 'I or F' would contain an 'X' if there were any Input or Feedback difficulties found in performance of the task. Similarly, the column titled 'A' would contain an 'X' if there were any Action difficulties found in performance of the task.

Table one. Part of the original tabular format

No.	Description of Operation and Training Notes (R = re-description)	I or F	A	re-described

1	Operate acid purification plant. **R** Instructions when to start-up or shutdown the whole process given by supervisor.	------	X	2 to 4
2 . 1,1	Start-up plant. **R** Must memorise order of units, i.e., C10, R2, C12	------	X	5 to 7
3 . 1,2	Run plant. **R** Log keeping and sampling tests for contamination at intervals fixed by supervisor. Alarm signal dynamic failure.	------	X	8 to 10

Annett et al (1971) intended the 'I or F' and 'A' columns as memory aids for the analyst. They suggest that they analyst should ask of every task if there were any difficulties with the input-action-feedback cycle of behaviour. The order of the sub-goals were governed by a rule determining their exact sequence. In the original specification of HTA three types of rule were identified: procedure or chain, selection, and time-sharing. The procedure or chain rule required that the sub-goals were performed in a fixed sequence. The selection rule indicated that the sub-goals were selected depending upon the outcome of another sub-goal. The time-sharing rule required some sub-goals to be performed in tandem. Annett et al (1971) argued that if the HTA is conducted properly it could be applied immediately to training design.

Some criticisms of the original specification of HTA were brought forward by Shepherd (1976), who proposed enhancements to the tabular format. Shepherd applauded the use of the tabular format to supplement the hierarchical diagram, but identified some potential weaknesses with the original table layout. His objections were: the remoteness of plans; combining information on operations, plans and training notes into one column; and, the usefulness of the two columns for sensory information/perceptual feedback (I/F) and motor action (A). Shepherd argued that close proximity of plans to the operations to which they refer would reduce confusion for the analyst and anyone else who has to interpret the analysis. He proposed that the plans and operations should be grouped together so that the control structure governing the sequence of operation is easy to refer to. Shepherd also argued that the plans, operations and training notes should not appear within the same column. To deal with these criticisms, Shepherd proposed an improved tabular format to overcome the problems as he saw them. An example of the revised tabular format is illustrated in table two.

Table two. Part of the improved tabular format proposed by Shepherd

Super-ordinate	**Task component - operation or plan**	**Reason for stopping the analysis**	**Notes on performance, training and further analysis**
1.	OPERATE ACID PURIFICATION PLANT Plan 1: Instructions to start-up or shut-down are given by the plant supervisor. -- 2. Start-up plant 3. Run Plant 4. Shut-down plant		
2.	START-UP PLANT Plan 2: Units must be started up in the following order: first column 10, second reactor 2, third column 12. -- 5. Start-up column 10 6. Start-up reactor 2 7. Start-up column 10		Plan 2. The sequence must be memorised

Further changes and simplifications have been proposed over the years. For example, a HTA training manual by Patrick et al (1986) has proposed only three columns. They proposed that the notes column should be used for suggestions on how the analyst can improve the sub-goals. A variety of formats for doing this have emerged over the years, such as separate columns for job design, job aids, training, and procedures (Kirwan and Ainsworth, 1992).

The hierarchical numbering system proposed in the original format was more complex that it needed to be and has subsequently been replaced with the decimal format. In the original proposal all sub-goals were numbered by integers from left to right, from 1 onwards. The also has their relationship with their immediate super-ordinate goal expressed underneath. Thus sub-goal 2 in table two was the first sub-division of super-ordinate goal 1, so was denoted 2/1,1., whereas sub-goal 3 was the second sub-goal of super-ordinate goal 1, so was denoted 3/1,2. The first number refers to the unique number of the sub-goal , the next number refers to the super-ordinate goal and the last number refers to the position under the super-ordinate goal. Under the decimal system these sub-goals would be referred to as 1.1 and 1.2 respectively, to show that they were the first and second sub-goals of super-ordinate goal 1. The advantages of this newer system is that it makes it far easier to trace the family tree of any sub-goal. Imagine trying to find the genealogy of sub-goal 1.3.2.4.6 under the original system in the tabular format. An illustration of how the newer system of hierarchical decimal numbering represents the sub-goal is illustrated in table three.

Table three. Part of the tabular format with hierarchical numbering

Super-ordinate	**Task component - operation or plan**	**Notes**
1.	OPERATE ACID PURIFICATION PLANT Plan 1: Instructions to start-up or shut-down are given by the plant supervisor. --- 1.1. Start-up plant 1.2. Run Plant 1.3. Shut-down plant	
1.1.	START-UP PLANT P1.1: 1→ 2 → 3 → EXIT --- 1.1.1. Start-up column 10 // 1.1.2. Start-up reactor 2 // 1.1.3. Start-up column 10 //	Plan 1.1. Provide a memory prompt for the sequence

Some researchers have presented examples of their semi-structured approach to questioning the problem under analysis (Piso, 1981; Hodgkinson & Crawshaw, 1985; Bruseberg & Shepherd, 1997). Three examples of the problem domains are presented in table four, these are training design, interface design, and job design. Potentially, at each stage in the sub-goal re-description, all of these questions could have been asked - depending upon the problem domain.

Table four. Questions for sub-goals.

Training Design Piso (1981)	**Interface Design** Hodgkinson & Crawshaw (1985)	**Job Design** Bruseberg & Shepherd (1997)
What is the goal of the task? What information is used for the decision to act? When and under what conditions does the person (system) decide to take action? What are the sequence of operations that are carried out? What are the consequences of action and what feedback is provided? How often are tasks carried out? Who carries the tasks out? What kinds of problems can occur?	What are the sensory inputs? How can the display of information be improved? What are the information processing demands? What kind of responses are required? How can the control inputs be improved? What kind of feedback is given? How can the feedback be improved? How can the environmental characteristics be improved?	How does information flow in the task? When must tasks be done? What is the temporal relation of tasks? What are the physical constraints on tasks? Where can and cannot error and delay be tolerated? Where is workload unacceptable? Where is working knowledge common to more than one task element? Where do different tasks share the same or similar skills?

The questions in the training and job design studies were devised from the four-stage control loop model of performance (Piso, 1981): perception → decision → action → evaluation. This general model can be used to describe all tasks and is probably implicit in all HTA, as it would be rather cumbersome to ask each of the questions explicitly at every single sub-goal.

The enduring popularity of HTA can be put down to two key points. First, it is inherently flexible: the approach can be used to describe any system. Astley & Stammers (1987) point out that over the decades since its inception, HTA has been used to describe each new generation of technological system. Second, it can be used to many ends: from person specification, to training requirements, to error prediction, to team performance assessment, and to system design. Again, Astley & Stammers (1987) point out that although HTA was originally used to develop an understanding of training requirements, it has subsequently been used for a variety of applications. Despite the popularity and enduring use of hierarchical task analysis, and the fact that the analysis is governed by only a few rules, it is something of a craft-skill to apply effectively. Whilst the basic approach can be trained in a few hours, it is generally acknowledged that sensitive use of the method will take some months of practice under expert guidance (Stanton & Young, 1999).

A more recent innovation in HTA has been the proposal for a sub-goal template, to help formalise the process and help guide the novice analyst. Omerod & Shepherd (2004) propose the adoption of sub-goal and plan templates to assist in the process of re-description in HTA. They argue that these two tools could help make the process of HTA less daunting and reduce the inevitable learning curve associated with acquiring a new analytical technique. The sub-goal templates comprise action templates (e.g., activation, adjustment, and deactivation), exchange templates (e.g., entering and extracting data), navigation templates (e.g., locating, moving, and exploring), and monitoring templates (e.g., detecting, anticipating, and observing). A fuller description of the sub-goal templates is provided in table five.

Table five. Sub-goal templates

SGTs	Task element	Context for assigning SGT and task element
Act To operate as part of a procedure	A1: Activate	To make a subunit operational, e.g. to switch from an 'off' state to an 'on' state
	A2: Adjust	To regulate the rate of operation of a unit maintaining an 'on' state
	A3: Deactivate	To make a subunit non-operations, e.g., to switch from an 'on' state to an 'off' state
Exchange To exchange Information	E1: Enter	To record a value in a specified location
	E2: Extract	To obtain a value of a specified parameter
Navigate To search	N1: Locate	To find the location of a target value or control

for information	N2: Move	To go to a given location and search it
	N3: Explore	To browse through a set of locations and values
Monitor To monitor system state and look for Change	M1: Detect	To routinely compare the system state against the target state in order to determine the need for action
	M2: Anticipate	To compare the system state against the target state in order to determine readiness for a known action
	M£: Transition	To routinely compare the rate of change during a system state transition

Although the SGTs were developed with process control operations in mind, they can be applied more widely. As people start to use the SGTs in other domains, new SGT might become necessary. Within each of the sub-goal templates, the analyst may choose a plan template to help determine the sequence of the sub-goals. Omerod & Shepherd (2004) proposed four plan templates, as illustrated in table six.

Table six. Plan templates

Code	**Plan Type**	**Syntax**
S1	Fixed sequence	Do X, Y, Z
S2	Contingent sequence	If (c) then do X If not (c) then do Y
S3	Parallel sequence	Do together X, Y, Z
S4	Free sequence	In any order do X, Y, Z

Omerod, Richardson & Shepherd (1988, 2000) report studies evaluating the effectiveness of novice analysts performing HTA with the SGT tools. They show that the SGT tools can help novice analysts, particularly with mastery of more difficult analyses. Computerisation of the SGT tools led to even better performance, as measured by fewer errors and quicker solutions, over the paper-based counterparts.

In one of the few comparative studies, Miller & Vicente (2001) compare HTA with the Abstraction Hierarchy in the analysis of the DURESS II (DUal REservoir System Simulation developed at the University of Toronto) with the purpose of producing display requirements. Although they do not present the output of the analysis in their paper, Miller & Vicente compare the types of information produced. They report that the two methods produce different, but complementary, sets of display requirements. Their research points to some shortcomings of HTA, such as the lack of representation of physical objects, propagation effects, causal understanding, and social-organisational knowledge. These criticisms might have been withdrawn if they had used some of the extensions of HTA (as described in section five). Miller & Vicente argued that HTA is a useful addition to the Abstraction Hierarchy. Some of their comments on the level and type of the analysis show that they are using HTA in a very constrained way. For example, they note that HTA focuses on human action whereas the abstraction hierarchy focuses on the whole system. Annett and others have argued that HTA can provide sub-goal hierarchies at many levels within a system. The analyst can choose to focus on the human agents, machine agents or the entire system. Thus one is drawn to the conclusion that some of the critique could be due to an incomplete understanding of HTA or the way it has been portrayed in some of the materials they have cited.

In a comparison of different task analysis representations, Stanton (2004) identified five forms that encompassed most methods: list, narratives, flow diagrams, hierarchical diagrams, and tables. In a comparison of 22 methods, only three had three different forms of representation. Most methods relied upon only one form of representation. It seems fair to suggest that HTA benefits from multiple forms of representation, and this is indicative of the flexibility of the approach.

3. A Framework for conducting Hierarchical Task Analysis

Notwithstanding the problems with HTA, is has proved to be a popular and enduring method. As previously stated, this longevity is probably due to the versatility of the analysis. Despite this popularity, or perhaps because of it, there does seem to be many different conventions for expressing HTA that have developed from peoples' own adaptation and mutations. It is difficult, therefore, to propose that there is one right way of doing this, although some have tried (Shepherd, 1989; 2001; Annett 2004). Rather, this section will follow the examples of Stammers (1996) and Shepherd (1998; 2000) to propose a framework within which HTA can be conducted, allowing for personal adaptation for the purpose at hand.

The number of guidelines for conducting HTA are surprisingly few. Annett (1996) has pointed out that the methodology is based on some broad principles (as detailed in section 2), rather than a rigidly prescribed technique. This fits well with Shepherd's (2001) view that HTA is a framework for task analysis. The broad principles mainly guide the progressive sub-goal re-description and nomenclature, although there is an underlying psychological model of feedback and control loops in the analysis, as described in section 1. That said, the basic heuristics for conducting a HTA are as follows.

(i) Define the purpose of the analysis

Although the case has been made that HTA can be all things to all people, the level or re-description and the associated information collected might vary depending upon the purpose. Examples of different purposes for HTA would include system design, interface design, operating procedures design, developing person specifications, analysis of workload and manning levels, and training design. The name(s), contact details, and brief biography of the analyst(s) should also be recorded. This will enable future analysts to check with the HTA originator(s) if they plan to re-use or adapt the HTA.

(ii) Define the boundaries of the system description

Depending upon the purpose, the system boundaries may vary. If the purpose was to develop a person specification then the system boundary might be drawn around the tasks performed by that individual. If the purpose of the analysis is to analyse co-ordination and communication in team work, then the entire set of tasks of a team of people would be analysed. If the purpose of the analysis is to determine allocation of system function to human and computers, then the whole system will need to be analysed. Both Shepherd (2001) and Annett (2004) emphasise the need to perform the analysis appropriate to the intended purpose to which it is to be put.

(iii) Try to access a variety of sources of information about the system to be analysed.

All task analysis guides stress the importance of multiple sources of information to guide, check and validate the accuracy of the HTA (Patrick et al, 1986; Kirwan & Ainsworth, 1992; Shepherd, 2001; Annett, 2004). Sources such as observation, subject matter experts, interviews, operating manuals, walkthoughs, and simulations can all be used as a means of checking the reliability and validity of the analysis. Careful documentation and recording of the sources of data needs to be archived, so that the analyst or others may refer back and check if they need to. Annett (2004) points out that cross-checking the data between sources is the best guarantee that the information is accurate.

(iv) Describe the system goals and sub-goals

As proposed in the original principles for HTA, the overall aim of the analysis is to derive a sub-goal hierarchy for the tasks under scrutiny. As goals are broken down and new operations emerge, sub-goals for each of the operations need to be identified. As originally specified, it is not the operations that are being described, but their sub-goals (Annett et al, 1971). All of the lower level sub-goals are a logical expansion of the higher ones (Patrick et al, 1986). A formal specification for the statement of each of the sub-goals can be derived, although most analyses do not go such lengths. Patrick et al (1986) describe the three components of these statements, as indicated in table seven. Obviously this is a trivial task, but it does show how the task statement can be composed and its relationship with the goal (by referring back to figure three).

Table seven. The elements of task statements.

Task statement element	**Questions**	**Example**
Activity Verb	Is it clearly defined? Is it differentiated? Does it state the objective of the behaviour?	To make the nail flush
Performance standards	Is the quantity or quality of the performance specified (e.g., speed, accuracy, errors, etc.)?	...without damaging the surface of a piece of wood...
Conditions	Are the conditions under which the task is to be performed described (e.g., environment, tools, materials, etc.)?	....using a hammer.

As table seven shows, the goal is presented in the activity verb. The performance standards and the conditions could be expressed in the notes section of the tabular format.

(v) Try to keep the number of immediate sub-goals under any super-ordinate goal to a small number (i.e, between 3 and 10).

There is an art to HTA, which requires that the analysis does not turn into a procedural list of operations. The goal hierarchy is determined by looking for clusters of operations that belong together under the same goal. This normally involves several iterations of the analysis. Whilst it is accepted that there are bound to be exceptions, for most HTA's any super-ordinate goal with have between 3 and 10 immediate subordinates. Patrick et al (1986) recommend keeping the sub-goals between 4 and 8, but if there are more than 10 sub-ordinates, the analyst should check to see if any of the sub-goals can be grouped together under another super-ordinate. It is generally good practice to continually review the sub-goal groupings, to check if they are logical. HTA does not permit a single subordinate goals.

(vi) Link goals to sub-goals, and describe the conditions under which sub-goals are triggered. Plans are the control structures that enable the analyst to capture the conditions which trigger the sub-goals under any super-ordinate goal. Plans are read from the top of the hierarchy down to the sub-goals that are triggered and back up the hierarchy again as the exit conditions are met. Shepherd (2001) identified six basic types of plan: fixed sequences, contingent sequences, choices, optional completion, concurrent operations and cycles. These different types of plans take the variety of different sub-goal triggers into account. He states that complex tasks will require combinations of these different sorts of plans. As each of the sub-goals, and the plans that trigger them, are contained within higher goals (and higher plans) considerable complexity of tasks within systems can be analysed and described. The plans contain the context under which particular sub-goals are triggered. This context might include time, environmental conditions, completion of other sub-goals, system state, receipt of information, and so on. For each goal, the analyst has to question how each of its immediate subordinates is triggered. Omerod & Shepherd (2004) have proposed some basic plan templates to guide this process (see table seven). As well as identifying the sub-goal trigger conditions, it is also important to identify the exit condition for the plan, that will enable the analyst to trace their way back up the sub-goal hierarchy. Otherwise, the analysis could be stuck in a control loop with no obvious means of exiting.

(vii) Stop re-describing the sub-goals when you judge the analysis is fit-for-purpose. When to stop the analysis has been identified as one of the more conceptually troublesome aspects of HTA. The proposed P x C stopping rule is a rough heuristic, but analysts may have trouble quantifying the estimates of P and C. Annett et al (1971) proposed that it is likely to be preferable to stop the analysis early than to continue it beyond the point at which it will be useful. The level of description is likely to be highly dependent upon the purpose of the analysis, so it is conceivable that a stopping rule could be generated at that point in the analysis. For example, in analysing team work, the analysis could stop at the point where sub-goals dealt with the exchange of information (e.g. receiving, analysing and sending information from one agent to another). For practical purposes, the stopping point of the analysis is indicated by underlining the lowest level sub-goal in the hierarchical diagram, or ending the sub-goal description with a double forward slash (i.e., "//") in the

hierarchical list and tabular format. This communicates to the reader that the sub-goal is not re-described further elsewhere in the document.

(viii) Try to verify the analysis with subject-matter experts.
Annett (2004) makes the point that it is important to check the HTA with subject matter experts. This can help both with verification of the completeness of the analysis and help the experts develop a sense of ownership of the analysis.

(ix) Be prepared to revise the analysis.
HTA requires a flexible approach to achieve the final sub-goal hierarchy with plans and notes. The first pass analysis is never going to be sufficiently well developed to be acceptable, no matter what the purpose. The number of revisions will depend on the time available and the extent of the analysis, but simple analyses (such as the analysis of the goals of extracting cash from an automatic teller machine) may require at least three interactions, where as more complex analyses (such as the analysis of the emergency services responding to a hazardous chemical incident) might require at least ten iterations. It is useful to think of the analysis as a working document that only exists in the latest state of revision. Careful documentation of the analysis will mean that it can be modified and re-used by other analysts as required.

A procedure for development of the sub-goal hierarchy with the plans is presented in figure five. This procedure only describes the steps (iv) to (vii) in the aforementioned guidance, but offers a useful heuristic for breaking the tasks down into a sub-goal hierarchy.

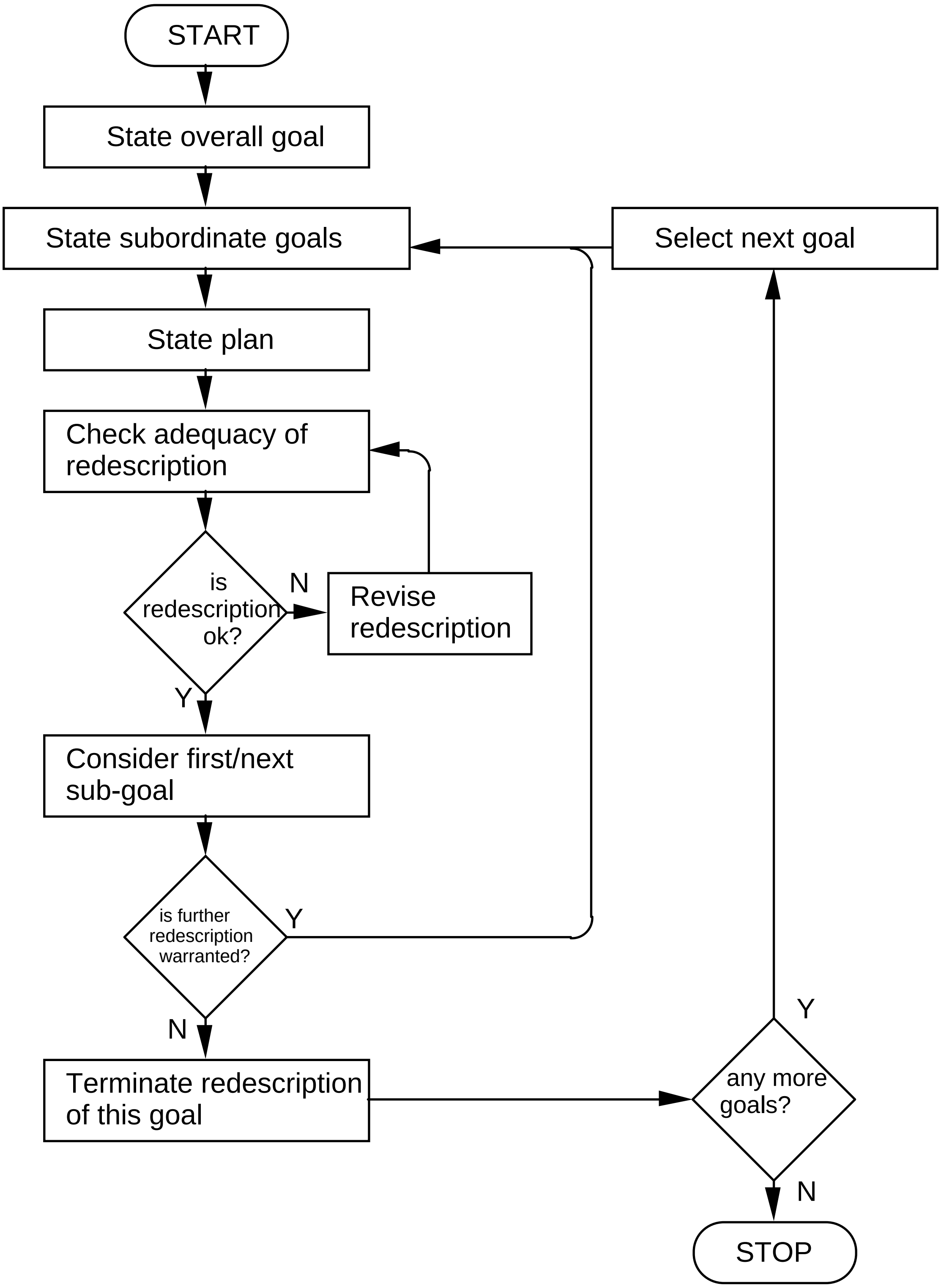

Figure five. Procedure for breaking down the sub-goal hierarchy.

The notation used by HTA analysts can be standardised to help to ensure the analysis can be interpreted by others (Patrick et al, 1986; Shepherd, 2001; Annett, 2004). Standard conventions tend to use either text or symbols (Shepherd, 2001). Examples of the text and symbols that have been used are indicated in table nine.

Table eight. Notation used in HTA.

TEXT	**SYMBOLS**
then	> →
and	+ &
or	/
any of	:
decide	?
if *condition X* then	X ? >

The notation in table eight is used in the plans to indicate the sequence, and trigger condition, for the sub-goals. Six different forms of plans with three different notation conventions are shown in table nine. A more detailed description of the forms that plans can take may be found in Shepherd (2001), who devotes an entire chapter to plans in his book.

Table nine. Different plan types with three notation conventions.

Type of Plan	**Types of Notation**
Linear sequential plan	1 > 2 > 3 > 4
	1 then 2 then 3 then 4
	Do in order
Non-linear non-sequential plan	1/2/3/4
	N/A
	Do in any order
Simultaneous concurrent plan	1 + 2 + 3 + 4
	1 and 2 and 3 and 4
	Do at the same time
Branching choice plan	X? Y > 2 N > 3
	if X present then 2 else 3
	Do when required
Cyclical repetitious plan	1 > 2 > 3 > 4 > 1.....
	1 then 2 then 3 then 4 then repeat from 1 until
	Repeat the following until
Selection exclusive plan	1:2:3:4
	1 or 2 or 3 or 4
	Choose one of the following

Some plans may use one of these basic types whereas others may be a hybrid combining two or more of these types. The three different representations of HTA are hierarchical diagrams, hierarchical lists and the tabular format. Each of these is illustrated with a team work task presented by Baber et al (2004). These examples show the compatibility of the three different representations. The HTA was based upon the analysis of the emergency services responses to a hazardous chemical incident. In the scenario analysed, some youths had broken into a farm and disturbed some chemicals in sacking. One of the youths had been taken to the hospital with respiratory problems, whilst the others were still at the scene. The police were sent to investigate the break-in at the farm. They called in the fire service to identify the chemical and clean up the spillage. The overall analysis shows four main sub-goals: receive notification of an incident, gather information about the incident, deal with the chemical incident, and resolve incident. Only part of the analysis is presented in figures six and seven, to illustrate HTA.

In figure seven, the overall goal is shown at the top of the hierarchy with the main sub-goals underneath. Plan 0 shows the conditions under which each of the sub-goals are triggered. As sub-goal 1 is not re-described, it has been underlined. Sub-goal 2 is re-described, and has 8 sub-goals of its own. Plan 2 refers to the conditions under which the sub-goals of super-ordinate goal 2 will be triggered. As none of the sub-goals under super-ordinate goal 2 are re-described further they have been underlined.

As multiple agencies and people are involved in the team task, they have been identified under each of the sub-goals. In figure six, police control, fire control, the hospital and the police officer have all been assigned to different sub-goals.

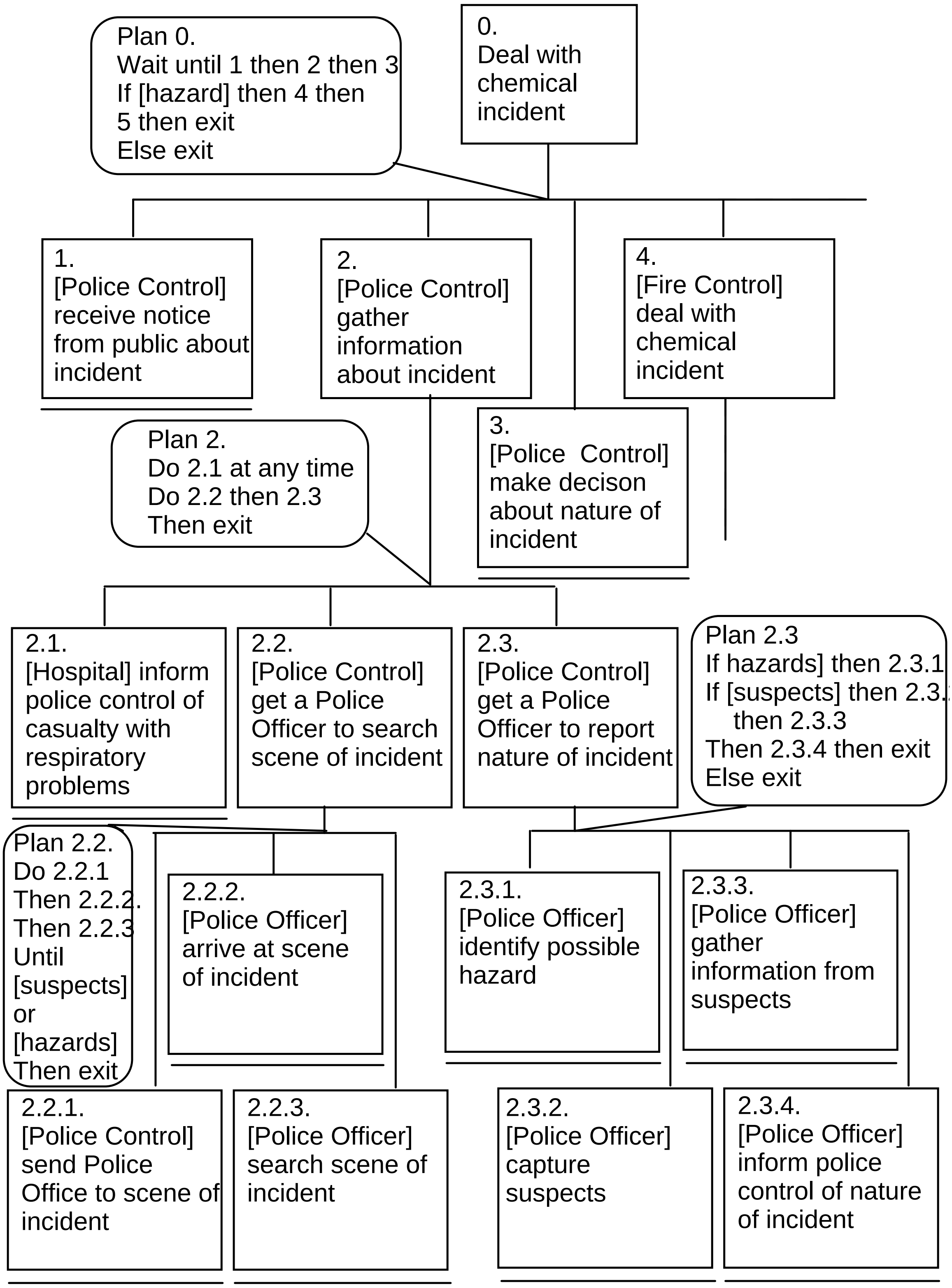

Figure six. Part of the hierarchical diagram for the goal of "Deal with chemical incident"

As figure six shows, the tree-like structure of the hierarchical diagram makes it reasonably easy to trace the genealogy of sub-goals for small scale analyses. For larger scale analyses, the hierarchical diagram can become cumbersome and unwieldy. For these analyses a hierarchical list approach might be more useful. The same analysis in figure six is presented as a hierarchical list in figure seven for comparison.

0. Deal with chemical incident
Plan 0: Wait until 1 then do 2 then 3 - If [hazard] then 4 then 5 then exit -
Else exit

- 1. [Police control] receive notice from public about incident //
- 2. [Police Control] gather information about incident
  Plan 2: Do 2.1 at any time if appropriate
  Do 2.2 then 2.3
  Then exit
  - 2.1. [Hospital] inform police control of casualty with respiratory problems//
  - 2.2. [Police Control] get a Police Officer to search scene of incident
    Plan 2.2: Do 2.1.1 then 2.2.2 then 2.2.3
    Until [suspects] or [hazards] then exit
    - 2.2.1. [Police Control] send Police Officer to scene of incident//
    - 2.2.2. [Police Officer] arrive at scene of incident//
    - 2.2.3. [Police Officer] search scene of incident//

  - 2.3. [Police Control] get Police Officer to report nature of incident
    Plan 2.3: If [suspects] then 2.3.1
    If[suspects] then 2.3.2. then 2.3.3
    Then 2.3.4. then exit
    Else exit

2.3.1. [Police Officer] identify possible hazard//
2.3.2. [Police Officer] capture suspects//
2.3.3. [Police Officer] gather information from suspects//
2.3.4. [Police Officer] inform police control of nature of incident//

3. [Police Control] make decision about nature of incident//
4. [Fire Control] clean up chemical spillage
    etc...
5. etc...

Figure seven. Part of the hierarchical list for the goal of "Deal with chemical incident"

The hierarchical diagram and hierarchical list present exactly the same information on the sub-goal hierarchy in two different forms. The advantage of the diagram is that it represents the groups of sub-goals in a spatial manner which is useful for gaining a quick overview of the HTA. The hierarchical lists show the same information in a more condensed format, which is useful for very large analyses. It is possible to annotate the sub-goal hierarchy with the tabular format, as illustrated in table ten.

Table ten. Part of the tabular format with hierarchical numbering for the goal of "Deal with chemical incident"

Super-ordinate	**Task component - operation or plan**	**Notes**

0	**Deal with chemical incident** Plan: Wait until 1 then do 2 - If [hazard] then 3 then 4 then exit - else exit --- 1. [Police control] receive notice from public about incident // 2. [Police Control] gather information about incident 3. [Fire Control] clean up chemical spillage	This is a multi-agency task involving the police and fire service as well as the hospital with a possible casualty The response to the incident is initiated by a phone call The re-description is missing, to shorten the example
2	**[Police Control] gather information about incident** Plan 2: Do 2.1 at any time if appropriate Do 2.2 then 2.3 Then exit --- 2.1. [Hospital] inform police control of casualty with respiratory problems// 2.2. [Police Control] get a Police Officer to search scene of incident 2.3. [Police Control] get Police Officer to report nature of incident	The hospital may call in about a casualty at any time, but it has to be linked with this incident The police officer has to find his/her way to the scene of the incident

2.2.	**[Police Control] get a Police Officer to search scene of incident** Plan 2.2: Do 2.1.1 then 2.2.2 then 2.2.3 Until [suspects] or [hazards] then exit --	
	2.2.1. [Police Control] send Police Officer to scene of incident//	The police officer may have to find a remote location based on sketchy information
	2.2.2. [Police Officer] arrive at scene of incident//	
	2.2.3. [Police Officer] search scene of incident//	The police officer has to search for signs of a break-in and hazards
2.3.	**[Police Control] get Police Officer to report nature of incident** Plan 2.3: If [suspects] then 2.3.1 If[suspects] then 2.3.2. then 2.3.3 Then 2.3.4. then exit Else exit --	
	2.3.1. [Police Officer] identify possible hazard//	Any potential hazard needs to be identified, including the chemical ID number
	2.3.2. [Police Officer] capture suspects//	Any suspects on the scene need to be identified
	2.3.3. [Police Officer] gather information from suspects//	Suspects need to be questioned about the incident
	2.3.4. [Police Officer] inform police control of nature of incident//	Incident details need to be passed on so that the clean-up operation can begin

The tabular format permits more detail of how the emergency services deal with the incident. The analysis is not exhaustive, nor is it complete. Rather it is presented to serve as an illustration of how the three different representations of HTA present information on the same sub-goal hierarchy. HTA serves as a springboard for a variety of other techniques. Once the sub-goal hierarchy has been broken down, many other forms of analysis may be carried out on it. This is the subject of the following section.

4. Some applications of Hierarchical Task Analysis

One of the reasons for the enduring success of HTA is that it has the flexibility to be applied to many tasks. Most, if not all, application areas in Ergonomics require some form of task representation. Kirwan & Ainsworth (1992) claim that HTA may "*be used in almost every circumstance*" (page 29). They cite that this offers a major cost saving in a system design programme, rather than continually re-analysing the task for every different type of application. Annett (2004 - personal communication) has made the point that the form of the HTA could vary depending upon the application, so that the first or subsequent drafts of HTA might not serve all purposes, and some modifications might have to be made. This view sits comfortably with Shepherd's proposal of HTA as a framework. Most applied ergonomists will be familiar with the notion of HTA asliving documentation of the sub-goal hierarchy that only exists in the latest state of revision.

In the large-scale design and development of a new nuclear reactor, Staples (1993) describes how HTA was used as the basis for virtually all of the ergonomics studies. The sub-goal hierarchy was produced through reviews of contemporary operating procedures, discussions with subject matter experts, and interviews with operating personnel from another reactor. Both the hierarchical diagram and the tabular format versions of HTA were produced. The resultant HTA was used to examine potential errors and their consequences, the interface design verification, identification of training procedures, development and verification of operating procedures, workload assessment and communication analysis. Staples argued that HTA is of major benefit in system design as it makes a detailed and systematic assessment of the interactions between human operators and their technical systems possible. As Annett and colleagues have pointed out on many occasions, conducting the HTA helps the analyst become familiar with the processes and procedures so that they can critically assess the crucial aspects of the work. Staples also notes that reference to the HTA for the analysis of all aspects of the system can highlight inconsistencies between training, procedures and system design. Staples draws the general conclusion that the broad application of HTA can make it a very cost-effective approach to system design.

Most books containing descriptions of HTA also contain examples of application areas that it can be, and has been, applied. This serves to demonstrate that HTA has been applied in areas far wider that the training applications for which it was originally devised. Annett (2000) has pointed out the HTA is a general problem solving approach, and performing the analysis helps the analyst understand the nature of both the problem and the domain. An indication of some of the application areas is illustrated in table eleven.

Table eleven. Application of HTA from ergonomics texts

Application	Kirwan & Ainsworth (1992)	Wilson & Corlett (1995)	Stanton (1996)	Annett & Stanton (2000)	Shepherd (2001)
Interface evaluation	■	■	■		■
Training	■	■	■	■	■
Allocation of function	■	■		■	
Job description	■		■	■	■
Interface design	■	■	■	■	■
Work organisation	■	■	■		■
Manuals design	■	■	■		■
Job aid design	■	■	■		■
Error analysis	■	■	■	■	
Error prediction	■	■	■	■	
Team task analysis					■
Workload assessment			■	■	■
Procedure design			■		■

As table eleven shows, there are at least twelve additional applications to which HTA has been put. This list is not intended to be exhaustive, rather it illustrates that HTA as a means-to-an-end, rather than an end in itself (Stanton, 2004). The reader is referred to the appropriate texts for examples of the applications. Duncan (1972) has argued that a task description should not be biased in terms of any particular solution. An example of HTA applied to the evaluation of radio-cassette machines demonstrates this point. In a study comparing a Ford and a Sharp in-car radio-cassette, Stanton & Young (1999) showed that HTA of the drivers' sub-goal task structure did not indicate which was a better interface. Rather the analysis just showed that the sub-goal structures were different for the two machines. To determine which was a better interface required an extension of the analysis, such as an examination of the error potential or task time when interacting with the device. With the HTA completed first, the subsequent analyses are possible. Many method and techniques either depend upon output of HTA or are made easier when HTA is performed first.

Ainsworth & Marshall (1988, 2000) describe a survey of reports on task analysis methods, including HTA, conducted in the armed services and nuclear industries. The results of their survey showed that "*HTA is perhaps the nearest thing to a universal task analysis technique.*" (Ainsworth & Marshall, 2000: p.83). The areas that HTA was used in the armed services are presented in table thirteen, together with the methods of data collection that were used and the number of reports analysed.

Table twelve. Areas of application of HTA in the armed services.

Area	**Data collection methods**	**Number of reports**
Systems procurement	Technical expert interviews, informal discussions, and scenario modelling	2
Manpower analysis and personnel requirements	Walkthoughs, interviews, and discussions with experts	7
Operability	Walkthoughs and discussions with experts	5
Interface design	Walkthoughs, interviews, and discussions with experts	9
Training	Direct observation, discussions with experts, and questionnaires	2

As with table eleven, table twelve shows that HTA was put to many uses across a wide spectrum of activities. Table thirteen also shows that discussions and interviews with experts were a core source of data. This method was supplemented by walkthoughs, direct observation, questionnaires, and scenario modelling, depending upon what was possible in the area of application. Ainsworth & Marshall (1988, 2000) were critical about the quality of reporting in the task analysis reports. They state that the purpose of the analysis was not always clear and the sources of the data were poorly documented. They also note that some of the analyses were very superficial and showed poor insight into the problem under investigation. Many of these problem may have been overcome if the analyst had been properly trained in HTA and had followed the guiding principles laid out in section three of this paper.

5. Some Extensions of Hierarchical Task Analysis

As illustrated in tables eleven and twelve, HTA has been put to many different uses. The tabular format has enabled a mechanism for extending the analysis beyond the system description provided in the sub-goal hierarchy and plans. It is perhaps ironic that, whilst initial developments in HTA sought to simplify the tabular format, latter developments have sought to extend it. These extensions in HTA have enabled the analyst to: investigate design decisions, analyse human-machine interaction, predict error, allocate function, design jobs, analyse team work, and assess interface design. It is impossible to cover all of the extensions to HTA (for that, the reader is referred back to source books - some of which are indicated in table elven), rather the aim of this section is to indicate some of the variety of the extensions to HTA.

Shepherd (2001) has numerous examples of the application of HTA, including one of investigating redesign opportunities in a batch control process. The tabular format he devised for investigating this problem contains a task taxonomy that analyses the context and constraints of the tasks and their associated sub-goals. The taxonomy comprises 12 factors that need to be considered when investigating the adequacy of design decisions in support of task performance. These factors are: the difficulty of the task; the predictability, controllability and frequency of events; the severity of consequences of error and possibility for recovery; information representation and feedback; the presence of environmental, situational and task stresses; access to help and advice; physical and environmental constraints; and legal, industrial and cultural compliance. Table thirteen shows part of the analysis presented by Shepherd, to illustrate the task taxonomy. In Shepherd's work he argues that the contextual constraints and conditions interact with the design decisions in a safety critical task.

Table thirteen. An analysis of the contextual constraints and conditions for a safety critical task

		Context and constraints													
TASK ANALYSIS	**Stop analysis?**	Task difficulty	Predicability of events	Control of risks	Frequency of events	Severity of error	Information representation	Task feedback	Recoverability	Stressors	Access to help	Environmental constraint	Cost of training support	Legal compliance	**Comments**
1. Deal with emergencies Plan 1: Do 1, then 2 or 3 as appropriate															This entails having a good understanding of systems to enable flexible operations. Analytical skills needed and intelligent planning aid may help
1.1. Assess situation to establish the extent of the emergency	**N**	hi	lo	lo	lo	hi			lo	hi			hi	hi	
1.2. Deal with local isolation	**Y**														
1.3. Deal with emergency evaluations	**Y**														
1.2 Deal with local isolation Plan 1.2. Do 1 then 2															
1.2.1. Assess extent of problem	**N**	hi	lo	lo	lo	hi			lo	hi			hi	hi	
1.2.2. Isolate affected area	**Y**														
1.2 Deal with emergency evaluationsetc....															

As shown in table thirteen, the context and constraints have been estimated at the lowest level where the sub-goal analysis has been stopped (indicated by 'N' in the 'Stop analysis?' column). Shepherd notes that these estimates may be based on data or informed comment from subject matter experts. These contextual analyses can help guide the analyst to consider what aspects of the task need to be improved and the form that those improvements could take. The design hypotheses are presented in the 'Comments' section of the table. In the first pass analysis, all relevant design hypotheses should be included, for screening at a later point in time.

Stammers & Astley (1987) have shown how HTA can be extended to help determine the information requirements for human-computer interface design. Their method extends the tabular format to include three additional sections on information flow (i.e., the information flow to and from the interface), information assumed (i.e., information that is a prerequisite for the performance of the task), and task classification (i.e., a taxonomy of operations that will be performed). The analysis of information flow can detail the information necessary to perform each part of the task. The taxonomy developed by Stammers & Astley was based on process control operations and comprised eight distinct types of task, namely:

- monitoring (watching developments in the process);
- procedure (following a set sequence of tasks);
- fault diagnosis (determining the cause of a fault or alarm);
- fault detection (detecting that a fault or alarm has occurred);
- decision making (choosing between alternate courses of action);
- problem solving (finding a solution to a problem);
- operation (conducting manual control).

An example of the output of analysis for the coal preparation plant operators task (Astley & Stammers, 1987) is shown in table fourteen, where the information flow to the human operator(s) from the technical system is shown by a right pointing arrow (→) and information flow to the technical system from the human operator(s) is shown by a left pointing arrow (←). The plans are a hybrid of symbols and text.

Table fourteen. Analysis of human-computer interaction

Super-ordinate	Plan	Operations	Information flow across interface	Information assumed	Task classifica-Tion	Notes

0. Operate coal preparation plant	1 → 2 & 3 until 4. Do 5 as appropriate and 6 at end of shift.	1. Start-up plant	→ initiate start ← plant items selected	start up procedure	Procedure	
		2. Run plant normally	← plant operation & monitoring → control information	knowledge of plant flows and operational procedures	operation	
		3. Carry out fault detection and fault diagnosis	← fault data	some understand-ing of faults	fault detection fault diagnosis	
		4. Shut down plant	→ initiate shut down	shut down procedures	procedure	
		5. Operate telephone and tannoy	--------------	operational knowledge	operation	
		6. Make daily reports	← plant data for log	reporting procedure	procedure	

Astley & Stammers propose that an extended tabular format can be used for underlying assumptions about the operators' knowledge and skills, allocation of function issues, operator characteristics and training issues. The tabular format allows for scrutiny of the sub-goals and the format is easily adaptable to many different types of analysis.

HTA has also bee used to assess the error potential in tasks. Hellier et al (2001) describe how they performed HTA of a sample analysis procedure by conducting observations and interviews with chemists. They argued that HTA helped uncover the complexities of the task. Then they identified error potential for each sub-goal, also using observation and interviews. This time the HTA served as a frame for the observational stdues and interviews, through which potential errors could be assessed. As weel as observing errors, HTA can be used as a basis for predicting errors. Systematic Human Error Reduction and Prediction Approach (SHERPA) for example, uses an error taxonomy to predict potential errors from the HTA sub-goal hierarchy (Stanton & Young, 1999). The idea is that each task can be classified into one of five basic types. Each of these task types links with an error taxonomy to identify credible errors associated with a sequence of human activity. In essence the SHERPA technique works by indicating which error modes are credible for each task step in turn. This indication is based upon the judgement of the analyst, and requires subject matters experts. The process begins HTA. For the application of SHERPA, each task step from the bottom level of the sub-goal hierarchy is taken in turn. First each task step is classified into a type from the taxonomy, into one of the following types:

- Action (e.g. pressing a button, pulling a switch, opening a door)
- Retrieval (e.g. getting information from a screen or manual)
- Checking (e.g. conducting a procedural check)
- Information communication (e.g. talking to another party)
- Selection (e.g. choosing one alternative over another)

This classification of the task step then leads the analyst to consider credible error modes associated with that activity, as shown in table fifteen.

Table fifteen. Error modes and their description

Error Mode	**Error Description**
Action	
A1	Operation too long/short
A2	Operation mistimed
A3	Operation in wrong direction
A4	Operation too much/little
A5	Misalign
A6	Right operation on wrong object
A7	Wrong operation on right object
A8	Operation omitted
A9	Operation incomplete
A10	Wrong operation on wrong object
Information	
Retrieval	Information not obtained
R1	Wrong information obtained
R2	Information retrieval incomplete
R3	
Checking	
C1	Check omitted
C2	Check incomplete
C3	Right check on wrong object
C4	Wrong check on right object
C5	Check mistimed
C6	Wrong check on wrong object
Information	
Communication	
I1	Information not communicated
I2	Wrong information communicated
I3	Information communication incomplete
Selection	
S1	Selection omitted
S2	Wrong selection made

The sub-goal hierarchy (without the plans) for the task of programming a video cassette recorder is presented in the left-hand column of table sixteen. This example is taken from Stanton (2003). Where the sub-goals are broken down further, the SHERPA analysis has not been undertaken. This is in keeping with the general

SHERPA approach. For each sub-goal that is analysed, credible error modes (i.e. those judged by a subject matter expert to be possible) are identified and labelled using the codes from table fifteen. A description of the form that the error would take is also given. The consequence of the error on the system is determined in the next column, as this has implications for the criticality of the error. The last four steps consider the possibility for error recovery, the ordinal probability of the error (high, medium of low), its criticality (high, medium or low) and potential remedies. Again, all of these analyses are shown in table sixteen.

Table sixteen. The SHERPA table

Sub-goal	**Error Mode**	**Error Description**	**Consequence**	**Recovery**	**P**	**C**	**Remedial Strategy**
1. Prepare VCR	N/A	N/A	N/A	N/A			N/A
1.1 Switch VCR on	A8	Fail to switch VCR on	Cannot proceed	Immediate	L	L	Press of any button to switch VCR on
1.2 Check clock time	C1 C2	Omit to check clock Incomplete check	VCR Clock time may be incorrect	None	L	H	Automatic clock setting and adjust via radio transmitter
1.3 Insert cassette	A3	Insert cassette wrong way around	Damage to VCR	Immediate	L	H	Strengthen mechanism
	A8	Fail to insert cassette	Cannot record	Task 3	L	H	On-screen prompt
2 Pull down front cover	A8	Fail to pull down front cover	Cannot proceed	Immediate	L	L	Remove cover to programming
3. Prepare to programme	N/A	N/A	N/A	N/A			N/A
3.1 Set timer selector to program	S1	Fail move timer selector	Cannot proceed	Immediate	L	L	Separate timer selector from programming function
3.2 Press 'Program'	A8	Fail to press PROGRAM	Cannot proceed	Immediate	L	L	Remove this task step from sequence
3.3 Press 'On' button	A8	Fail to press ON button	Cannot proceed	Immediate	L	L	Label button START TIME
4. Enter Program details	N/A	N/A	N/A	N/A			N/A

4.1. Select channel	N/A	N/A	N/A	N/A			N/A
4.1.1 Press 'Channel up' button	A8	Fail to press UP button	Wrong channel selected	None	M	H	Enter channel number directly from keypad
4.1.2 Press 'Channel down' button	A8	Fail to press DOWN button	Wrong channel selected	None	M	H	Enter channel number directly from keypad
4.2 Press 'Day' button	A8	Fail to press DAY button	Wrong day selected	None	M	H	Present day via a calendar
4.3 Set start time	I1	No time entered	No programme recorded	None	L	H	Dial time in via analogue clock
	I2	Wrong time entered	Wrong programme recorded	None	L	H	Dial time in via analogue clock
4.4 Wait for 5 seconds	A1	Fail to wait	Start time not set	Task 4.5	L	L	Remove need to wait
4.5 Press 'Off' button	A8	Fail to press OFF button	Cannot set finish time		L	L	Label button FINISH TIME
4.6 Set finish time	I1	No time entered	No programme recorded	None	L	H	Dial time in via analogue clock
	I2	Wrong time entered	Wrong programme recorded	None	L	H	Dial time in via analogue clock
4.7 Set timer	A8	Fail to set timer	No programme recorded	None	L	H	Separate timer selector from programming function
4.8 Press 'Timer record' button	A8	Fail to press TIME RECORD button	No programme recorded	None	L	H	Remove this task step from sequence
5 Lift up front cover	A8	Fail to lift up front cover	Cover left down	Immediate	L	L	Remove cover to programming

As table seventeen shows there are six basic error types associated with the activities of programming a VCR. These are:

A. Failing to check that the VCR clock is correct.
B. Failing to insert a cassette.
C. Failing to select the programme number.
D. Failing to wait.
E. Failing to enter programming information correctly.
F. Failing to press the confirmation buttons.

The purpose of SHERPA is not only to identify potential errors with the current design, but to guide future design considerations. The structured nature of the analysis can help to focus the design remedies on solving problems, as shown in the remedial strategies column. As this analysis shows, quite a lot of improvements could be made. It is important to note however, that the improvements are constrained by the analysis. This does not address radically different design solutions, that may remove the need to programme at all.

Marsden & Kirby (2004) describe the application of HTA to function allocation. Allocation of system function has been a problem that has challenged ergonomics researchers and practitioners for the past fifty years. Numerous methods have arisen, but all depend upon an adequate description of the system within which functions are to be allocated to humans or machines. Marsden & Kirby argue that the most suitable system description is that provided by the sub-goal hierarchy in HTA, because it focuses attention on the purposes (i.e., goals and sub-goals) of the system in question. They suggest that many of the function allocation problems can be circumvented by getting the 'stakeholders' to agree upon the description of the purpose of the system. As with Duncan's (1972) comments about the neutrality of HTA, Marsden & Kirby propose that the analysis should present the sub-goals of what should be done by the system, rather than how it should be done. The former will enable impartial function allocation whereas the latter may bias function allocation. They also suggest that the stopping rule should be replaced with a no-solution heuristic, i.e., the sub-goal decomposition stops at a point just before an allocation of function solution would become apparent. This is to prevent premature function allocation. The sub-goal hierarchy for the goal of "Checking the desirability of meeting a potential increase in demand" is presented in the first two columns of table seventeen.

Table seventeen. Using HTA in function allocation.

Super-ordinate goal	**Subordinate goal**	**Human or Computer?**
1.1 Forecast demand		H
	1.1.1 Review regular sales	H
	1.1.2 Review demand from pub chains	H
	1.1.3 Review potential demand from one-off events	H
1.2 Produce provisional resource plan		H-C
	1.2.1 Calculate expected demand for each type of beer	H-C
	1.2.2 Make adjustment for production minima and maxima	C
1.3 Check feasibility of plan		H-C
	1.3.1 Do materials explosion of ingredients	H-C
	1.3.2 Do materials explosion of casks and other packaging	C
	1.3.3 Check material stocks	H-C
	1.3.4 Calculate materials required	C
	1.3.5 Negotiate with suppliers	H
	1.3.6 Check staff availability	H
	1.3.7 Check ability to deliver beer to customers	H
1.4 Review potential impact		H
	1.4.1 Review impact of plan on cash flow	H
	1.4.2 Review impact of plan on staff	H
	1.4.3 Review impact on customer relations	H
	1.4.4 Review impact on supplier relations	H

Marsden & Kirby (2004) outline a number of criteria to be considered when allocating system functions to humans or computers, some of which are contradictory. This means that there is considerable discretion on the part of the analyst to resolve "keeping the job as simple as possible" and "having a challenging job to do". The function allocation in table seventeen has been coded for human only (H), human and computer with the human in control (H-C), computer and human with the computer in control (C-H), and computer only (C). After the initial functional allocation, Marsden & Kirby recommend a review of the potential impact of the allocations to consider the likely impact on job satisfaction, human error, attention, workload, productivity, and cost-effectiveness. An overall analysis of the proposed allocation may also reveal any potential conflicts or incompatibilities in the allocations. When the allocations have been confirmed, more detailed analyses may be undertaken to propose how the sub-goals may be achieved with the proposed resources.

Kirwan & Ainsworth (1992) report on how HTA may be used to assess the adequacy of interface design. The example is based on a study of tasks in emergency shut-down procedures on an off-shore oil and gas rig in the North Sea (Pennington, 1992). The analyses suggest that good communications between the production and the drilling teams play an important part in maintaining safety. An extract of this analysis is presented in table eighteen. The analysis sought to investigate the adequacy of the input, action and feedback cycle in the tasks. This analysis harks back to the original formulation of HTA proposed by Annett et al (1971) some twenty years earlier.

Table eighteen. Analysis of two sub-goals in emergency shut-down procedures.

Sub-goals	**Control**	**Purpose**	**Method**	**Feedback**	**Adequacy of Feedback**	**Comment**
Formulate action to control the incident in the case of an emergency shut down	N/A	Inform appropriate personnel to take effective action as soon as possible	Production team assess importance themselves and if in drilling area contact drill team	No information available to drill team of location of the incident	Unaccept-able	Some direct feedback should be provided to the drill team

Stop the drill	Brake on foot control	Halt the progress of the drill	Depress	Gauge	Acceptable	
	Handle	Stop the rotary table	Turn handle	RPM on digital and analogue displays	Acceptable	
	Clutch pedal	Pick up drill string off bottom of hole	Depress	Tactile (pedal down = drill up)	Acceptable	
	Handles	Shut off pumps	Turn handles	Position indicators	Acceptable	

As table eighteen shows, the sub-goal of "Formulate action to control the incident [...]" is criticised for lack of feedback, whereas the sub-goal of "Stop the drill" is shown to have adequate feedback. In the original example, Pennington (1992) presented a more detailed analysis of communications in a separate table. The advantage of the tabular format is that it permits new columns to be added to the analysis and it focuses the analysis on each sub-goal in turn. This leads to an audit trail of tables that can be checked, verified, acted upon and archived.

Annett et al (2000) have shown how HTA can be used to analyse team tasks. Annett et al argued that team goals must share common performance criteria (i.e., the team product) with which the success or failure of the team can be judged against. Team processes normally stress the importance of communication and co-ordination activities. In his model of team processes, Annett proposed that the communication activities are likely to include information sent and received and discussions between team members. The same model shows co-ordination activities as the collaboration and synchronisation of team members towards the team goals. The example Annett et al used is based upon the analysis of the tasks of an anti-submarine warfare team. An extract of the hierarchical sub-goal analysis is presented in figure eight.

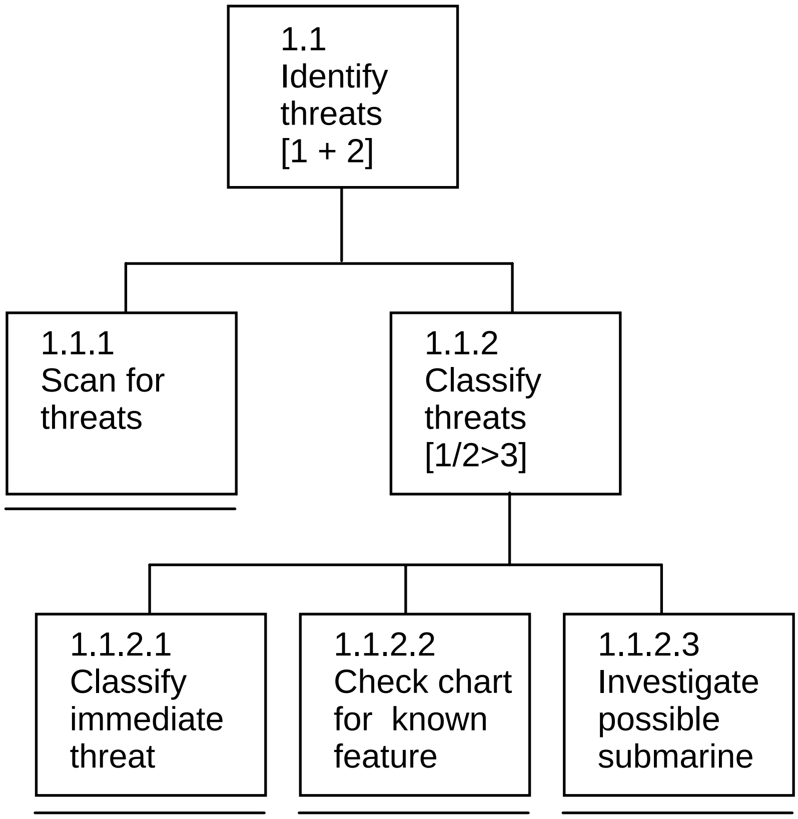

Figure eight. Hierarchical diagram for the goal of "Identify threats"

Figure eight shows that the Anti-Submarine Warfare team have to simultaneously scan for threats and classify threats. They can either immediately classify the contact as a threat or investigate for local features (such as rocks, wreck and pipelines) that could show as a contact. If a threat is classified as high priority then the team investigate the possibility that it is a submarine.

Annett at al (2000) argued that it is important that the task analysis captures the three principle components of team work, namely the communication, co-ordination activities as well as team goals. These components, and the corresponding activities, are indicated in table nineteen.

Table nineteen. Components of team processes.

Team Process	**Category**	**Observable activities**
Communication	Send information	Transmit data or comment to another party
	Receive information	Receive data or comment to another party
	Discussion	Discuss situation and/or options with other team members

Co-ordination	Collaboration	Share or rearrange work according a plan
	Synchronisation	Keep to planned time or event schedule

Annett at al analysed the components of team work in a tabular form, as shown in tables twenty and twenty one.

Table twenty. Team work to identify and classify anti-submarine contacts.

Criteria	**Description of criteria**
1.1. Identify and classify all anti-submarine warfare contacts	
Measure	Contacts are identified and classified as quickly and accurately as possible
Teamwork	Team compiles information from various sources. Principal Warfare Officer (PWO) monitors and directs the team
Plan	[1.1.1. + 1.1.2] Scanning all sources for information on potential threats is continuous [1.1.1.]. classification procedures [1.1.2.] follows identification as soon as possible

Table twenty shows that various members of the team are seeking data on contacts. These activities are being overseen by the PWO. This activity is going on constantly. By contrast, table twenty one shows and activity that is triggered by discovery of a new contact.

Table twenty one. Team work to check the chart.

Criteria	**Description of criteria**
1.1. 2.2 Check chart for known feature, such as rock, wreck, pipeline, etc...	
Measure	Chart checking procedures should be executed correctly and the conflicts resolved. All units should be informed of outcome.

Teamwork	The sonar operator passes the information onto the Active Sonar Director who confers with the Principal Warfare Officer. The Principal Warfare Officer calls for a "Chart check, poss. sub BRG/RG" The Officer of the Watch plots the position to agreed margin of error. The Active Sonar Director directs the Sonar Controller to investigate the location. The Action Picture supervisor inputs the data into the system. The Electronic Warfare and Radar teams check returns on that bearing. The Officer of the Watch and Missile Director check the bearing visually. All report the results of their checks.
Plan	If the chart check is negative then go to Respond to Threats [1.2]. If the information is inconsistent the go to Investigate Possible Submarine [1.1.2.3].

The team work described in table twenty one is rather more complicated than that in table twenty. This information could have been expressed at deeper levels in the sub-goal hierarchy, but the tabular format allows for the complexity of the activity to be captured in a narrative form.

All of the analyses shows specialised enhancements of the basic HTA tabular format to perform specific analyses, such as: analysis of human computer interaction, error analysis, allocations of function, and the analysis of team tasks. It is possible to combine these analyses into one large table, as shown in table twenty two. Gramopadhye & Thaker (1998) illustrate the multiple column format that can be used to record several forms of analysis within the same document. The table in this example of PC operation has been split into two parts because there were 16 analysis columns to support.

Table twenty two. HTA for work design

Task	**Alloca-tion**	**Info. required**	**Info. presented**	**Human input**	**Computer input**	**Coordina-tion**	**Cognitive demand**	**Possible errors**
1.1.1 Place ON/OFF switch in ON position	Human	Position of ON/OFF switch	Switch label	Update switch position	N/A	None	Low	Failure to locate switch

1.1.2 Access RTS directors	Human	Human	Current directory	Change directory command	N/A	None	Low	Specify wrong directory or issuing wrong command
Task	**Consequences**	**Task duration**	**Frequency**	**Who**	**Knowledge**	**Skill level**	**Complexity**	**Task criticality**
1.1.1 Place ON/OFF switch in ON position	Unable to run the system	< 1 minute	Once a day	Clerk	Basic operation of a PC	Low	Simple	High
1.1.2 Access RTS directors	Unable to run the system	< 1 minute	Once a day	Clerk	Basic operation of DOS	Medium	Simple	High

As table twenty two shows, the analysis can be very comprehensive, but the format may be unwieldy. It might be difficult to perform all of the analyses as part of a single study. Rather there are likely to be separate studies for allocation of function, interaction, error analysis, and knowledge requirements. Then each of these separate analyses could be compiled into a single table. What table twenty three does show is an overview of the tasks demand and constraints in one single source. There may be occasions when all of this information is needed together.

Future extensions of HTA have considered the possibility of modelling task scenarios. Baber & Stanton (1999) have proposed a method that combined HTA with state-space diagrams and transition matrices to model human-computer interaction as part of an analytical prototyping process. The TAFEI (Task Analysis For Error Identification) methodology combines scenario analysis, structural analysis and functional analysis to test device design prior to development of an operational prototype. Annett (2004 - personal communication) has considered developing HTA into dynamic programmable models that may be used to evaluate the performance of a system. He proposed that the methodology could be used for system design, performance estimation, and allocation of system function. Both of these approaches represent a departure from the table and taxonomy approaches that have been used in contemporary extensions of HTA.

7. Future requirements for software support of Hierarchical Task Analysis

Previous attempts have been made to develop software support for HTA (e.g., Bass et al, 1995). Although there are varying degrees of success with which these applications have been met, none supports the full range of applications to which HTA may be put. The software tool reported by Bass et al (1995) was only developed to prototype form. It sought to simplify the production of the hierarchical diagrams and the tabular format by allowing direct manipulation of the data objects and easy editing of the analysis. Other examples have been developed for specific applications, such as error prediction or workload analysis. Some analysts have used outline processors, organisational charting and planning tools such as More, OrgPLUS, and Inspiration. Their tools tend to support some, but not all, aspects of HTA. It is therefore proposed that any future HTA software support for HTA should support the wide range of applications. As Kirwan & Ainsworth (1992) point out, once the HTA has been conducted it can be reused many times for ergonomics and human factors analysis as described in the previous section.

Any future software tool designed to support HTA needs to combine four principle facets of HTA use:

(i) Support the development of the sub-goal hierarchy and plans in the three different formats of HTA representation;

(ii) Enable editing and verification of the analysis to percolate through each of the representations;

(iii) Support extended analysis of the sub-goal hierarchy;

(iv) Enable further extensions of the analysis to be added.

Each of these requirements will be dealt with in turn.

First, the software should support development of the sub-goal hierarchy and plans. Examples of templates for development of the hierarchy and plans have been proposed by Omerod and colleagues (see tables six and seven) and also in table ten. The questions to be addressed in development of sub-goals are presented in table five. Development of task statements was presented in table eight. The software could support each aspect of the sub-goal and plan development following through the stages outlined in figure five. Each form of representation should interact with the others, so that as the hierarchical diagram (see figure six) is developed, so is the hierarchical list (see figure seven) and the tabular format (see table ten). The development of the plans should be automated as far as possible, using the templates as suggested previously.

Second, as HTA involves reiteration and revision, the software tool should enable the sub-goal hierarchy and plans to be edited with ease. Any change made in one form of the representation should propagate through the other forms of the representation. For example, a change sub-goal hierarchy or plans in the hierarchical diagram should work through to the hierarchical list and tabular format automatically, and vice versa. As far as possible, the editing of the sub-goal hierarchy and plans should be possible though direct interaction with the objects and text on the screen.

Third, the software should support extended analysis of the sub-goal hierarchy and plans, as shown in (but not limited to) the examples in sections five and six of this paper. Templates of the tabular formats, with their associated symbology and taxonomies, would need to be provided. The facility to edit the templates or remove columns and add symbols and taxonomies or elements also needs to be provided for. This is to allow maximum flexibility for the analyst. This means that after the sub-goal hierarchy and plans have been constructed, the HTA can be subjected to further analysis, such as error potential, allocation of function, and team work.

Finally, the software should, as far as is reasonably practicable, enable further extensions to be added. A simple means of adding additional functionality would be to allow the analyst to create their own templates for plans, tabular forms, taxonomies and symbols. A more complex means of allowing additional functionality would be to leave the software architecture open to additional development so that different approaches, such as TAFEI (Baber & Stanton, 1994) and Annett's (2004 - personal communication) dynamic programmable task models, can be added at a future date.

8. Some general conclusions

The future for HTA seems assured, at least in the short to medium term. The variety of domains and applications that it has been used for is a testament to its usefulness.

The developments and extensions of the approach suggest that it is likely to remain in the core repertoire for ergonomists. HTA should also serve as a benchmark for all other ergonomics methods and approaches. The key features of the approach are that it was not only developed on strong theoretical foundations but also focused on solving real-world problems. The approach was flexible enough to enable it to be applied to a wide variety of domains and applications. It has continued to be developed, extended, and improved throughout the past 37 years, but the original three guiding principles remain as true today as when they were first put forward. The reasons behind the endurance of HTA are likely to include the fact that it can provide a comprehensive model of a sub-goal hierarchy in a system. This model could be of an existing system or one that is anticipated. The sub-goal hierarchy lends itself to all manner of analyses, which is the real point of HTA. HTA was never meant to be the end point in the analyses, just the start. The original aims of HTA were quite modest. The authors of the first report hoped that it would spread the ideas of "*a new approach to tasks analysis even more widely in British Industry*" (Annett et al, 1971: p. iii). It would be fair comment to say that they have exceeded these aims many-fold, to provide ergonomists in industry and academia throughout the world with a core approach to systems analysis of sub-goals.

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