AN ABSTRACT OF THE THESIS OF

JOHN PETER van GIGCH for the DOCTOR OF PHILOSOPHY
(Name) (Degree)

in INDUSTRIAL ENGINEERING presented on April 25, 1968
(Major) (Date)

Title: THE IMPACT OF TECHNOLOGY ON THE MENTAL CONTENT OF WORK IN INDUSTRIAL OPERATIONS

Abstract approved: [redacted]
Dr. James L. Riggs

Industrial operations are becoming more mechanized and automated. The increasing complexity of work affects the proportion of physical to mental effort which workers spend in the performance of their jobs. Traditional work measurement techniques which are primarily designed to measure the individual's physical load have to be complemented with other techniques to evaluate his mental load. This study is aimed at developing a methodology which can be applied to the analysis and measurement of the mental contribution of workers and its associated effects.

Information Theory and the Theory of Communication are used to provide a conceptual framework in which information processes employed in the performance of industrial tasks are identified and evaluated.

Depending on their complexity, the various information processes called mental therbligs, are classified according to four levels of integrative behavior. Information processing rates are calculated on the basis of the amount of

information transmitted in the performance of these therbligs. Average and, where possible, peak rates are obtained for typical jobs representing two or more technological levels in four different segments of the forest products industry:

a. Lumber Sorting

b. Lumber Grading

c. Groundwood Pulp Production, and

d. Sulfate(Kraft) Pulp Production.

Thus, the mental content of jobs in each of these industry segments is evaluated.

The mental contribution of industrial workers is then analyzed in terms of some of the following:

1. The effects of the repetition cycle rate and the variability of the tasks' sequence.

2. The effects of increased system complexity on the ability of operators to cope with the high informational load, equipment malfunctions and emergency situations.

3. The effects of increased system entropy on the operator's speed of responses and on the requirements of system design.

4. The effects of the addition of a process control computer on the variability of the process parameters and on the operator's mental load.

5. The implications regarding training and compensation of workers slated for the jobs created by new technology.

# The Impact of Technology on the Mental Content of Work in Industrial Operations

by

John Peter van Gigch

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

June 1968

APPROVED:

[redacted]

Professor of Industrial Engineering
in charge of major

[redacted]

Head of Department of Mechanical and Industrial Engineering

[redacted]

Dean of Graduate School

Date thesis is presented April 25, 1968

Typed by Arlene Cutts for John Peter van Gigch

ACKNOWLEDGMENT

The idea of studying the mental content of work in industrial operations grew from a summer's association with Dr. E.R.F.W. Crossman of the Human Factors in Technology Research Group, Department of Industrial Engineering and Operations Research, University of California, Berkeley. Through Dr. Crossman, I became interested in the field.

Dr. James L. Riggs provided the patient guidance which was necessary in building an idea into a sound project. If the results are meaningful, it is due to his clear vision and practical wisdom.

This project would not have been possible without the cooperation of industry. Among all the managers, engineers and operating personnel who assisted me, I would like to single out the following:

Mr. J. M. McEwen, Area Manager, and Mr. L. M. Vance, Chemical Engineer, Weyerhaeuser Company, Wood Products, Springfield, Oregon.

Mr. John E. Grammel, Technical Superintendent, Publishers Paper Co., Oregon City, Oregon.

Mr. K. Roth, Larson Lumber Company, Corvallis, Oregon.

Mr. R. Culbertson, Superintendent, American Can Company, Brownsville, Oregon (formerly: Schneider Lumber Company).

Mr. Dennis Frank, Frank Lumber Company, Lyons, Oregon.

Mr. W. Zimmerman and Mr. V. Kreick, Pacific Coast Association of Pulp and Paper Manufacturers, Portland, Oregon.

I would like to express my appreciation to the Pacific Northwest Personnel Management Association who contributed to this project with two one hundred dollar grants. These grants were approved while Messrs. J. T. Brattain, S. T. Ford, W. A. Noel, and W. Zimmerman were in charge of the affairs of the Association.

Dr. J. G. Knudsen, Assistant Dean of Engineering, Oregon State University, provided material support in the reproduction of some of the pictorial exhibits which were obtained as courtesies of the Bauer Brothers Company, the Irvington Machine Works Company and the Moore Oregon Company.

I thank my wife for five years of endurance.

TABLE OF CONTENTS

Chapter Page

LIST OF FIGURES

| Figure | | Page |
| --- | --- | --- |

## LIST OF TABLES

| Table | | Page |
|---|---|---|

# THE IMPACT OF TECHNOLOGY ON THE MENTAL CONTENT OF WORK IN INDUSTRIAL OPERATIONS

## I. INTRODUCTION

### The Changing Nature of Work

The nature of work[1] and its components are in a continuous state of flux. Industry tries to take advantage of all the technical innovations it can afford in an effort to remain competitive. In an age of technological knowledge explosion it is easy to see why work and jobs are being continuously modified and updated.

The industrialized nations of the world are said to be at the threshold of the second phase of the Industrial Revolution. The first phase was mechanization when the mechanical power of the machine replaced the physical effort of man. The second phase, automation, has been defined as the replacement of the information processing ability of the individual by the similar capability of the machine-instrumentation-computer combination (Crossman, 1965).

"Level of mechanization" refers to the "degree of mechanical accomplishment in the equipment" (Bright, 1958, p. 41). The higher the mechanization level the higher the degree of mechanization and automation. A comparison of jobs in the same process found at different levels of mechanization reveals the following changes which have taken place in jobs and work:

---

[1] Work, in this context, will be an activity or effort directed to the accomplishment of a goal.

## Increase in Complexity

In modern plants workers are seldom seen tending a single machine anymore. Increasingly, they are responsible for several machines or a complex system of equipment which combines several operations.

## Vertical Integration

Increasingly, operators control a portion of a complex system of jobs and processes where the consequence of a single action can have serious repercussions throughout the system.

## Speed and Productivity

Invariably, the new equipment is installed to increase output and to reduce the ratio of direct labor to units of output. As throughput is increased, machine idle time becomes more costly. The operator is only valuable to the extent that he keeps the equipment running without costly stoppages.

## The Meaning of Work

In the recent past, the worker guided the machine and controlled the quality and the quantity of its output. Today, the operator supervises complicated equipment which to a large degree is automatic. He gains knowledge of the state of the process through intermediary instruments and controls. In many instances, he never sees or touches the product which is being manufactured.

Work is said to be losing its 'meaning' (Blauner, 1964, p. 23).

## Timing and Reaction Time

As the speed of the process increases, the operator is allowed a shorter time to react to a malfunction or to a breakdown. In addition, the situation is compounded by the intricacy of the system. As a result, a decision of increasing complexity must be resolved in a shorter span of time.

## Adapting to Change

As the methods of production change, the environmental working conditions both in the physical as well as in the psychological sense are modified. Management has always assumed that given a new job and given the proper technical training, the operator would easily adapt to change and make a smooth transition from old to new. Appearances are deceiving. As the size of the equipment becomes larger and as systems become more complex, workers are becoming increasingly reluctant to accept promotions from old installations to newer ones. They prefer to 'freeze on the lower rank job' than to assume the responsibility of the new process. As Blauner (1964) puts it, the worker is becoming increasingly 'alienated' from his work, from the concern in which he works and from the society in which he lives.

Industry desperately needs skilled operators to man the equipment and installations of the future. It is, therefore, indispensable that management understand the meaning and the nature of the very changes which it fosters and that it realize the impact of these changes on the physical as well as on the psychological environment of the worker.

The present study was motivated in part by the desire of making a contribution to the long list of studies which in recent years have addressed themselves to the investigation of the impact of technology on the worker and his work.

More specifically the research described herein aims at evaluating the effects of changes in technology on the mental contribution of workers performing industrial tasks.

## The Problem

A worker makes two types of contributions in the performance of his work. He makes a contribution of physical energy and a contribution provided by his mental faculties which we shall call 'mental contribution'.

In the last one hundred years a marked shift has occurred whereby the content of work requiring physical effort has markedly declined whereas the mental load has been on the increase.

The traditional methods of Industrial Engineering such as work measurement, time and motion study and the like were designed for the most part to provide evaluation of physical work. These methods are not well suited to situations where the worker's contribution is mostly of a mental nature and where no overt motions are performed except when a process change is effected.

Nowadays, the worker's function is to act as a receiver and an interpreter of information. The industrial engineer must provide methods for the evaluation of the information processing load of the individual in situations where long periods of inactivity may occur and where the amount of physical exertion is no longer a yardstick of the energy expended at work.

The study presented here attempts to provide an approach to this problem. First, it attempts to identify the information processes which are performed by the human communication channel. Information Theory and the Theory of Communication are then used to provide a quantitative measure of the amount of information which is processed and is transmitted in the human channel when performing a task in the industrial setting. Most previous applications were solely made to isolated laboratory situations or to forced-rate tasks.

For the purposes of the present study the measurement of amounts of information were carried out for jobs found in industry. In particular, the amount of information measures were applied to jobs accomplishing similar functions but found at different levels of technology.

The jobs chosen for comparison were all located in the Forest Products Industry of the state of Oregon. The vertical integration of the study was a useful by-product of the research design not found in other studies of this nature.

## Objectives

1. To identify basic information processes carried out in

the performance of typical industrial tasks.

2. To build a model of integrative behavior in the context of which the above information processes can be identified, evaluated and measured.

3. To use the model and modifications thereof, for the measurement of the information processing load of comparable jobs found at different levels of technology.

4. To draw conclusions about the trend followed by the information processing requirements of industrial work as a result of the impact of increased mechanization and of automation.

5. To reflect on the skill requirements of operators, in particular on the training required to cope with the mental load of modern operations.

## Procedures

1. A basic set of information processes found in the performance of industrial operations are identified as mental therbligs.

2. A model of integrative behavior is developed where the mental therbligs can be measured in terms of the amount of information processed and transmitted through the human communication channel.

3. New units of information are defined and developed which reflect the degree of complexity of the information processing function exercised.

4. Average information processing rates of similar

jobs found at several levels of technology are calculated and compared.

5. Inferences as to skill requirements and training needs are made on the basis of the information processing rates obtained above.

## General Significance

The proposed measurements of mental content of work complement traditional work measurement methods of evaluating the physical load of industrial operations. The results obtained provide a basis for better evaluating the total contribution of workers to their jobs as physical load declines and mental effort increases under the impact of technological change.

The study offers significant insight in the nature of present and future jobs which result from automation.

Conclusions regarding appropriate compensation for the mental content of work are drawn and compared to present job evaluation and wage plans.

Whereas this study was carried out in the context of only one industry for reasons of accessibility, its methodology and conclusions can be extended to other settings and will find general application in other industries.

# II. HUMAN INFORMATION PROCESSES

In order to understand and classify the various mental functions which the operator performs at work, we must categorize the information processes which take place between the reception of information by the individual and his body's response.

Before overt action can occur, the nervous system must process the information received in the form of sensations or stimuli. In order for sensation to take place the body is endowed with sensitive cells and structures called receptors which have the capacity of responding to energy changes in the environment and to translate physical and chemical events into neural events (Sanford, 1966, p. 95). According to the same author:

> "There must be a central nervous system that translates neural events into awareness, and, if there is to be muscular response to the incoming signals, the nervous system must also make connections between the incoming sensory messages and the nerves running to the body's effectors - its muscles and glands (Sanford, 1966, p. 280)".

The human information system can be, therefore, characterized by three components:

1. The receptor system which basically consists of the sensory organs and which converts the input stimuli into nerve impulses.

2. The effector system which consists of the muscles and limbs and which converts nerve impulses into muscular activity.

3. Mediating between the receptor system and the effector system is a central nervous system also called the central mechanisms which connects the other two.

The human communication system has been shown to be analogous to an electrical communication system (e. g. Shannon and Weaver, 1949, p. 6). Ross (1960, p. 27) has noted that while the communications engineer considers information as the throughput of a man-machine-man system, the psychologist is concerned with a machine-man-machine system. It is this last analogy that best represents the role of the worker in the industrial context.

In order to evaluate the transmission capabilities of the human communication system, the various information processes taking place in it will be defined.

## Information Processes in the Receptor System

### Sensing or Sensory Processes

The translation of the physical and chemical stimuli from the environment into neurological events or impulses (Sanford, 1965, p. 317).

### Perception or Perceptual Processes

A process whereby the organism selects, organizes and interprets sensory data available to it (Sanford, 1965, p. 573).

### Scanning

The process by which an individual attends successively to different classes of inputs or their properties and characteristics. Scanning implies a deliberate search of input elements in order to classify them according to predetermined patterns. Scanning will describe in this study the function performed by an operator when he observes sensory inputs to assess whether the work which he is performing is proceeding according to plan.

Decoding

This process implies changing the information received by the senses into some meaningful form which can be utilized by the system. It is worthwhile to point out that, in general, the equipment designer stresses the importance of coding i. e. to present the observer with input variables which can be unambiguously differentiated from each other. Obviously, if we consider a machine-man-machine system, decoding occurs as the signals or stimuli impinge on the observer and coding when he communicates with the environment.

Recognition

The process by which the input stimuli can be assigned as belonging or not to a particular category or class. As will be described below, the receptor system can be described as possessing in storage, pattern elements which are drawn from memory and compared to the incoming signals. Recognition implies discrimination, identification and classification.

Processes of Judgement and Estimation

Categorization or classification can be followed by assigning an estimated value, size, dimension and the like to the incoming variable. This involves judgements which can be of two kinds: absolute judgements where a definite number or value may be assigned to the variable, or a comparative or relative judgement where the value of objects can only be assigned in comparison one to another (Garner and Hake, 1951)(Gregg, 1966). To make judgements and estimates, information carried in temporary or permanent storages must be called into play. The processes of judging and estimating also implies the process of comparing.

Figure 1 shows the component functions of the human receptor system (Cited in: Crossman, 1964).

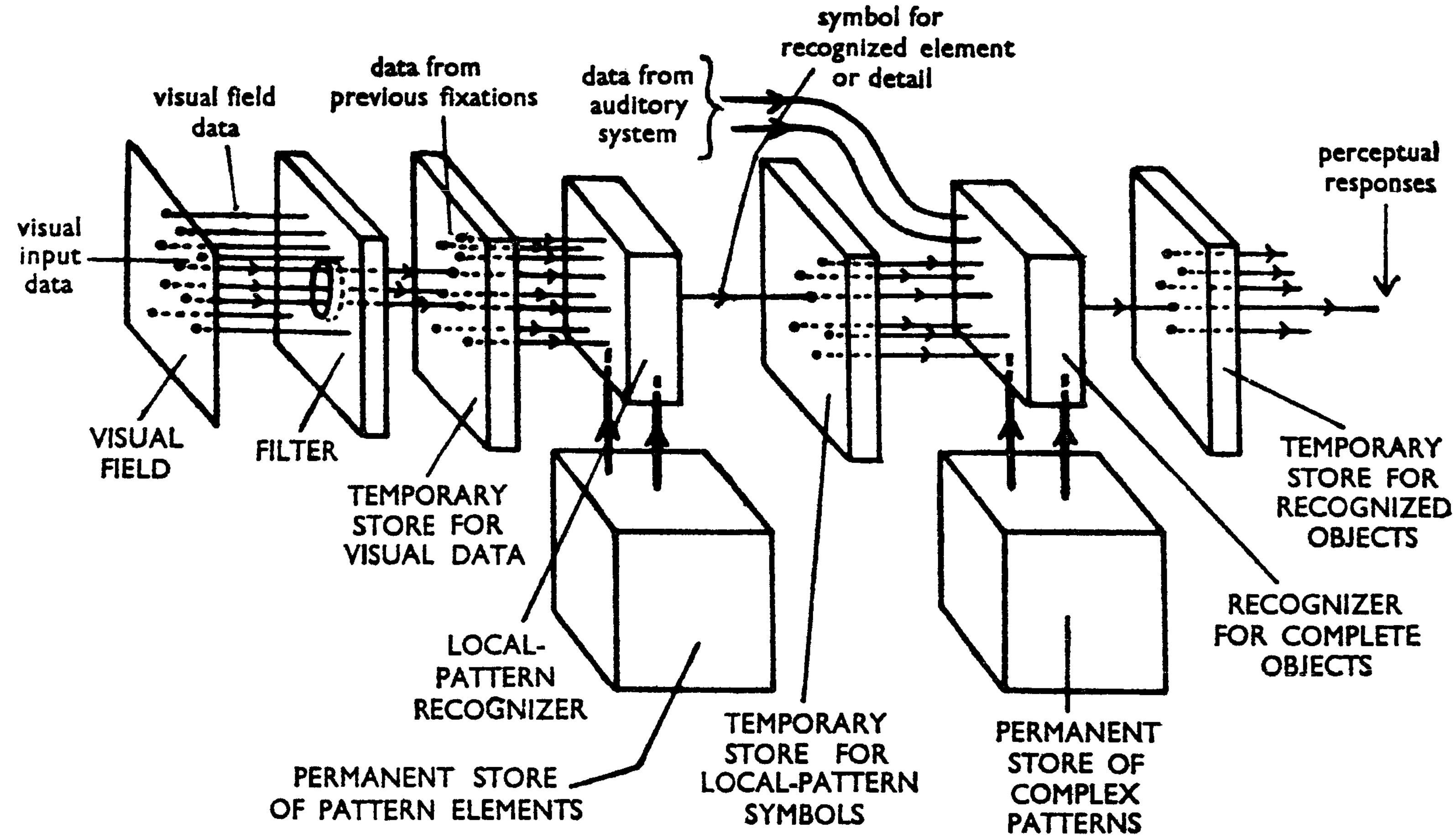



Figure 1. Component functions of the human receptor system.
(Cited in: Crossman, 1964)

This model comprises the following:

a. Filters which act to screen the incoming data in order to leave only a small number of alternative patterns which require identification.

b. Temporary storages where data such as visual or auditory signals can be retained for short spans while recognition takes place.

c. Permanent storages from which pattern elements can be drawn for comparison to recognize input stimuli.

In summary, the mental processes which can be attributed to the receptor system are: sensing, scanning, perceiving, recognizing, identifying, discriminating, classifying, matching, judging and estimating and comparing. "The output of the receptor system is a sequence of so called 'perceptual responses' giving a summary description of the environment in a prearranged code" (Crossman, 1964). According to the same author, the receptor responses are channelled to the central mechanisms whose function is to "interpret data from the receptor system in relation to current objectives and issue 'commands' to the effector system". We now turn to the consideration of the mental processes taking place in the central mechanisms.

## Information Processes in the Central Mechanisms

The central mechanisms are the least understood portions of the nervous system. To it are attributed, however, the higher mental processes which mediate between the stimulus and response and which can be given the name of 'thinking'.

There are many activities related to thinking. The following will be defined in turn: concept formation and abstracting, goal setting, problem solving, decision making, creating, relating, integrating and unitizing.

## Concept Formation

It is the acquisition or utilization of a common response to dissimilar stimuli. It requires 'abstracting' of a common property from several different objects, events, or situations (Costello and Zalkind, 1963, p. 353). Concepts are needed in all aspects of the problem solving process. It is also reasonable to assume that they contribute to the recognition and classification function of the receptor system where they may be stored in the pattern recognizers postulated by Crossman (1964).

## Goal Setting

Human behavior is always assumed to satisfy a purpose. For thinking to be meaningful it must also be goal oriented. The central mechanisms direct thinking within the requirements set by the individual's needs and control the performance of outputs in the direction of set objectives.

## Problem Solving

Sanford (1965, p. 422) points to two characteristics of of problem solving behavior which do not exist in organisms simpler than man. One is the capacity to react to external stimuli not physically present, and the other is the fact that the organism appears to approach its problems with a plan, strategy or insight. In addition, problems cannot be solved without knowledge. The problem solving activity subsumes, therefore, the ability of the organism to learn. "As it is caught up in the psychological process, the organism responds to the consequences of its own behavior: it learns" (Sanford, 1965, p. 368). The availability of concepts referred earlier also facilitates the solution of problems.

## Decision-Making

The process which obviously must follow the problem solving activity in order that the end may be achieved. Decision-making is defined as the process of making a choice among several alternatives prior to overt action. Decision rules, strategies and pre-established rules of procedure facilitate the decision making process when an individual is faced with situations he has already experienced before.

## Controlling

As mentioned earlier, the central mechanisms are thought to issue the commands to the effector system in order that the outputs be related to the objectives set for the task. In order to evaluate the results of the outputs, a new round of input stimuli must take place. The central mechanisms are considered the center where the evaluation of results takes place, in spite of some evidence that, in certain cases, they may be by-passed (Pierce and Karlin, 1957).

For the purposes of this study, checking the trend of a variable will be considered a process related to controlling and, therefore, taking place in the central mechanisms. When the operator monitors a trend, he is comparing the variable against a standard. The decision as to whether some action to modify the operation of the machine is necessary will be taken in the central nervous system.

The coordination of action according to established objectives and strategies can also be considered as part of the controlling function.

## Ordering

Refers to the mental process involved in keeping track of the serial order of numbers, objects, tasks and the like. In a certain sense the ordering function can be considered a part of the controlling function mentioned above. For the purposes of this study it will be important to differentiate between the mental effort required from an operator in repeating the same sequence of operations and the load involved when the sequence is not repeated each cycle. Batch production versus continuous production is an appropriate example of this distinction.

## The Unitization Function

"Unitization" is the name given by Miller (1956 a) to the process which a person carries out to organize the information input into a scheme sufficiently simple to permit easiest retention. It is important to realize the generality of such a procedure as it applies to individual behavior. All learning is accomplished by fitting the newly acquired knowledge into a framework.

Miller (1956 a) describes it this way:

> "When (a person) sets out to learn something that he is personally interested in and that he expects to have use for, ..... he is careful to organize the material in a way that fits well into his established cognitive structure. Without the pressure of time, he can explore various alternative unitizations until he finds one that works best for him and promises the best recall at any later date. ..... His task is to create a hierarchy of units in such a way that by recalling a few informationally rich and suggestive units at the top of the hierarchy, he can then recover the more numerous, more detailed items at the bottom."

There is no doubt that the unitization function takes place whenever an individual attempts to fit new facts within the fund of previously acquired knowledge. For instance, a teacher has the responsibility to organize the material presented in class into meaningful chunks. Providing meaningful chunks is equivalent to performing, at least in part, the unitization function for the student i. e. providing the material in a hierarchical structure for ease of understanding, retention and recall. The unitization process can only in part be accomplished by the instructor because each individual finds the unitization which suits him best: he must fit each new fact into his own hierarchical organization of knowledge.

In the industrial operations studied for this report, the unitization function was found to be extremely important. The operator whose job is to monitor a process is constantly receiving information of events from instrument displays, equipment records and other devices. His job is to interpret the incoming data within the context of the process as he knows it. The decisions he makes are in direct relation to his own interpretation of the information received and to his own idea of what the results of the process should be. In spite of working with the same equipment and with the same instructions, every operator will unitize differently. This remark points to some of the difficulties encountered in allowing workers to be trained on-the-job: they do not understand the process in the same way and are liable to take different decisions in similar circumstances.

Relating

Unitizing can also be interpreted as the mental process of relating variables together. In other words, the picture which the operator has in his mind of the progress of an operation depends on his interpretation of the instrument readings and on the significance he attributes to the value of each variable. Furthermore, the value of each variable must be fitted to the whole picture i. e. must be 'unitized' or 'related' to the rest of the system. Of all the mental functions performed by the industrial worker, the unitizing or relating function was considered the one to which he must contribute the most effort. Unitizing and relating can be compared to considering a matrix of n x m alternatives when two variables can each assume n and m values respectively. When more than two variables are at work, the matrix of relationships must be enlarged. This case will be illustrated in chapter VI, section 4, when the work of the operator controlling the intricate process of kraft pulp production will be considered.

### Creating

This function is thinking that usually results in "a new esthetically pleasing or innovative and valuable production" (Costello and Zalkind, 1963, p. 334). Whereas this form of thinking may draw on the highest capabilities of the human intelect, it does not apply to the type of work encountered in this study.

## Information Processes in the Effector System

According to Crossman (1964) the organization of the effector system is in many ways similar to the organization of the receptor system. See figure 2.

### Coordinating Outputs

The processes of the receptor system which consist in executing the commands originating in the central mechanisms will be known as the coordination of outputs. The receptor system "controls the timing and patterning of movement" after the decision to carry it out has been given (Fitts and Peterson, 1964).

It has been postulated (Crossman, 1960) that time relations are provided by visual as well as kinesthetic or internal feedbacks. The outline of the methods to be pursued and the detailed instructions to be followed are kept in temporary and permanent storages or memories similar to those encountered earlier when discussing the receptor system. In the present case, the effector system can

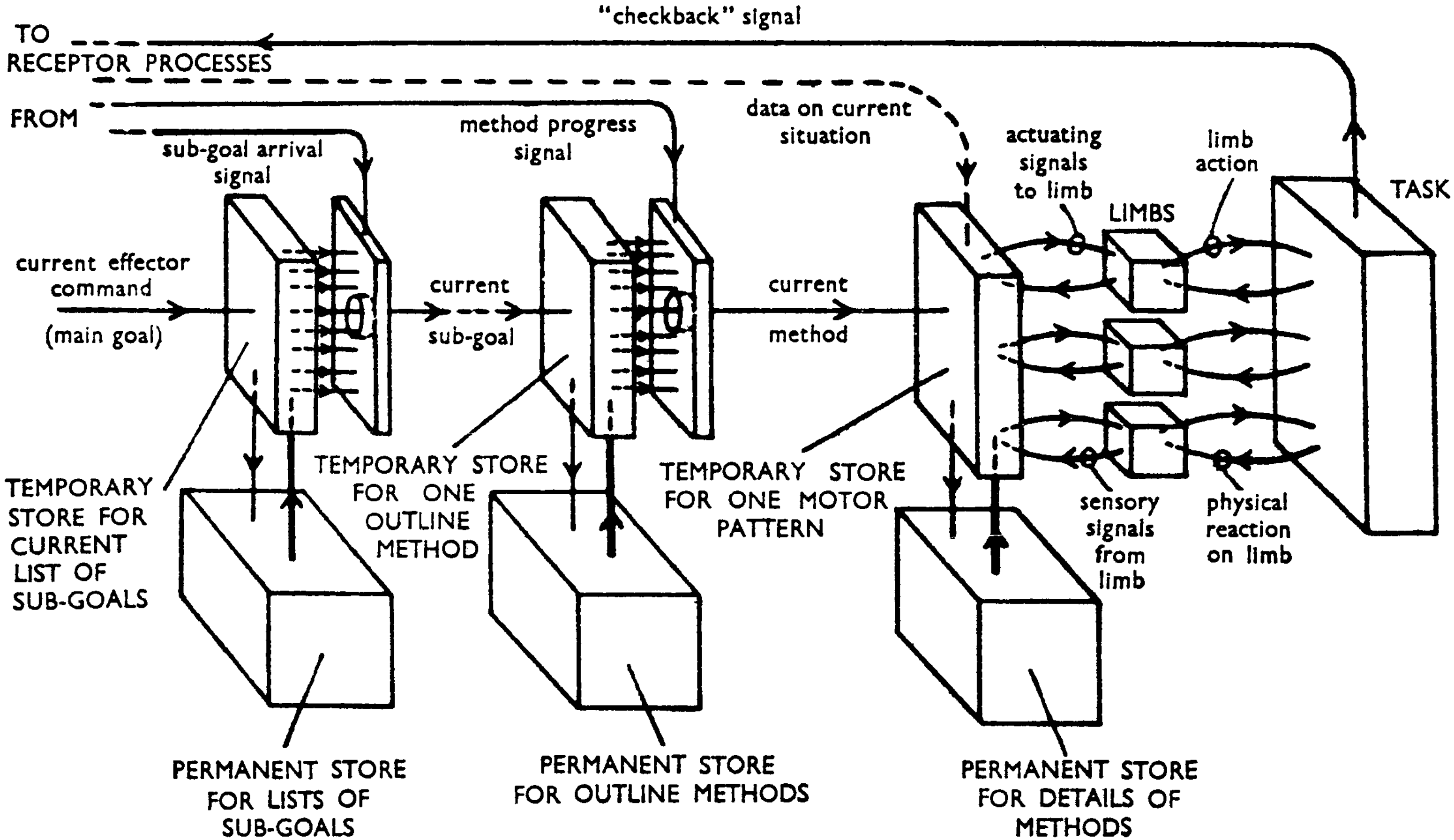



Figure 2. Schematic organization of the human effector system.
(Cited in: Crossman, 1964)

marshall methods and patterns of motions from these stores so as to accomplish the response ordered by the decision center.

## Open and Closed Loop Control

The degree of control which the central mechanisms must exercise over the effector system during the performance of a movement will depend on the complexity of the task to be performed and on the extent to which the individual has been trained. According to Fitts and Radford (1966):

> "Continued practice in a skill is assumed to result in the establishment of a hierarchical organization in which simple movements become relatively independent of cognitive control and are executed as open loop responses."

It is clear, however, that at least some form of kinesthetic or internal feedback is always present.

## Symbolic Versus Non-Symbolic Processes and S-R Compatibility

The mental load of the operator will also depend to a great extent on the correspondence which exists between the perceptual response and the control action which is required. Symbolic refers to the type of process in which the relationship between the display and the control is not direct whereas non-symbolic means that the display and the control can be easily matched (Crossman, 1956). Additional translating mechanisms relating stimulus reception and response execution are said to be at play in symbolic tasks. More simply, it can be said that the coding between input and output is more direct in non-symbolic than in symbolic processes. Complex operations where the controller must interpret the results obtained before modifying the process are definitely in the realm of symbolic tasks: the instrument reading cannot be directly translated into action without further cogitation. Fitts and Seeger (1953) called the matching of stimulus coding and response coding 'S-R compatibility'.

Table 1 summarizes the information processes which take place in the human communication system. These processes are categorized according to the three sub-systems: The receptor system, the central mechanisms and the effector system. In chapter V the information processes will be taken up again and considered on the basis of their complexity or the 'level of integration' in behavior. A similar description of the component processes of human performance and their capacities is given in Fitts and Posner (1967, p. 42-82).

Table 1. Information processes and the human communication system.

| Receptor System | Central Mechanisms | Effector System |
|---|---|---|
| Sensing input stimuli | Concept formation | Coordinating outputs |
| Perceptual processes: | Goal setting | Open loop vs. closed loop control |
| Scanning | Problem solving (computing) | Symbolic vs. non-symbolic tasks |
| Decoding | Decision-making | S-R compatibility |
| Recognizing | Controlling | |
| Judging and estimating | Ordering | |
| | Unitizing | |
| | Relating | |

# III. INFORMATION THEORY IN PSYCHOLOGY

As noted earlier, the Theory of Communication has provided rich analogies between a radio transmission system and the human information system. In addition, psychologists and, more recently, industrial engineers have successfully applied certain concepts found in the Mathematical Theory of Communication and in Information Theory to the measurement of human informational capabilities. It is to the description of these concepts and yardsticks that we now turn prior to a discussion of how they can be applied to our particular study.

As W. C. Gore (1960, p. 583) points out:

> "There are two major aspects of the subject called information theory. The first is concerned with the quantitative definitions of the amount of information conveyed in a message and of the capacity of the communication channel to transmit information ..... The second major aspect of information theory ..... is that communication problems are related to games involving the laws of chance or probability theory."

The concepts contained in the first aspect mentioned by Gore will be defined below. The second aspect is actually implied in the first.

## Amount of Information

Information consists of messages and messages of signals. In all cases a probability distribution can be said to exist over the population of signals which can be used to transmit the message. Each signal in the message will be chosen with a certain probability which depends on the structure of the language used for sending the message. If each signal i has probability $p_i$ of being transmitted, we define the following:

1. The amount of information of each signal i as:

$$H_i = - \log_2 p_i \qquad \text{in bits.}$$

$H_i$ represents the uncertainty as to which signal i will occur.

2. The expected amount of information in the message as:

$$H = - \sum_{i=1}^{n} p_i \log_2 p_i \qquad \text{in bits.}$$

This measure is the sum of the amount of information carried by each signal multiplied by the probability of its occurrence in the message. Because each signal is weighed by its chances of occurring, we get an expected or average measure of the uncertainty in the total message. The above definitions were given in terms of a message and its component signals. They can just as easily apply to a source and its component messages in which case the probability distribution occurs over the population of messages and we can define the amount of information of each message and the expected amount of information transmitted by the source.

When we are faced with a set of possible actions to reach a goal, we need information to choose the action which will lead to the required end. Reducing the number of alternatives by half is said to provide 'one bit' of information. In an assumed case of eight possible actions, progress toward the goal would be achieved if the set of eight alternatives could be divided into two sets of four alternatives each. As shown below, a choice of these two sets implies a gain of information of one bit assuming that each action has the same probability of taking place. A further reduction of our uncertainty by one half provides an additional 'bit' of information.

Given a set of eight alternatives, the uncertainty regarding which alternative will be selected is: $H_i = -\log_2 {}^1/_8 = 3$ bits.

Given a set of four alternatives: $H_i = -\log_2 {}^1/_4 = 2$ bits.

Given two alternatives: $H_i = -\log_2 {}^1/_2 = 1$ bit.

A message carrying three bits of information would reduce the degrees of freedom to zero. For illustration, see figure 3. The expected amount of information in the message would be:

$$H = -\sum_{i=1}^{n} p_i \log_2 p_i = -\sum^{8} {}^1/_8 \cdot \log_2 {}^1/_8$$

$$= -8 \cdot {}^1/_8 \cdot \log_2 {}^1/_8 = 3 \text{ bits.}$$

H is a measure of the amount of information required to remove uncertainty or the amount of information transmitted by a source which would direct us to a unique action from a field of possible alternatives.

In general, if a source involves N alternatives per cycle, which for ease of treatment are considered equi-probable:

$$H = -\sum^{N} \frac{1}{N} \log_2 \frac{1}{N}$$

$H = \log_2 N$ in bits/cycle.

Given that there are n cycles per unit of time in the source, the average amount of information transmitted per unit of time is:

$I = n \log_2 N$ in bits/unit of time.

$I \neq I_t$ where $I_t$ is the channel capacity i.e. the maximum value of I which can be obtained. In all cases, the logarithm of the number of alternatives is taken to the base two. Unless otherwise indicated, log N will mean $\log_2 N$ throughout this paper.

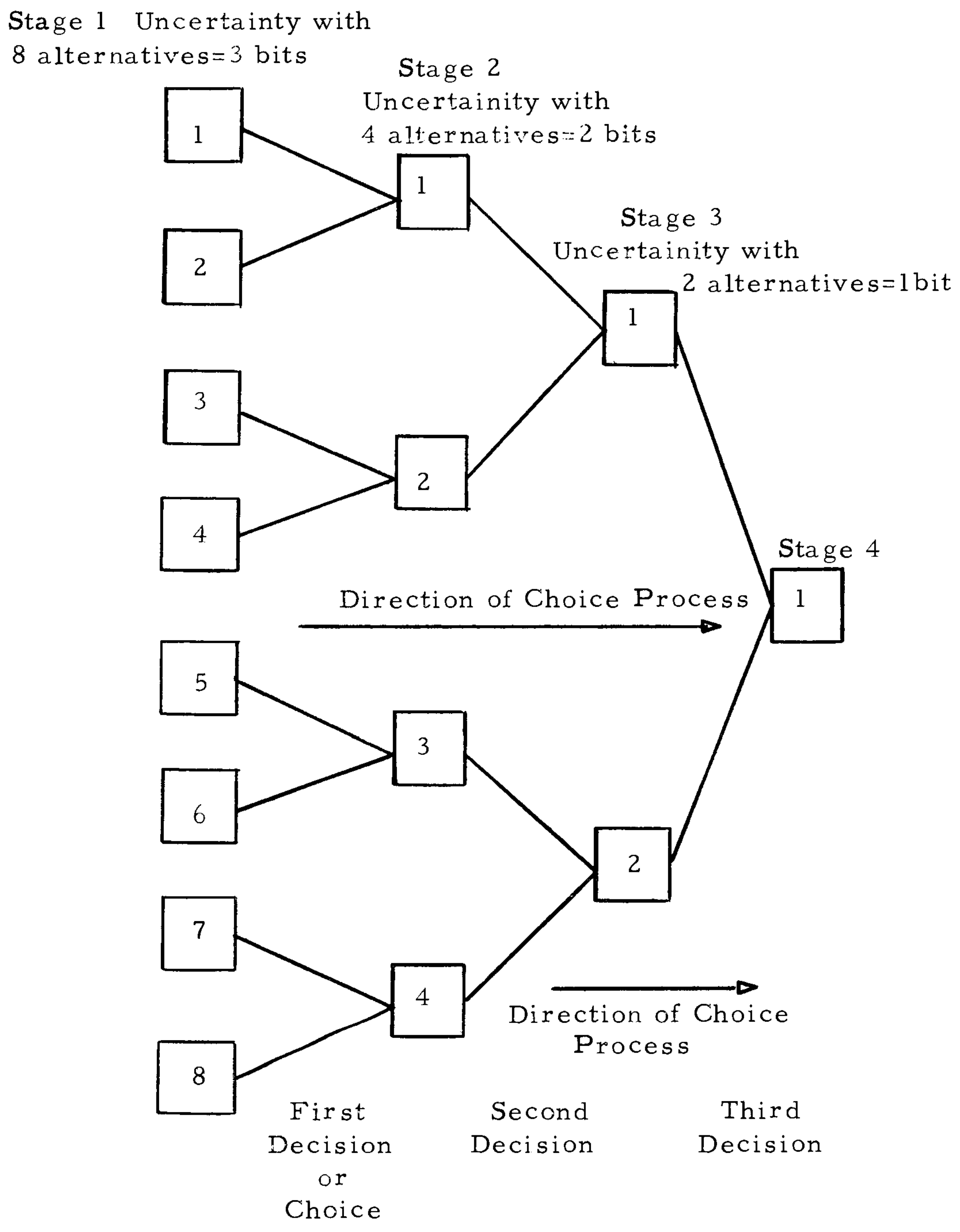



Figure 3. How bits reduce uncertainty. Modified from "Schematic portrayal of the concept of bits in information theory." (Cited in: Nadler, 1963, p. 373.)

This approach to the measurement of the amount of information is borrowed directly from statistical mechanics and from the Theory of Communication (Shannon and Weaver, 1949). The measure of uncertainty is also called entropy, disorganization, measure of freedom, variety, etc. Man is said to live in a universe which is always tending toward increasing disorganization. The role of the human being on this earth is to create order and to struggle against the natural forces which are pulling toward ever increasing variety or disorder. According to N. Wiener (1954, p. 36):

> "There are local and temporary islands of decreasing entropy in a world in which entropy as a whole tends to increase, and the existence of these islands enables us to assert the existence of progress."

Wiener (1954, p. 21) adds:

> "Just as entropy is a measure of disorganization, the information carried by a set of messages is a measure of organization. In fact, it is possible to interpret the information carried by a message as essentially the negative of its entropy ....."

To bring these concepts to their practical conclusions, it can be said that keeping a process 'under control' is to fight its natural tendency to get 'out of control' and that his actions and his observations, the control operator is gaining information i.e. he is reducing entropy.

Information is gained by reducing a field of alternative actions to a single choice. Information is also gained by determining the position of an instrument pointer or calculating the value of a process variable among all those which could possibly take place.

It is important to understand the limitations of information theory measures. As explained by Quastler (1955, p. 9):

> "The measure of information transmitted refers to the results of information processing and not to its mechanism. It does not measure utility of a piece of information."

Miller (1953) states:

> "This term (information) occurs in the theory in a careful and particular way. It is not synonomous with 'meaning'. Only the 'amount' of information is measured - the amount does not specify the content, value, truthfulness, exclusiveness, history, or purpose of the information."

Information measures reflect the extent to which the human communication channel deals with variety and uncertainty. As will be explained below, limitations exist to this capability.

## Channel Capacity

In communications the channel is "the medium used to transmit the signal from transmitter to receiver" (Shannon and Weaver, 1949, p. 34). The capacity of the channel is "defined to be equal to the maximum rate (in bits per second) at which useful information ..... can be transmitted over the channel" (Shannon and Weaver, 1949, p. 21).

By analogy, the capacity of the human communication system can be defined as the upper limit of the rate at which information received in the receptor system can be transmitted to the receptor system and result in a response.

Starting in 1952, experimental psychology, human engineering and other disciplines addressed themselves to the determination of average and peak information transmission rates through the human communication channel. Most of this evidence has been obtained under controlled laboratory conditions. It is appropriate to present a summary of this research at this point.

## Reaction Times

In 1952, W. E. Hick published a paper describing experiments during which S's were asked to react to the appearance of a light on a display board mounted with ten pea-lamps. The response consisted in depressing the appropriate morse key as soon as the light was seen. The degree of choice was altered by changing the number of lamps used during each experimental run. The results obtained gave rise to what Welford (1960) called Hick's Law, according to which there is a linear relationship between the time it takes a S to react (RT) and the degree of choice exhibited in the stimulus (N, the number of alternatives). See figure 4 a.

Hick's Law $RT = k \log N$ in secs.

Rate of information transmission or 'rate of gain of information' $k' = \frac{\log N}{RT}$ in bits per sec.

The linear relationship between RT and the amount of information transmitted gives rise to the conclusion that the 'rate of gain of information' is constant or that the capacity of the human communication channel in transmitting a stimulus to obtain a related response is limited. The maximum information transmission rates recorded by Hick (1952) were in the order of six bits/sec. Any attempts to increase this rate resulted in a deterioration of the S's accuracy. A trading relationship exists between speed and accuracy. The constancy in the rate at which information can be transmitted has been attributed to the time required by the central mechanisms to operate (Miller, 1956a; Crossman, 1953; Quastler and Wulff, 1955, p. 61) and lends weight to the single channel hypothesis according to which the central mechanisms behave as if they could only handle one signal at a time (Welford, 1960).

Reaction times and, in turn, information processing rates are very dependent on the degree of 'compatibility' between the stimulus or display and the task to be performed. In the particular experiment which he devised, Crossman (1956) reports the average information capacity in symbolic choice tasks of six bits/sec. and the capacity in non-symbolic tasks of 17 bits/sec. See figure 4 b. In real life, the S-R compatibility is thought to increase with repeated practice, but will always depend on the inherent complexity of the work to be performed.

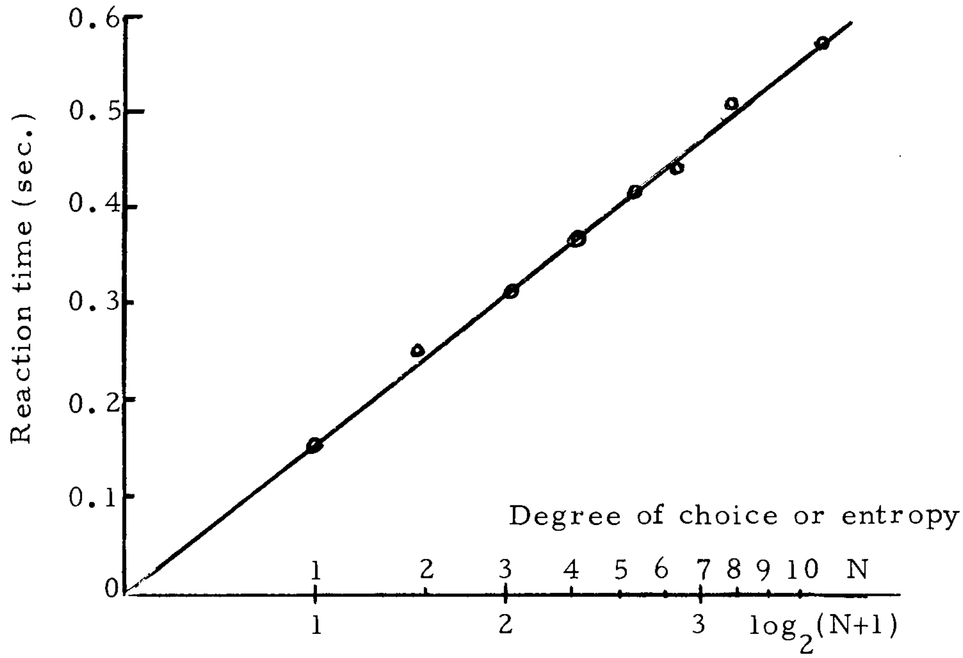



Figure 4a. Data from a choice experiment by Hick (1952) (Cited in: Welford, 1960).

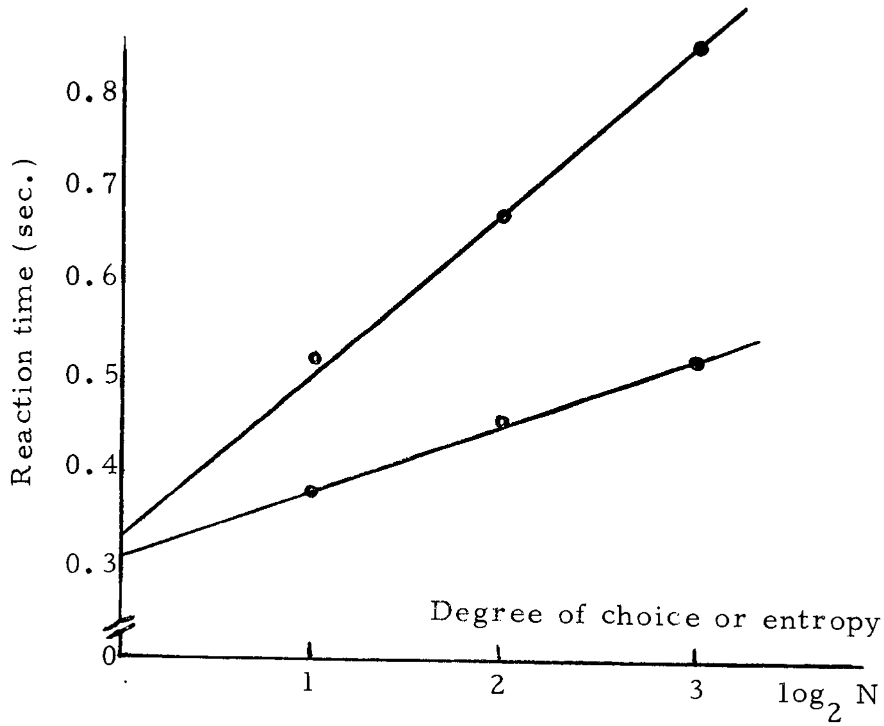



Figure 4b. Data from an experiment by Crossman comparing performances with symbolic and non-symbolic displays (Cited in: Welford, 1960).

Movement Times

In 1954, Fitts initiated a series of experiments which consisted of 'generating' information in the sense that S's were asked to perform a motor task such as hitting as quickly as possible one of a set of appropriate targets when a signal is given. Fitts (1954) experimented first with serial movements i.e. with self-paced cyclical tasks and found the combined total (TT) of reaction time (RT) and movement time (MT) to be proportional to what Fitts defined as ID, the index of difficulty, a measure of the uncertainty or variability allowed in the movement, analogous to the concept of entropy defined previously.

| | |
|---|---|
| Combined time | $TT = a + b \, ID$ in secs. |
| Capacity of motor system | $C = \frac{ID}{TT}$ in bits per sec. |

According to Fitts (1954) the upper limit of man's capacity for 'generating' amounts of information is in the order of ten to 12 bits/sec.

Subsequent work by Fitts and his associates led them to the conclusion that inputs and outputs to the human channel could be treated independently. According to experiments performed by Fitts and Peterson (1964), reaction times are related to perceptual processes and are influenced by the degree of uncertainty (the entropy) of the stimulus to a movement, whereas the movement times are influenced by the degree of uncertainty (entropy) permitted in executing the movement.

As Fitts and Peterson (1964) point out:

> "..... RT reflects the time required for perceptual or cognitive processes, and is determined in part by the preparations which S makes prior to a stimulus, such as those resulting from his knowledge of stimulus probabilities. Movement time (MT) in contrast appears to reflect the duration of the motor system processes that are necessary for the control of the timing and patterning of a movement, and which begin after the decision is made to execute a movement."

The relationship obtained in 1954 for serial tasks between the combined total of RT and MT vs. ID is shown in figure 5 a. The independent relationships between RT and ID and MT and ID for discrete tasks are shown in figure 5 b and 5 c, respectively. According to the data accumulated by Fitts and Peterson (1964), they were able to account for the feedback required in the performance of the serial tasks and concluded that:

> "the processing of feedback data in serial or continuous tasks introduces some small delay relative to simple open-loop movements, but less delay than would be expected if every response involved separate reaction times."

In more recent papers, Fitts and his colleagues added support to the conclusion that "the human motor system has a relatively constant information capacity over rather wide limits" (Fitts and Radford, 1966). In addition, they also confirmed the distinction postulated earlier by Fitts and Peterson (1964) that perceptual processes are relatively independent of motor processes.

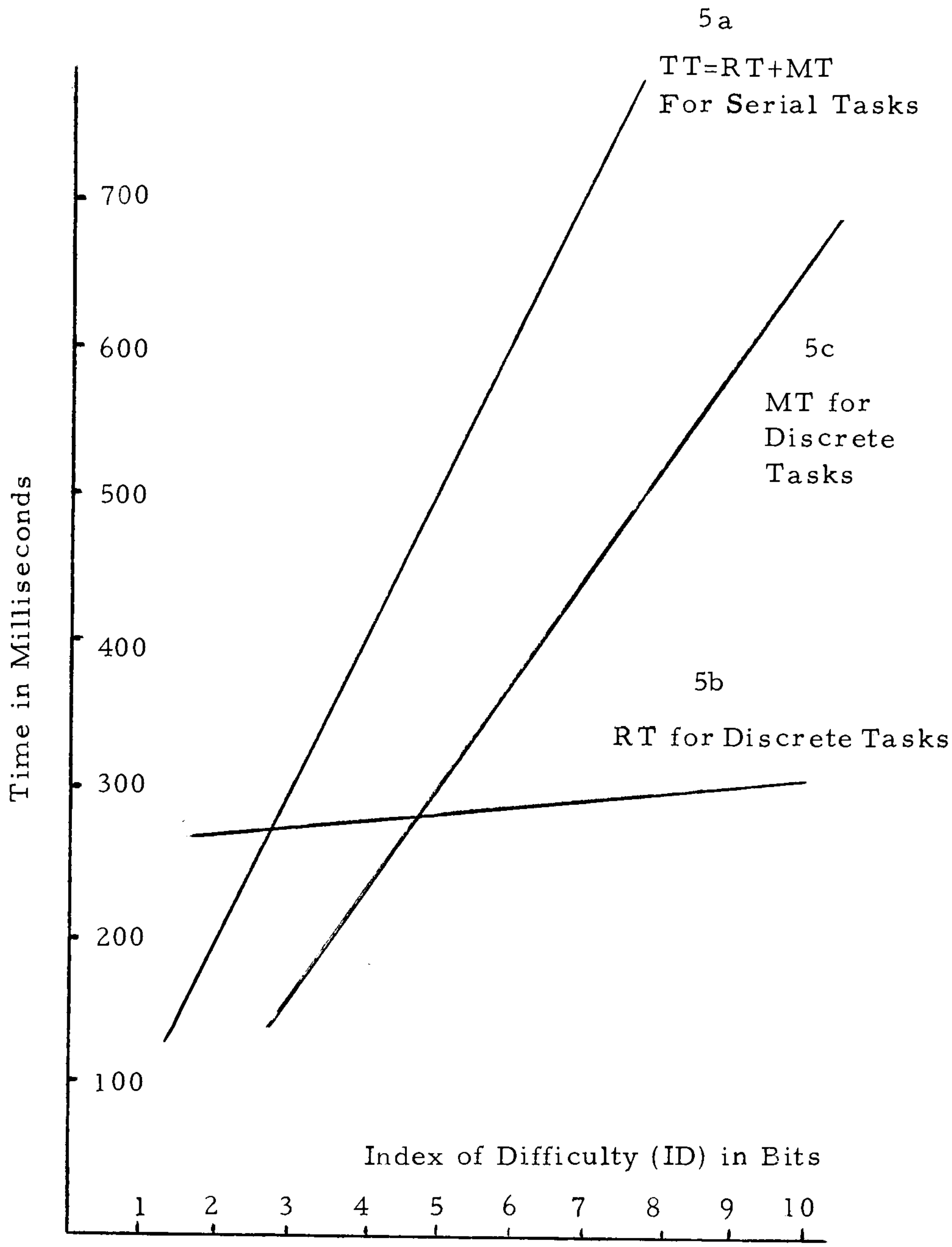



Figure 5. Relation of reaction time and movement time to the index of difficulty (Cited in: Fitts and Peterson, 1964).

## Sequential and Overlearned Tasks

Quastler (1955, p. 341-349) and Quastler and Wulff (1955, p. 7) "were interested in finding how much information man can process at best, that is if his performance is only limited by information processing itself."

They chose piano playing and typewriting as two activities which met the following requirements.

1. The stimuli in the form of music sheet or text to be typed are sequentially shown i.e. large stretches of the input can be shown to the S's at one time. It appears that

> "if the stimuli are arranged in groups sequentially shown, the response rate can be greatly increased. This improvement is due to the overlapping of perception and response; i.e. while the subject is responding to one set of stimuli he can perceive the next" (Quastler & Wulff, 1955, p. 8).

2. The activities are overlearned i.e. subjects are so proficient that no problems of learning occur.

3. The activities are so simple that no judgement is involved.

4. As a result of extensive practice, the stimuli-response sets can be considered compatible.

Under those experimental conditions, Quastler and Wulff found the peak information transmission rates to be in the neighborhood of 22 and 17 bits/sec. for piano playing and typewriting, respectively. See table 2. Experiments in other activites such as reading aloud and mental arithmetic provided rates ranging between ten and 24 bits/sec. depending whether the average rate or the peak rate was considered.

Table 2. Information processing rates for forced-pace overlearned activities.

| | Peak Rate bits/sec. | Average Rate bits/sec. |
|---|---|---|
| Piano playing[1] | 22 | |
| Typewriting[1] | 17 | |
| Reading aloud[1] | 24 | 18 |
| Mental arithmetic[1] | 24 | below 10 |
| Reading random words[2] | 50 | |
| Solving puzzles[3] | 0.2 | |

[1] Cited in Quastler & Wulff (1955, p. 58).

[2] Cited in Pierce & Karlin (1957).

[3] Richards and Swaffield (1953) (Cited in: Quastler & Wulff, 1955, p. 59).

All these experiments provide useful terms of reference against which the processing rates obtained in other activities can be compared for reasonableness. Peak information processing rates are useful to evaluate the human being's capacity for withstanding heavy surges of mental load which take place in situations of emergency. The human-factors engineer is also interested in average information processing rates which could measure the human performance in the environment of industry and the ability of the operator to sustain information loads for relatively long periods of time such as those found at work (e. g. four hour shifts).

## Span of Absolute Judgement

There are two ways in which input observation presented to an observer can be increased. One is to increase the rate at which information is given, and the other is to increase the number of alternatives disregarding time as a variable. Experiments in 'absolute judgement' involve the second alternative. S's are asked to identify different stimuli which are varied along a single dimension. Thus they are asked to recognize several auditory pitches of different frequency or sounds of different intensity, etc. These experiments reveal that "there is a clear and definite limit to the accuracy with which we can identify absolutely the magnitude of a unidimensional stimulus variable" (Miller, 1956 b). Miller (1956 a&b) proposed to call this limit 'span of absolute judgement'. Whereas no time element is involved and hence no rate of information transmission in bits/sec. can be calculated in these cases, the span of absolute judgement still constitutes evidence of the limited capacity of the human communication channel to transmit information.

Miller (1956 a) reports that when the simplest stimuli were varied along a single dimension, S's were able to identify accurately from five to 15 alternatives at the most, i.e. their capacity to discriminate ranged from two to four bits/judgement. See, for example, figure 6a.

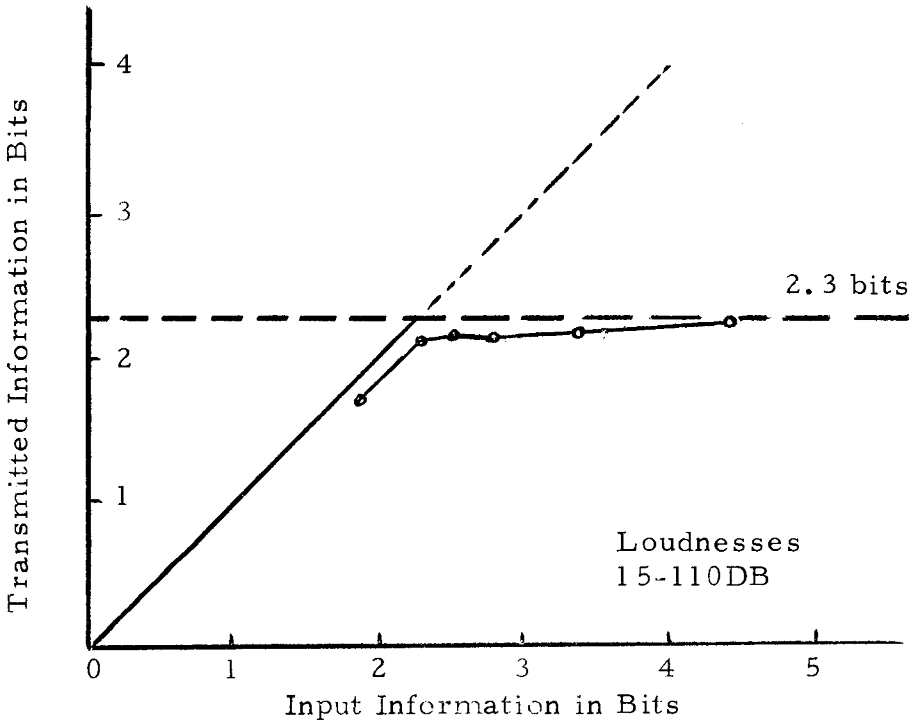



Figure 6a. Data from Garner (1953) on the channel capacity for absolute judgements of auditory loudness (Cited in: Miller 1956b).

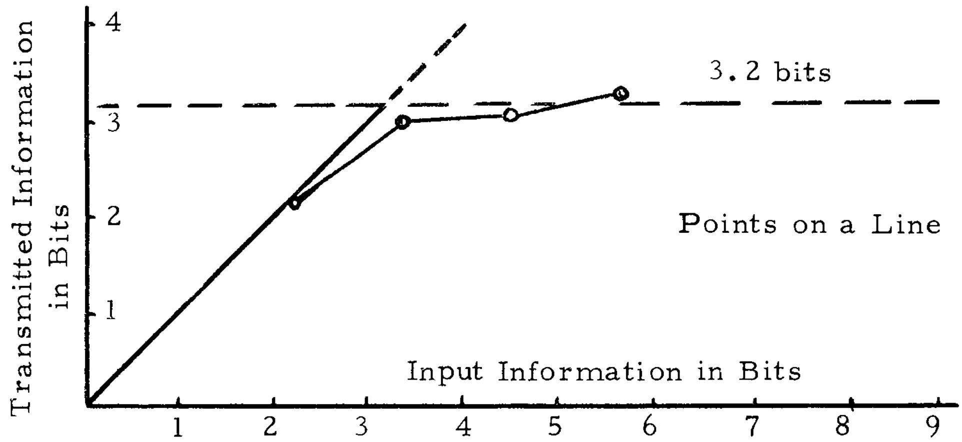



Figure 6b. Data from Hake and Garner (1951) on the channel capacity for absolute judgements of the position of a pointer in a linear interval (Cited in: Miller 1956b).

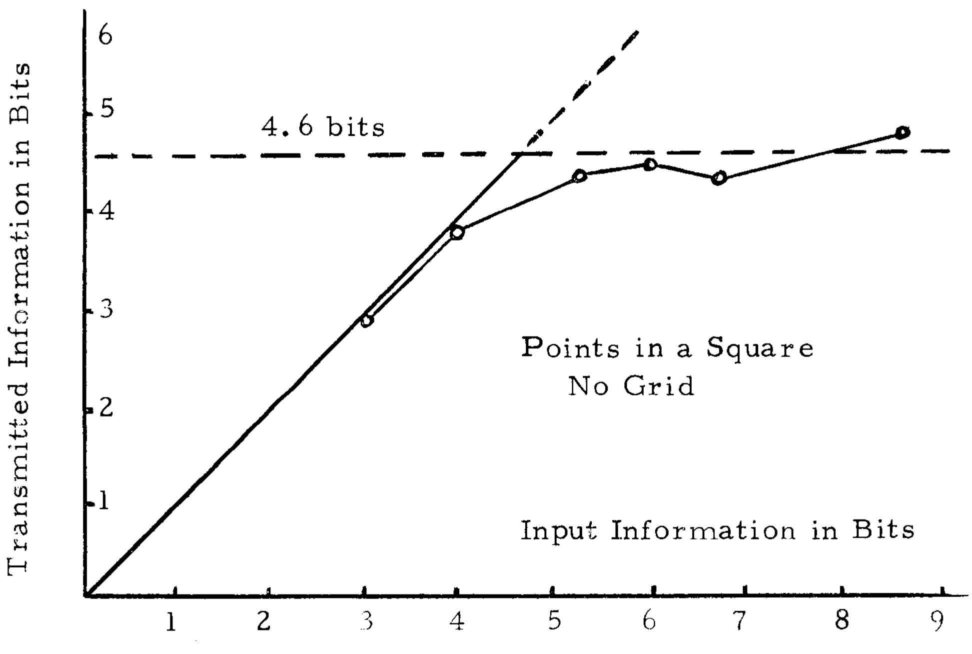



Figure 6c. Data from Klemmer and Frick (1953) on the channel capacity for absolute judgements of the position of a dot in a square. (Cited in: Miller 1956b).

Multidimensional Stimuli

In general, we acquire information about our environment along many dimensions at the same time i. e. we observe an event and receive a multidimensional stimulus from it. Miller (1956 b) cites evidence from experiments which have been conducted to assess the individual's informational capacity resulting from this type of inputs. Contrary to what could be expected, if the S's were asked to judge an event along two variables or dimensions, the information transmitted in the compound event is not the sum of the information transmitted in two single experiments. For example, Miller (1956 b) cites:

a. Hake and Garner (1951) who report the channel capacity for absolute judgements of the position of a pointer in a linear interval at about 3. 3 bits or equivalent to differentiating among ten alternate positions. See figure 6b.

b. Klemmer and Frick (1953) who report the channel capacity for absolute judgement of the position of a dot in a square as 4. 6 bits, equivalent to identifying accurately 24 positions. See figure 6c.

Miller (1956 b) makes the point that if the event of judging the position of a dot in a square were to be considered as the compound event of judging the position along two dimensions, a vertical and a horizontal one, the channel capacity would be given by 2 x 3. 3 bits = 6. 6 bits, equivalent to discriminating among about 100 alternatives. However, as stated above, this is not supported by experimental evidence. See figure 6c.

Miller (1956 b) cites other examples such as asking people to identify both the saltiness and the sweetness of solutions, or to ask listeners to judge both the loudness and the pitch of pure tones. When the dimensionality of the stimuli was increased to more than two, as in the case where listeners were asked to make a separate rating for each of six different dimensions of tones presented, (Pollack and Ficks, 1954) the information transmitted was in the order of 7.2 bits.

> "This is a large increase over the three bits/judgement obtained with unidimensional stimuli, but it represents a relative decrease to 1.2 bits/judgement/dimension. Apparently we are designed to operate best when we must make relatively crude judgements of several attributes imultaneously. We are not able to make extremely precise identifications along a single dimension" (Miller, 1956 a).

Our own observations in the present study lead us to believe that when we are faced with a multidimensional stimuli we give one dimension more importance than another and, therefore, weight discriminations along each dimension differently.

## Span of Immediate Memory

Experiments in span of immediate memory consist in determining the ability of individuals to retain several stimuli which are given in succession and repeating them after the whole sequence has been presented. The maximum number of digits which can be repeated without error is usually seven or eight. This number is called the 'span of immediate memory'.

Early experimental evidence suggested that the span of immediate memory did not behave like the span of absolute judgement and that the amount of information retained after one exposure (the information transmitted) was not a constant but increased as the amount of information per item in the input increased. Miller (1956 b) suggested the hypothesis that the span of immediate memory is limited by the 'number of items' presented and not by their informational content or entropy.

Crossman (1961) modified the simple information theory model in order to account for what appeared to Miller as a discrepancy. Crossman (1961) reasoned that immediate memory has "a measurable information capacity" and that the information theory model can make reasonable predictions when one postulates that the total information transmitted is of two kinds.

The first kind, 'selective source entropy', results from the uncertainty as to which of several alternatives will obtain or which one must be selected. It corresponds to the conventional source entropy defined before.

The second kind, 'order source entropy', results from the necessity of retaining the order in which items in the list must be processed or repeated. According to Crossman (1961):

> "The order source entropy measures the structural information needed to provide a framework for messages. . . . . In most of the systems such as telegraphy and television. . . . the order of events is tied to real time and no auxiliary information is needed to preserve it. . . . . If, however, source and destination have no common structure each input selection will need to be given a label for use at destination."

Given that the number of items in a list is s, there are s! possible permutations of the order, therefore:

Order source entropy = log s! bits/list

When an operator performs tasks in a given order he not only processes information resulting from the selection of alternatives (selective source entropy) but information is also involved to keep the alternatives in their proper relative order (order source entropy). The information process of 'ordering' to which reference was made in relation to the central mechanisms (see chapter II) is directly related to this type of uncertainty.

## A Word of Caution

The limitations of the human communication system which were described in the above sections can also be treated from the point of view of the function of the system which imposes the restriction. Thus, limitations in the discriminatory function involve the receptor system. Limits in the ability to recognize input stimuli may be attributed to constraints in the memory capacity. Limitations in the capability to respond may involve the capacity of the effector system to translate signals into muscular activity. Miller (1956 a) can be quoted as saying: "We must be careful to specify what segment of the total organism is involved in producing the responses before our statements of channel capacity are meaningful." On the other hand, all cases involve inputs and outputs, and involve in some way the three sub-systems i. e the receptor and the effector system as well as the central mechanisms (except in certain open-loop responses devoid of cognitive control as inferred in chapter II). It is, therefore, not unusual to assign the concept of 'channel capacity' to the system as a whole and specify information transmission rates as an attribute of the total human communication system.

# IV. INFORMATION PROCESSING RATES OBTAINED IN PRIOR STUDIES

Published applications of Information Theory to the information processing load of workers in industry are very few.

## Information Content Analysis (INCAN)

Ross (1960, 1961) developed formulas based on Information Theory to be used in work analysis. In what he called INCAN (for Information Content Analysis), Ross developed 12 factors which he believed could be isolated in the performance of a task. These 12 information factors are:

1. Total number or range and probability of occurrence (equivalent to expected entropy H)
2. Noise and equivocation
3. Subjective probability
4. Timing of perceptions
5. Discrimination of perceptions
6. Redundancy
7. Short term memory
8. S-R compatibility
9. Number of sense modalities
10. Psychomotor performance
11. Errors
12. Decision making

Formulation of these factors can also be found in Nadler (1963, p. 380).

Ross (1960, p. 117) postulated the hypothesis that:

> ". . . . . a useful measure of human task difficulty is achieved if the information contained in all perceptual dimensions of the task is summed on the basis of the computed value of each of the information factors found in the task."

In order to obtain the amount of information in a job, he studied the tasks in a complete operation cycle. He first identified the tasks considered "devoid of any mental effort" i. e. those in which none of the listed factors could be found (Ross, 1960, p. 135). He then calculated the expected amount of information H (entropy) based on the number of tasks void of mental effort and added the value of the other 12 factors representing mental load, if applicable. As Ross (1960, p. 135) explains:

> "While this may be somewhat arbitrary, it does provide a means of obtaining a quantitative value, and has some basis because of the human ability to remember and act upon stimuli in chunks."

Ross' idea of searching for a rate of performance measure based on the amount of information processed was sound. However, in his study he did not go to the extent of calculating information processing rates. Based on data found in his dissertation, the information processing rates of two operations, for which information content and standard times were given, were calculated. The information processing rate of the can-feeder machine operation is 0.22 bits/sec. and that of the wax-wrapping machine operation is 0.084 bits/sec. They are both shown in table 3.

The following remarks regarding Ross' results and approach can be made:

i) The number of tasks of a job is an incorrect basis for calculating the range, information content or difficulty of the job. Ross (1960, p. 135) recognized his calculation of entropy based on the number of tasks to be "somewhat arbitrary". As has already been made evident in the present study, the amount of information measure or entropy should be based on the uncertainty or variability resulting from the number of alternatives present. The information processing rates based on Ross' data are not really meaningful and are only given in table 3 for comparison purposes.

ii) Ross' "Experimental Results and Analytical Determinations" (1960, p. 120) can hardly be given such a name because, in actual fact, he used experimental data accumulated by Crossman, Leonard and Poulton.

iii) The industrial tasks chosen by Ross to justify his model may be "typical factory jobs". However, they are much too simple to represent the type of work which skilled operators in industry perform today. Furthermore, Ross took jobs for which standards had already been calculated and to which he applied his own information factors. He did not go further to assess the context in which the jobs were performed or the relationship of the job to a process. As will be shown later, the present study takes a more empirical approach and actual industrial processes are studied on location in the plants.

iv) The information factors calculated in Ross' model and given justification in his INCAN model are too elaborate to be used in practice in the analysis of industrial jobs.

In summary, Ross' approach provided a useful stepping stone for further research in the analysis of the informational content of work. His main contribution is to have consolidated the knowledge of the applications of Information Theory to psychology.

Table 3. Information processing rates of industrial operations obtained or calculated from data found in prior studies.

| | Rates in bits/sec. |
|---|---|
| Empty can feeder machine operator[1] | 0.22 |
| Wax wrapping machine operator[1] | 0.084 |
| Pulp mill operator[2] | 0.52 |
| Bleach plant operator[2] | 0.59 |
| Stock preparation operator[2] | 0.61 |
| TV receiver assembly worker[3] | 3.5 |
| Communication between pilot and control tower[4] | 2.0 |

[1]Calculated from data cited in Ross (1960, p. 175-179).

[2]Calculated from data cited in Nadler & Seidel (1966).

[3]Cited in Arthur D. Little (1965, p. 64).

[4]Cited in Fritz, E. W. W. and Grier, Jr., G. (1951).

Seidel (1963) and Nadler and Seidel (1966) developed a method of measuring the mental task difficulty of jobs performed by operators monitoring a continuous process. They first distinguished between two types of jobs:

i) Jobs that require the operator to monitor information which is given in the form of a continuous signal. The operators control critical variables which are recorded in the form of a continuous waveform on an instrument panel. To calculate the information content of these tasks, Nadler and Seidel used Hartley's measure of information which considers continuous process signals.

ii) Jobs other than monitoring continuous signals are considered by Nadler and Seidel (1966) as "stationary events in time" or "intermittent processes where well defined repetitive sub-tasks are performed with definite end points." Performing the steps of an operation on a machine, making a test, filling out records can be considered jobs in this category.

The methods used by Nadler and Seidel to calculate the information content of the 'stationary events', the second type above, were based on Ross' approach. These methods were found lacking as described in the previous section and will, therefore, not be considered further. However, we will consider the methods used by Nadler and Seidel to measure information content of jobs involving continuous auditing of signals.

Measuring the Entropy of Continuous Process Signals

According to Nadler and Seidel (1966):

> "When an operator reads a chart he assumes a range of variation to establish a high and low point. After focussing on the high and low point the operator must make "bit" decisions to determine where the analog signal is located in the range of variations."

Thus the information content of the wave record is calculated according to the formula:

$$I = n \log N$$

where I is the amount of information in bits per unit of time

n = the number of consecutive cycles per unit of time. To calculate n, the number of points of inflection of the waveform are counted and multiplied by two on the assumption that an audit by the operator is required when a change in the process occurs. Changes are identified with the points of inflection. Two points of inflection occur for each cycle.

N = the number of graduations or levels between two inflection points is a measure of the sensitivity with which the audit is required.

The above formula is due to Hartley (1928) and is similar to the expected amount of information measure presented in chapter III for discrete signals.

The application of the above formula to the waveform in figure 7 yields an average information processing rate of 0.45 bits/sec. as N = 8 levels and n = 9 for 60 seconds.

The above method of calculating the entropy displayed by a continuous signal will be used in chapter VI to compare the mental content of an operator's job of controlling a process with and without a computer.

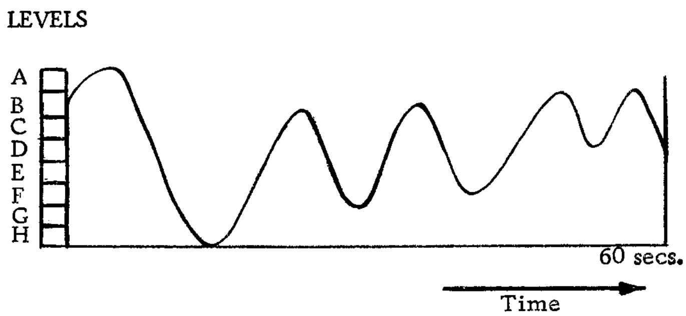



Figure 7. Illustration of Hartley's wave measurement.
(Cited in: Nadler and Seidel, 1966)

Nadler and Seidel (1966) report the results of the application of the above method to the evaluation of the information content of three process operator jobs.

Table 3 includes the average information processing rates calculated from Nadler and Seidel's data for three process control operators normally found in a pulp and paper industry. These rates range between 0. 52 to 0. 61 bits/sec. It is felt that these rates are fairly good representations of information processing rates in industrial operations of this type as will be confirmed by our data on very similar operations. Again we question validity of calculating the entropy of the so-called discrete or stationary events based on the probability of occurrence of the sub-tasks as suggested by Ross. However, in the three operations chosen by Nadler and Seidel, this type of work only occupied the worker about 25% of the time (approximately 15 minutes of each hour) and, therefore, the figures obtained for the total information content of the operations are probably underestimated.

## Other Previously Published Information Processing Rates

Table 3 also shows figures on information content of a TV Receiver Assembly operation and the communications between pilot and control tower. The latter were obtained in a study performed by Felton, Fritz and Grier (1951), also reported in Fritz and Grier (1955). The figure of 2. 0 bits/sec. is thought to be representative of the type of mental effort involved in the work of pilot and tower controller and represents one of the earlier examples of information processing rates obtained under conditions of normal work.

The figure of 3.5 bits/sec. obtained in a study carried out by Arthur D. Little, Inc. (1965) is only an estimate and has no empirical justification. However, it was calculated to find areas of industrial operations which offer large potential for automation. It is a thesis of Arthur D. Little, Inc.'s study that the potential for automation can be measured in terms of the relative amount of information processed by people in handling the variability of the process, the variety of raw materials, or products, etc. Variability is reduced by standardization and mechanization (removing variability in the process) or by leaving variability in the process but combatting it with automation i. e. by introducing sophisticated sensing, computing and control devices (Arthur D. Little, 1965, p. 12). The measurement of automation potential is, therefore, based on identifying large areas where variability exists. The authors of the Arthur D. Little, Inc.'s study (1965, p. 64) lament the scarcity of data on the information processing rates of human beings in an industrial context. The present study was motivated in part to fill this gap and to provide meaningful average information processing rates of operators found at work in industry.

# V. THE MODEL OF INTEGRATIVE BEHAVIOR

## Integration

The complexity of the mental processes involved in any response depends on what is called the "levels of integration in behavior" (Sanford, 1965, p. 95). Reflexes which are simple and unconscious processes are considered simple integrations. Walking and breathing, although they are still relatively automatic, are more elaborate than reflexes because they require

> "the integration of stimuli in sequences, and responses in patterns. . . . . At a still more complex level, there are integrations that may involve minutes or hours or days or months of integrative activity between the receptor action and the effector action. Such integrations involve the storage of past input, the interpretive rearrangement of things, a 'mulling over' of various inputs, and in the end, the eventual adaptive behavior" (Sanford, 1965, p. 96).

The mental load imposed upon an individual can be said to be related to the type of integrative behavior which the performance of a task demands of him. The mental load is measurable in units of amounts of information transmitted, if the types of information processes and the levels of integrative behavior demanded by the task can be determined. We now turn to the description of a model which will permit such a determination.

In this model, information processes will refer to the functions defined in chapter II as taking place in the receptor system, the effector system and the central mechanisms. The information processes taking place during the performance of a task are given the name of mental therbligs. A similar concept was used by Holmes (1945, p. 276 & p. 286). Mental therbligs are counterparts of the therbligs traditionally used in work measurement which are "motion elements." (Barnes, 1963, p. 136). A list of mental therbligs according to the major information processing system to which they can be related is given below:

| Receptor System | Central Mechanisms | Effector System |
|---|---|---|
| Sensing | Concept formation | Coordinating responses: |
| Decoding | Goal setting | -Symbolic responses |
| Recognizing | Controlling | |
| Judging & Estimating | Calculating | -Non-symbolic responses |
| | Problem solving | |
| | Decision-making | |
| | Unitizing | |
| | Relating | |
| | Ordering | |

It is evident that the above mental therbligs could be broken down into 'fine detail therbligs'. For instance, Nadler shows 21 different types of 'recognitions' in a model of human psychomotor-input-output activity (1963, p. 378-379). Such detailed breakdown is not required in our model.

## Levels of Integration

The level of integration in behavior or the level of integrative activity will express the complexity of the information and mental processes involved in the performance of a task.

The level of integration will depend on:

a. The components of the human communication system which are involved i.e. whether the receptor, the effector system and the central mechanisms are all involved.

b. The number, type and intricacy of the mental therbligs used.

c. The amount of training, skill and/or knowledge which is required to perform the therbligs. In certain cases the degree of S-R compatibility can be a determinant of the level used.

Mental therbligs can be classified according to four levels of integration as shown in table 4.

Table 4. Mental therbligs classified according to the level of integration in which they take place.

| | Receptor system | Central mechanisms | Effector system |
|---|---|---|---|
| First Level of Integration | Sensing<br>Perceiving:<br>Decoding<br>Recognizing<br>Judging & Estimating | | Coordinating non-symbolic outputs |
| Second level of Integration | | Concept formation<br>Goal setting<br>Controlling<br>Calculating | Coordinating symbolic responses |
| Third level of Integration | | Problem solving<br>Decision-making<br>Unitizing<br>Relating | |
| Fourth level of Integration | | Creating | |
| Special category | | Ordering (keeping track of serial order of tasks) | |

Amount of information processed or transmitted will be the average amount of information, in the Information Theory sense, which is required to reduce the entropy in bits or prevailing uncertainty to zero as defined in chapter III.

New information measures will be defined to reflect differences in the mental therbligs and in their level of integration. The new unit will be known as the _dubit_, the _tribit_ and the _quabit_. The new units can all be converted into the number of equivalent _bits_.

## Amount of Information Processed at First Level of Integration

Given the levels of integration in behavior defined in the preceding section, it is reasonable to assume that the amount of information processed at each level is different. A higher level of integration implies more complexity of mental function and, hence, a higher rate of information processing. At the first level of integration, only the receptor and the effector systems are involved. A sequential or overlearned task which does not require cognitive control (from the central mechanisms) may be categorized as pertaining to the first level of integration. An example of such task in industry is a job which requires the operator to recognize, let us say, four different inputs which result in four different alternative outputs or responses. In each cycle of the operation, as the operator scans the incoming material, the amount of information which the operator must process to identify one of four alternatives (i. e. to resolve the uncertainty or entropy) is:

$$H = - \sum^{4} {}^{1}/_{4} \log 4 = \log 4 = 2 \text{ bits/cycle.}$$

This assumes, of course, that all alternatives are equally likely and that no errors are committed. In order to chose one of four alternative output actions, the same amount of information or entropy must be processed in the effector system. Because the above example assumes that the operator is highly proficient in the task, no decision-making (a mental therblig defined as involving a high degree of integrating behavior) is involved.

In general, behavior at the first level of integration will be said to involve log N bits/cycle in the receptor system and log N bits/cycle in the effector system. The number of alternatives in the inputs does not have to be the same as in the outputs. In practice, they may be different.

## Amount of Information Processed at Second Level of Integration: The Dubit

At the second level of integration the central mechanisms become involved. Processes take place in the effector and in the receptor system. In addition, mental therbligs such as goal setting, concept formation, computing, controlling, etc. are involved. To account for the higher degree of complexity in the information processing, a new information measure is defined where the expected amount of information in a message involving N alternatives is equal to

$$H^{(2)} = - \sum_{i=1}^{N} p_i \log (p_i)^2 \text{ in bits.}$$

If the alternatives can be assumed equi-probable, $p_i = \frac{1}{N}$

$$H^{(2)} = - N \cdot \frac{1}{N} \cdot \log\left(\frac{1}{N}\right)^2 = \log (N)^2 \text{ in bits.}$$

The number of alternatives has been raised to the second power which is equivalent to multiplying the conventional measure of entropy by a factor of two, the implication being that twice as much information is being processed in the central mechanism at the second level than has been introduced at the first level.

To emphasize that the new entropy measure involves twice as much information as the entropy used at the first level of integration, a new unit is defined, as follows:

The entropy measure at the second level, $H^{(2)}$

$H^{(2)} = \log (N)^2$ in bits/cycle

or

$H^{(2)} = \log N$ in dubits/cycle.

The dubit (from double-bit) is equivalent to 2 bits.

The use of dubits obviates the necessity for raising the number of alternatives to the second power. Given that a source involves N alternatives and that the mental therblig takes place at the second level of integration, the amount of information transmitted will be log N dubits, which can be readily converted into bits if need be.

## Amount of Information Processed at Third and Fourth Level of Integration: The Tribit and the Quabit

As the level of integration grows higher, the complexity of the information processed increases. To reflect this fact, information measures are defined for mental therbligs taking place in the third and fourth level of integration in behavior.

The expected amount of information transmitted for a third level mental therblig is:

$$H^{(3)} = -\sum_{i=1}^{N} p_i \log (p_i)^3 \text{ in bits.}$$

If $p_i = \frac{1}{N}$, then $H^{(3)} = - N \cdot \frac{1}{N} \cdot \log\left(\frac{1}{N}\right)^3$ in bits/cycle

or

$$H^{(3)} = \log (N)^3 \text{ in bits/cycle.}$$

A new unit of entropy is defined according to which:

$$H^{(3)} = \log N \text{ in tribits/cycle.}$$

The tribit (from triple-bit) is equivalent to three bits. Given the number of alternatives of a source N, if the mental therblig which operates on this information takes place at the third level of integration, the entropy of the source can be expressed directly as log N in tribits/cycle.

The above definition implies that the amount of information processed at the third level of integration is three times as great as at the first level or that, considering the same information is involved, it implies that due to the complexity of the mental task it is 'fedback' through the central mechanisms three times before a response is decided upon. The concept of repeated processing of information in the central mechanisms is in keeping with the definition of the concept of integration introduced earlier

> "integrations involve the storage of past input, interpretive rearrangement of things, a 'mulling over' of various inputs, and, in the end, the eventual adaptive behavior" (Sanford, 1965, p. 96).

The performance of a task in the industrial context usually involves several observations from the environment. Thus the concept of 'mulling over' more than one input referred to by Sanford is introduced in the model by considering bits of information transmitted from several sources. The operator may observe two or three variables the entropy of which will be log $N_1$, log $N_2$, log $N_3$ bits/cycle respectively. In turn, these inputs will be processed through the central mechanism where they will be used in the same or in different mental therbligs.

The fourth level of integration has only one mental therblig, creating. The expected amount of information transmitted when performing this information function will be defined by the measure of entropy $H^{(4)}$, such that:

$$H^{(4)} = - N \frac{1}{N} \log \left(\frac{1}{N}\right)^4 = \log (N)^4 \text{ bits/cycle.}$$

A new unit of entropy at the fourth level of integration is defined to be known as the quabit and according to which:

$$H^{(4)} = \log N \text{ in quabits/cycle.}$$

1 quabit = 4 bits.

In this case, the higher level of integrative activity is reflected in a measure of entropy where the amount of information is four times the value which would be obtained with the conventional measure. As explained previously, this can be interpreted as processing the same information four times through the central mechanisms to obtain the desired results.

It is evident that the weights chosen to define the new units of amounts of information are arbitrary. There is no empirical justification for the particular values taken. Creating, for instance, may involve much more than four times the information processed for perceiving. However, it is felt that the scheme of new units is a useful description of an otherwise complex situation. While other weights may be thought more justified, the new units help to characterize the process and to provide comparison measures among the mental therbligs. The method of weighing the measures of entropy is analogous to the use of dimensionally consistent value functions, a subject which is discussed at the end of this chapter. Figure 8 shows the amount of information of all mental therbligs and their corresponding level of integration. Research describing quantification of the levels of information processing and of the complexity of integration is described in Schroder, Driver and Struefert (1967, p. 14, 179).

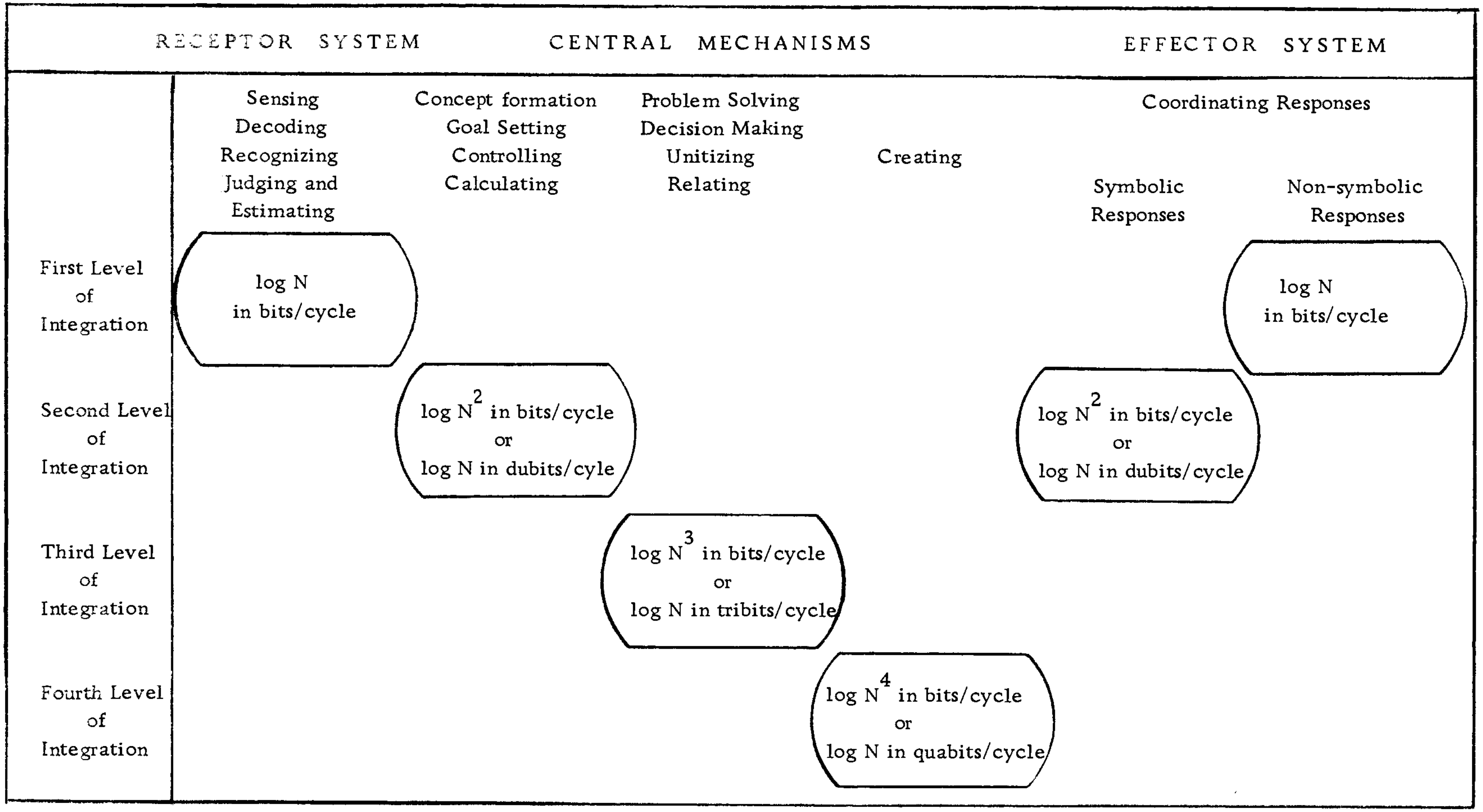



Figure 8. Amount of information processed by mental therbligs at four levels of integration.

## Path of Integrative Behavior and Related Path of Information Transmission

It is important to stress that integrative behavior means that information received in the receptor system is organized, unified and interpreted to obtain what may be called a 'rational' response, and that the integration takes place across the human communication system involving the three sub-systems. Thus, given that an amount of information log N/cycle is received in the receptor system, it will be transmitted to the central mechanisms and the process of integration will involve interaction between the two systems. In the central mechanisms, if a mental therblig in the second level of integration takes place, the input stimuli log N/cycle will generate an amount of information processing equal to log (N) dubits/cycle. Figures 9a and 9b show the path of integrative behavior and of information transmission from receptor to central mechanisms to effector system. It shows that integrative behavior occurs at different levels in each system depending on the mental therbligs which are involved. In figure 9 (a), the task to be performed requires perceptual response (a mental therblig at first level of integration), a mental therblig at the second level and finally a non-symbolic response of the first level. The amount of information processed/cycle is given by:

| Information in Receptor System, 1st Level Mental Therblig | | Information in Central Mechanism 2nd Level Mental Therblig | | Information in Effector System, 1st Level Mental Therblig | |
|---|---|---|---|---|---|
| $\log N$ in bits/cycle | + | $\log N$ in dubits/cycle | + | $\log N$ in bits/cycle | = |
| $\log N$ | + | $\log N^2$ | + | $\log N$ | = |
| $\log N$ | + | $2(\log N)$ | + | $\log N$ | = |

4 log N bits/cycle.

Figure 9 (b) shows the path of integrative behavior and of information transmission for a task which involves scanning (mental therblig, 1st level), controlling two different variables (controlling - a mental therblig, 2nd level), and coordinating a symbolic response (mental therblig, 2nd level). The total amount of information transmitted is:

| Information in Receptor System, 1st Level Mental Therblig | | Information in Central Mechanism 2nd Level Mental Therblig (two variables) | | Information in Effector System, 1st Level Mental Therblig | |
|---|---|---|---|---|---|
| $\log N$ in bits/cycle | + | $2 \times \log N$ in dubits/cycle | + | $\log N$ in dubits/cycle | = |
| $\log N$ | + | $2 \times \log N^2$ | + | $\log N^2$ | = |
| $\log N$ | + | $2 \times 2(\log N)$ | + | $2(\log N)$ | = |

7 log N bits/cycle.

We note that the number of alternatives N dealt with in the central mechanisms is the same as the number of input stimuli. However, this number may differ from the number of output responses effected.

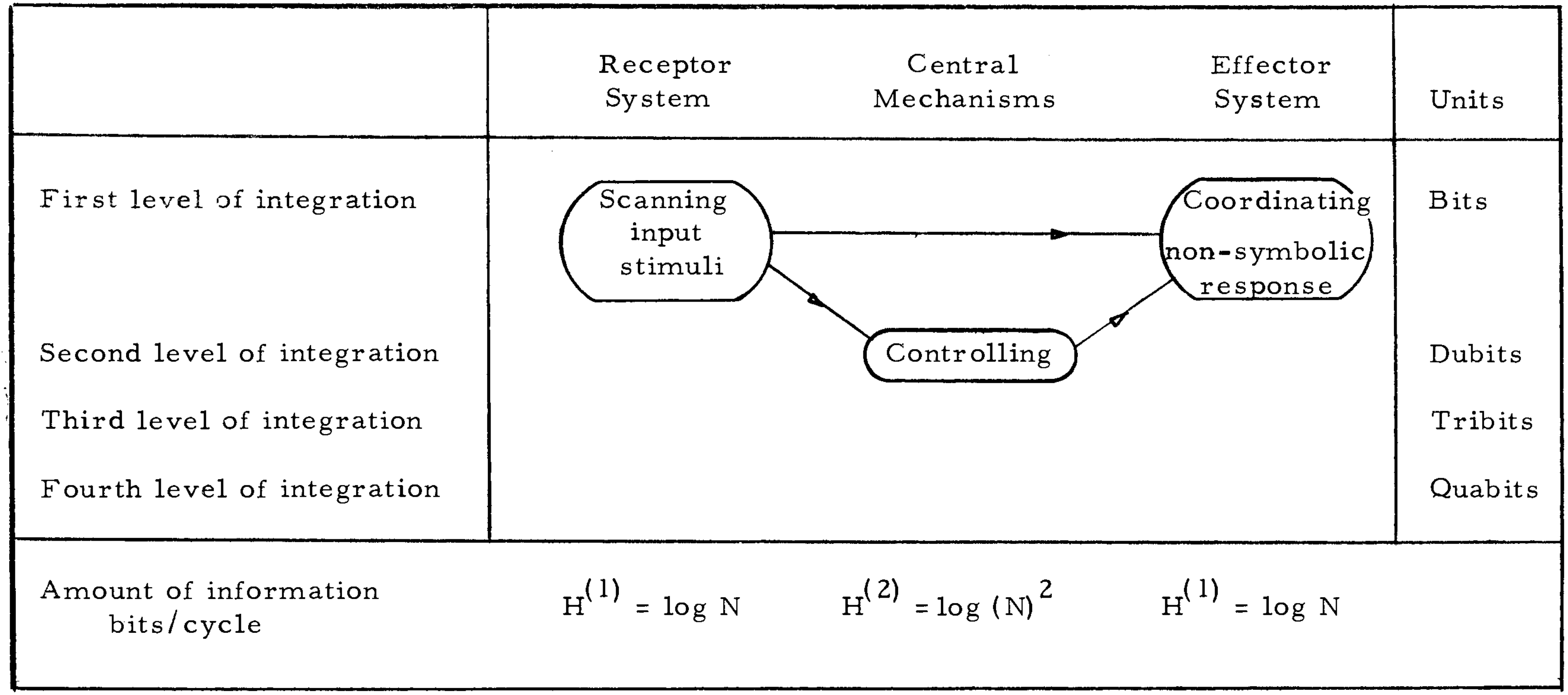



Figure 9a. Path of integrative behavior and information processing flow for a task involving coordination of non-symbolic responses.

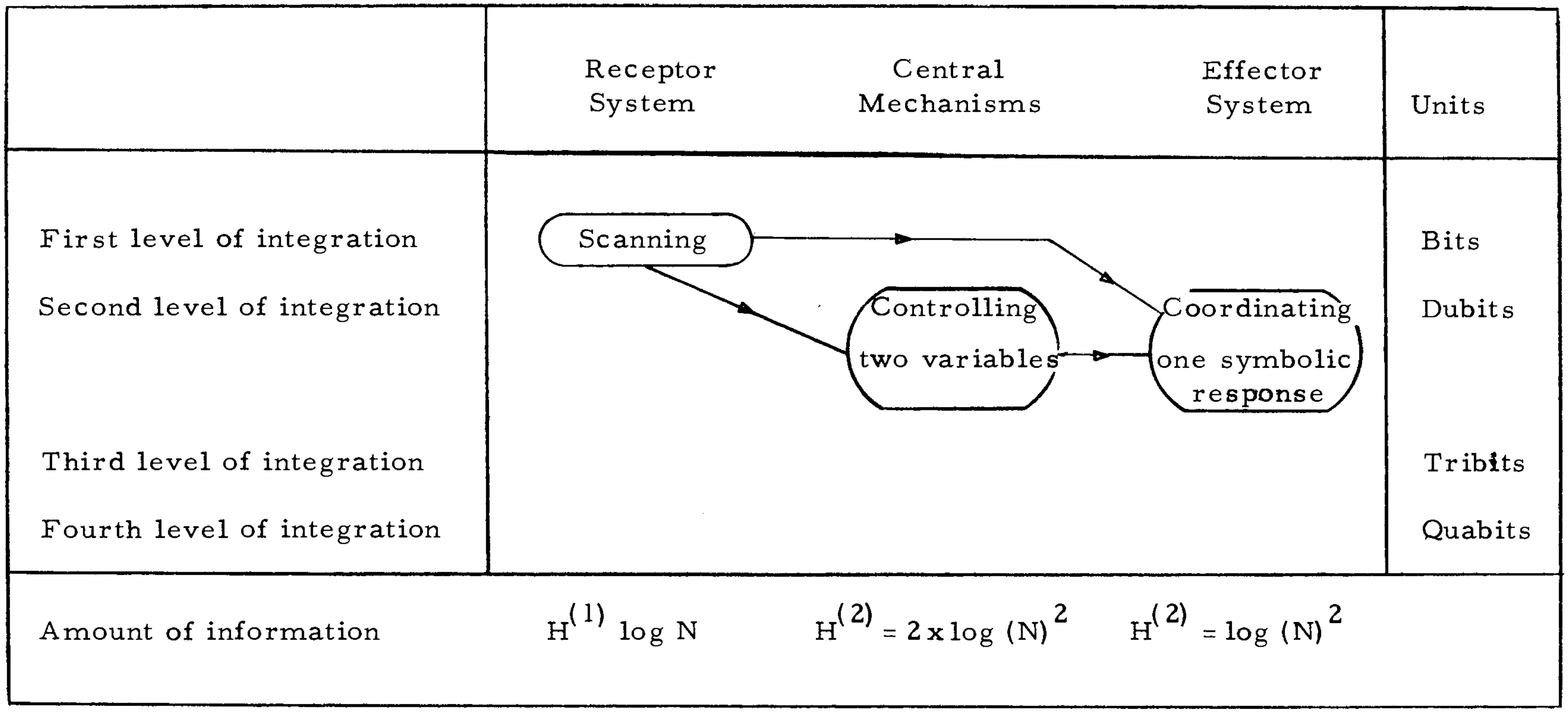



Figure 9b. Path of integrative behavior and information processing flow for a task involving symbolic responses.

## The Mental Content of Work

The mental content of a task will be measured in terms of the total amount of information of all mental therbligs in the task. Once the mental therbligs required in the task and their corresponding level of integration are identified, the amount of information processed for each therblig can be calculated in terms of the entropy measures $H^{(1)}$, $H^{(2)}$, $H^{(3)}$, and $H^{(4)}$. Usually industrial operations involve repeated sequences. Therefore, the total amount of information per cycle or for one repetition of the sequence can be obtained. Given the number of cycles/unit of time n, an average rate of information transmission I can be estimated.

$$H = H^{(1)} + H^{(2)} + H^{(3)} + H^{(4)} \text{ in bits/cycle}$$

$$I = n\left(H^{(1)} + H^{(2)} + H^{(3)} + H^{(4)}\right) \text{ in bits/unit of time}$$

Figure 10 shows how the average information processing rate was calculated for an operation which involves several tasks. For this operation, several instruments or variables are scanned. The mental therblig 'scanning' at the first level of integration involves identifying the position of instrument pointers. In the first case, five readings involving 65 alternatives were required for a total entropy of 30.1 bits/cycle. In the second type of scanning five readings involving 45 alternatives for an entropy of 27.1 bits/cycle and so on. Total information transmitted in the effector system = 83.9 bits/cycle.

At the second level of integration, the same input information is used for controlling the trend of variables. It is, therefore, easy to calculate the amount of information processed in this second level therblig. It is numerically identical to the information transmitted at the first level but will be expressed in <u>dubits/cycle</u> and equal to 83. 9 dubits or 83. 9 x 2 = 167. 8 bits/cycle.

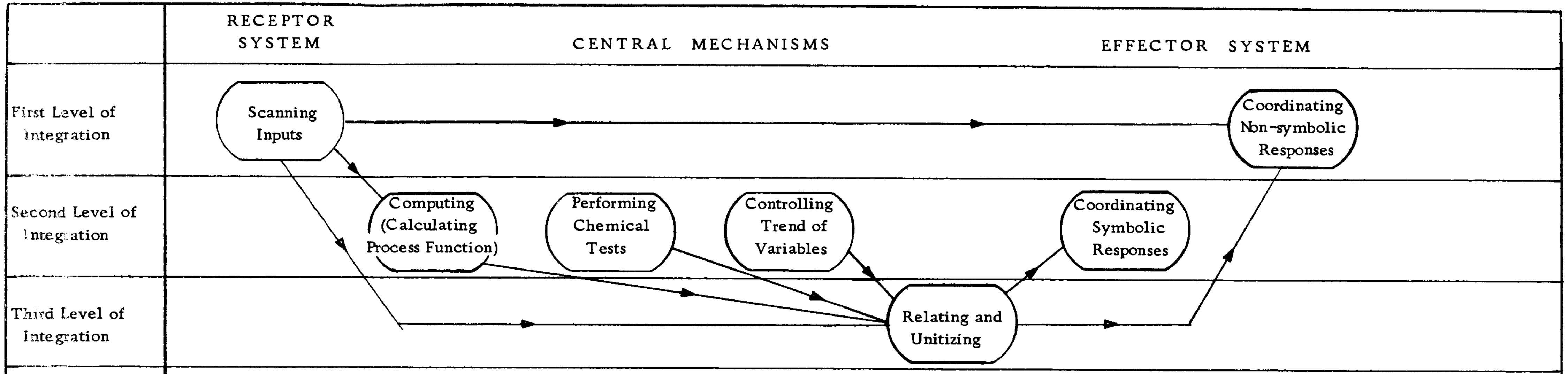
In addition to controlling the variables, another therblig is performed at the second level of integration, namely 'computing' which accounts for an additional 30. 1 dubits/cycle and performing chemical tests (a mental therblig associated with calculating) which accounts for another 90. 3 dubits/cycle.

At the third level of integration, the functions of relating and unitizing involve mental therbligs with entropies $H^{(3)}$. In the example shown, the same basic information is transmitted from the receptor system to the central mechanisms. It is an assumption of this model that in order for relating and unitizing to take place, the information must first be recognized at the first level of integration through the sensing and perceptual mechanisms.

The amount of information processed at the third level is expressed in tribits/cycle and equal to 83. 9 tribits/c. which is equivalent to 252 bits/c.

Figure 10 also shows the paths of integrative behavior and of information transmission which, of course, may be several. As a result of the relating and unitizing functions, decision on appropriate responses will take place. This is shown in the diagram as occurring in both the first and second level of integration because non-symbolic and symbolic responses are performed. The corresponding amount of information is calculated and shown in the proper column.

The total amount of information for all therbligs in the operation is summed to obtain 816 bits/cycle. Given that 2.1 operation cycles are performed in one hour, the total information transmitted per hour is of 1714 bits. On the basis of this total, an average rate of information processing in bits per second is calculated. The rate of 0.48 bits/sec. represents the measure of mental content that can be compared to other measures calculated for other operations with the same model. The measures developed here differ from the ones based on the model which considers the information transmitted as that portion of the total information which is common to the input and to the output (Shannon and Weaver, 1949, p. 70). That model requires that the marginal probabilities of the stimuli and their corresponding responses be known and tabulated.




| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Amount of Information | 5 log 65 = 30.1<br>5 log 45 = 27.1<br>4 log 20 = 17.3<br>log 70 = 6.1<br>log 10 = 3.3 | 5 log 65 = 30.1 | | 5 log 65 = 30.1<br>5 log 45 = 27.1<br>4 log 20 = 17.3<br>log 70 = 6.1<br>log 10 = 3.3 | 5 log 65 = 30.1<br>5 log 45 = 27.1<br>4 log 20 = 17.3<br>log 70 = 6.1<br>log 10 = 3.3 | log 6 = 2.58<br>log 50 = 5.64 | 5 log 90 = 32.5<br>18 log 2 = 18<br>log 7 = 2.8<br>log 3 = 1.6 | |
| tribits/cycle | | | | | 83.9 | | | |
| dubits/cycle | | 30.1 | 90.3[a] | 83.9 | | 8.22 | | Total bits/cycle |
| bits/cycle | 83.9 | 60.2 | 180.6 | 167.8 | 251.7 | 16.4 | 54.9 | 816 |

Total Information transmitted per cycle = 816 bits
Total information transmitted per hour = 1714 bits

Number of cycles/hour = 2.1
Average information processing rate bits/sec. = 0.48

[a] Results obtained from a separate calculation.

Figure 10. Path of integrative behavior and information preocessing flow for a hypothetical task involving therbligs at three levels of integration.

## Simplification of the Model

In some cases when detailed calculation of the exact information processed at each level is not required, a rough estimate of the total amount of information processed can be obtained as follows:

a. Identify the mental therbligs performed during each task of the operation with their corresponding level of integration.

b. Determine the entropy of the input stimuli to the operation. If it can be assumed that the same information is used for all mental therbligs in the communication system, the total information processed will be given by:

log N in bits/cycle x number of therbligs at first level
+ log N in dubits/cycle x number of mental therbligs at 2nd level
+ log N in tribits/cycle x number of mental therbligs at 3rd level
+ log N in quabits/cycle x number of mental therbligs at 4th level.

In the example examined in figure 10 the total entropy of the input stimuli was equal to 83.9 bits/cycle say 84 bits/cycle.

There are two (2) mental therbligs at first level of integration (scanning of inputs and coordinating non-symbolic responses), three (3) therbligs at second level (computing, controlling and coordinating symbolic responses) and only one (1) therblig at third level (relating). In this example, no therbligs at fourth level exist.

The total amount of information processed can be estimated as:

| | | | | |
|---|---|---|---|---|
| (log N) x 2 in bits/cycle information at first level | + | (log N) x 3 in dubits/cycle information at 2nd level | + | (log N) x 1 = in tribits/cycle information at 3rd level. |
| (log N) x 2 | + | 2 (log N) x 3 | + | 3 (log N) x 1 = |

11 x (log N) bits/cycle =

11 x 84 = 924 bits/cycle where log N = 84 bits.

The estimate of total information transmitted per cycle of 924 bits is within 15 percent of the estimate obtained by considering the entropy of each therblig in detail. The simplified model was found useful in those cases where a detailed analysis of each function was not warranted.

## The Justification for Weighing the Measures of Entropy

That the values of the average information processing rates are comparable and that they can be used as relative measures of mental content of different jobs can be proven by dimensional analysis.

When the entropy of each mental therblig occurring at a different integration level is added together, the total information processed is equal to

$$H = \log N_i + \log (N_j)^2 + \log (N_k)^3 + \log (N_m)^4$$

where $N_i$, $N_j$, $N_k$ and $N_m$ can be said to represent the set of available alternatives in each therblig or can also be interpreted as probabilities. In this case we consider an alternative with a probability of $N_i$ as if it were selected from a set of $\frac{1}{N_i}$ alternatives. An alternative with a probability of $N_j$ is considered as being selected from a set of $1/N_j$ alternatives, etc. (Miller, 1953).

If the antilogarithm of the total entropy measure were to be taken, the resulting expression represents the joint probability of all the events - the probabilities of the independent events are multiplied.

$$P = \log^{-1} H = (N_i)\,(N_j)^2\,(N_k)^3\,(N_m)^4$$

The exponents attached to $N_i$, $N_j$, $N_k$ and $N_m$ are constants independent of $N_i$, $N_j$, $N_k$ and $N_m$ and represent measures of significance, importance or weight given to the entropy $H^{(1)}$, $H^{(2)}$, $H^{(3)}$ and $H^{(4)}$ found at each level of integration.

It is important to emphasize that the function P has the characteristics of the value function designed by Bridgman (1922) which can be used to compare systems along several heterogeneous dimensions,as long as they are dimensionally consistent. A recent restatement of this approach was made by Epstein (1957). Thus, two functions $P_1 = P_1\,(N_i, N_j, N_k, N_m)$ and $P_2 = P_2\,(N_a, N_b, N_c, N_d)$ are comparable in spite of measuring the information content of dissimilar operations.

## Summary of the Model

1. The human communication system consists of three sub-systems: The receptor and the effector sub-systems and the central mechanisms.

2. An operation consists of several tasks that involve physical as well as mental processes.

3. Mental processes can be identified with the information functions which take place in the communication system. The elementary functions are called mental therbligs.

4. The sensing of input stimuli in the system gives rise to processes of different complexity which depend on what is called levels of integration in behavior. For the purposes of this model, four levels are defined.

5. Mental therbligs can be classified according to their complexity in the four levels of integration defined above.

6. The amount of information processed at each level of integration can be calculated on the basis of new measures of entropy which reflect the increased complexity of the processes.

7. The performance of a task involves mental therbligs at all levels of integration: The amount of information transmitted is the sum total of the entropy of each therblig in the task.

8. The mental content of an operation and its related tasks can be calculated and expressed in terms of an average information processing rate in bits/sec.

9. The mental content of work in industrial operations can be compared by measuring the average information processing rates.

# VI. FIELD OBSERVATIONS AND RESULTS

It is a distinct feature of this study to attempt a comparison of the mental content of work at various levels of technology. In order to find the impact of technology on manpower requirements Crossman, Laner, Caplan & Davis (1966) studied the interaction between skill level and technological level for two or more processes which could be matched in terms of relevant characteristics such as raw materials and finished product. For example, Crossman et al compared machine-aided hand processing of checks and deposit slips (old technology) versus electronic data processing (new technology). They also compared, among others, the process of annealing steel strip by batch annealing of coiled strip under portable furnaces (old) versus the continuous annealing of endless uncoiled strip through stationary furnaces (new).

A similar approach is used in this study: The mental content of work of operators involved in the same process found at two or more levels of technology were sought and compared. No attempt was made to obtain comparative skill distributions. Only the work of the operators which best characterize the changes were analyzed.

All of the processes studied were located in the state of Oregon and were taken from the forest products industry which embraces the production of lumber, pulp and paper. The choice of this industry has no particular significance except that it is the most important in the area. Similar studies such as Crossman et al's (1966) do not enjoy the vertical integration which is derived from concentrating all comparisons in a single industry (see Table 5).

Table 5. Processes and operations studied.

| | | |
|---|---|---|
| 1. The sorting of lumber | Old | Manual sorting |
| | New | Sorting with mechanical sorter |
| 2. The grading of lumber | Old | Grading without stress grading machine |
| | New | Grading with stress grading machine |
| 3. The production of groundwood pulp | Old | Pulping logs in a stone grinder |
| | New | Pulping chips in a disk refiner. |
| 4. The production of sulfate (kraft) pulp | Old | Cooking pulp in batch digester |
| | New | a) Cooking of pulp in a continuous digester without process control computer<br>b) Cooking pulp in a continuous digester with process control computer |

## 1. The Sorting of Lumber

Clapham and Lambe (1961, 1963) have studied the sorting of lumber from an operations research point of view. They developed a model to predict the best manual sorting system and to determine the most profitable sorting classifications to mechanize. As a prelude to the study undertaken in the present report, an operation analysis including the building of a mathematical model, lapse filming and video-tapes of the lumber sorting operation were performed (van Gigch, 1967).

Sorting of lumber is performed in a lumber mill at three or four stages of the process depending whether rough and green lumber, rough and dry lumber or dressed lumber is required by the consumer. In all cases the pieces of lumber must be graded, classified and segregated according to size, grade and quality. In the trade, grade and quality are interrelated. As the pieces of lumber are carried by mechanical conveyors, operators, known by the name of 'chainmen', pull the lumber onto loads or piles lying on both sides of the conveyor. In a typical layout each worker is in charge of four or seven loads and pulls the lumber corresponding to the loads for which he is responsible. Manual sorting is still prevalent in most mills due to the large investment required for mechanical sorters and the fact that it allows more flexibility in the number and types of sorting classifications handled. Pulling lumber from the conveyor has always been considered primarily a job of physical strength and very few people would concede that much mental effort is involved. In one case, a work sampling analysis revealed that the men on the manual chain appeared 'idle' 50 percent of the time. This concept of idleness refers to the work measurement definition of the word which means that no overt motions were observed. In actual fact, the men on the sorting chain are continually making decisions regarding the lumber passing in front of them. It is to the estimation of the mental content of their work that we now turn.

## Manual Sorting

The integrative behavior model developed in chapter V can be applied to the information processes which take place during manual lumber sorting.

Figure 11 is a flow diagram of the information processed during each cycle of operation. It shows the central mechanisms as issuing commands to the effector system to pull lumber according to the assigned sorting classifications. However, in analyzing the nature of the task it wasfelt that after continued practice, movements would become independent of cognitive control in the sense described by Fitts and Radford (1966) and discussed in chapter II in the section on 'open and closed-loop control'. In drawing up the integrative path for this operation (figure 12), independence of cognitive control was shown by linking the mental therblig in the receptor system to the one in the effector system without intervention of the central mechanisms. The assumption of independence of cognitive control can be debated, but it was reinforced by evidence drawn from the analysis of the lumber grading operation contained in the next section. If mental therbligs in the central mechanisms were to be included in the calculations, the average information processing rates obtained would be close to 10 bits/sec., a figure which represents the maximum channel capacity in forced-pace tasks and which could not be reasonably expected in the performance of industrial tasks.

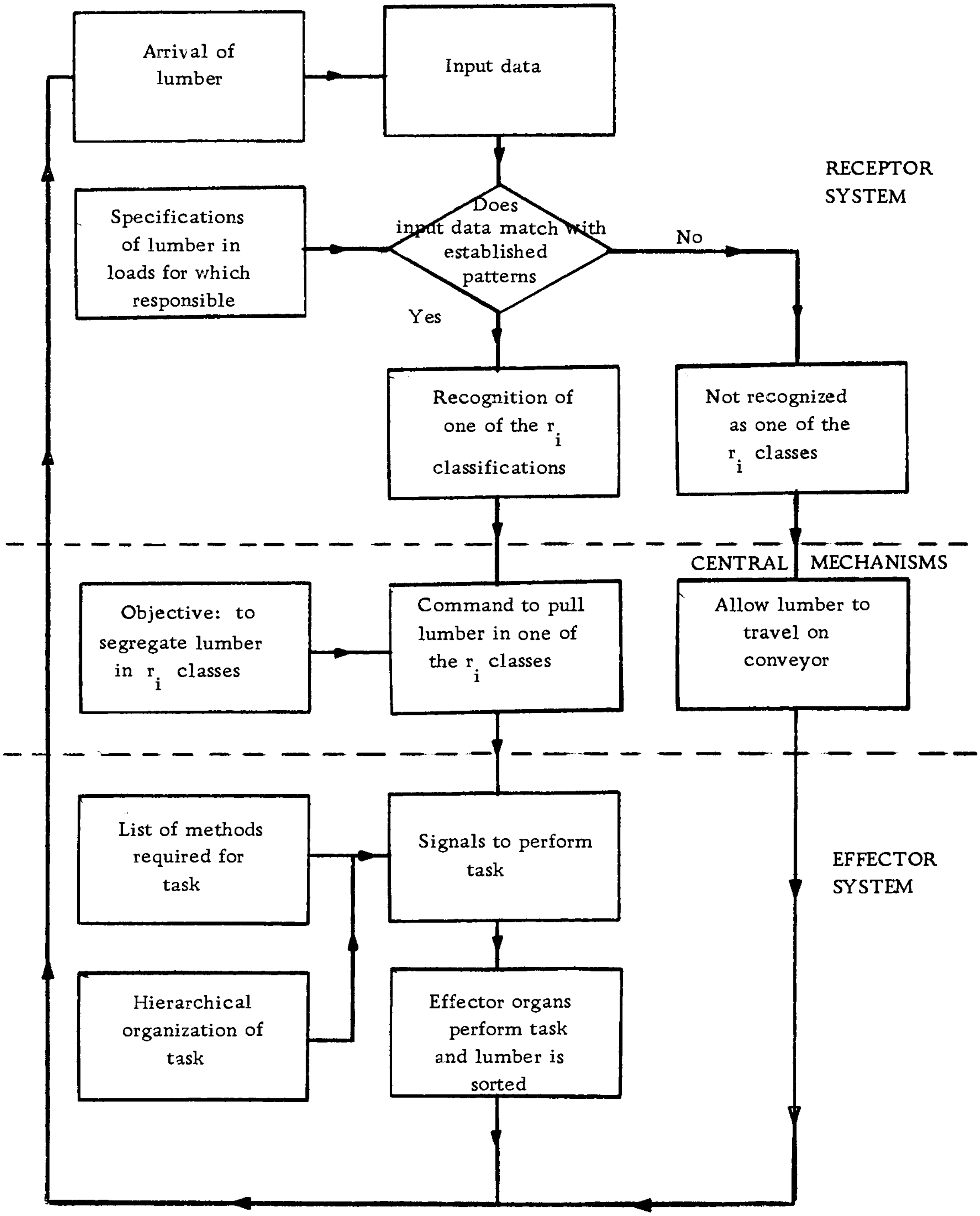



Figure 11. Diagram of information flow for lumber manual sorting operation.

| | RECEPTOR SYSTEM | CENTRAL MECHANISMS | EFFECTOR SYSTEM | Average Information Processing Rate |
|---|---|---|---|---|
| First Level of Integration | Perceiving | → | Coordinating<br>non symbolic responses | |
| Second Level of Integration | | | | |
| Third Level of Integration | | | | |
| Amount of Information | bits/Hr. | | bits/Hr. | bits/sec. |
| 1st Chainman | $I_1 = 400 \log 24 = 1832$[a] | | $I_2 = 100 \log 6 = 258$ | 0.59 |
| 2nd Chainman | $I_1 = 300 \log 18 = 1251$ | | $I_2 = 100 \log 6 = 258$ | 0.42 |
| 3rd Chainman | $I_1 = 200 \log 12 = 716$ | | $I_2 = 100 \log 6 = 258$ | 0.27 |
| 4th Chainman | $I_1 = 100 \log 6 = 258$ | | $I_2 = 100 \log 6 = 258$ | 0.16 |

[a] The numerical data is drawn from Figure 14.

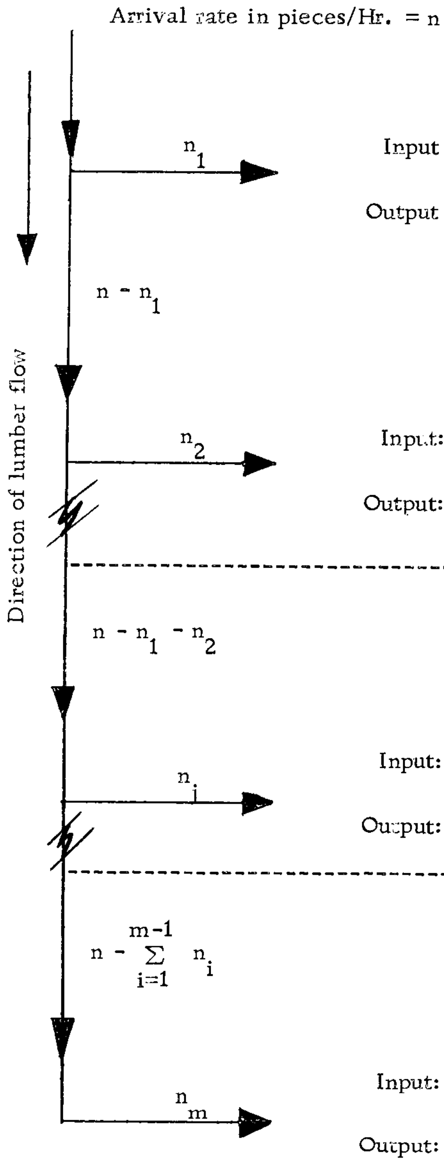
Figure 12. Path of integrative behavior and average information processing rates for four manual lumber sorting chainmen (Mill 1).

Figure 13 is a general model of the input and output information process taking place in the manual sorting chain. Figures 14 and 15 show the application of the general model to the sorting process in two different mills.

In the general model, the lumber arrival rate is given in terms of pieces per minute or pieces per hour. At each position $n_i$ pieces/unit of time are pulled by each man, thus reducing the flow of lumber down the line. The first man on the chain must select lumber for his $r_1$ sorting classifications from a total of r possible alternatives. However, the second man on the line only selects $r_2$ classes from the $(r-r_1)$ classifications left, after the first man on the line has pulled his own $r_1$ classes. The same reasoning applies to each man on the chain; the arrival rate and the possible selection are reduced as we go down the line. Theoretically, the last man on the line has the least physical and mental work because only $(n-\sum_{i=1}^{m-1} n_i)$ are left on the chain and of necessity, they all belong to his own sorting classes. In practice, the last man may be saddled by all left-overs which make his job more difficult. This model applied to the flow of lumber as observed in mills one and two is depicted in figures 14 and 15. Calculations show that the respective average information processing rates of the first man on the chain were 0.59 and 0.96 bits/sec. For the third chainman in each of the sawmills, these respective rates were 0.27 and 0.39 bits/sec. The differences are due to the arrival rates and number of sorting classifications prevailing in each location.

In mill two, operators are paced by a mechanical sorter which they complement. The lumber arrival rate in mill two is of 650 pieces per hour versus the rate of 400 pieces per hour in mill one. In the latter, there were more sorting classifications but each chainman was responsible for six classes as opposed to seven classes in the other mill studied.

Table 6 is a summary of the average information processing rates obtained for the mental content of work of the chainmen in two mills, plus the rates obtained for two jobs created by the mechanical sorter which will be treated next.




CHAINMAN 1

Input information: $I_1 = n \log r$ bits/Hr.

Output information: $I_2 = n_1 \log r_1$ bits/Hr.

CHAINMAN 2

Input: $I_1 = (n - n_1) \log (r - r_1)$

Output: $I_2 = n_2 \log r_2$

CHAINMAN j

Input: $I_1 = \left[ n - \sum_{i=1}^{j} n_i \right] \log \left[ r - \sum_{i=1}^{j-1} r_i \right]$

Output: $I_2 = n_j \log r_j$

LAST CHAINMAN

Input: $I_1 = \left[ n - \sum_{i=1}^{m-1} n_i \right] \log r_m$

Output: $I_2 = n_m \log r_m$

$r$ = total number of sorting classifications

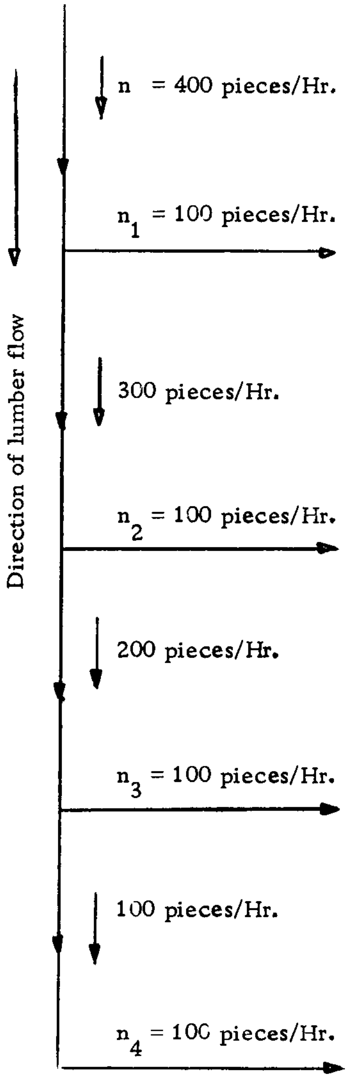
$n$ = total number of pieces arriving per unit of time

$n_i$ = total number of pieces sorted by each worker per unit of time

$r_i$ = number of loads for which each worker is responsible.

Figure 13. General model of the input and output information process in the manual sorting chain.

Arrival Rate = 3000 pieces/day in 7.5 hours shift
$n = 400$ pieces/Hr.
$r = 24$ classifications




CHAINMAN 1

Input information: $I_1 = 400 \log 24 = 1832$

Output information: $I_2 = 100 \log 6 = 258$

bits/Hr. 2090
bits/sec. 0.59

CHAINMAN 2

Input: $I_1 = (400-100) \log 18 = 1251$

Output: $I_2 = 100 \log 6 = 258$

bits/Hr. 1509
bits/sec. 0.42

CHAINMAN 3

Input: $I_1 = (400-200) \log 12 = 716$

Output: $I_2 = 100 \log 6 = 258$

bits/Hr. 974
bits/sec. 0.27

LAST CHAINMAN

Input: $I_1 = (400-300) \log 6 = 258$

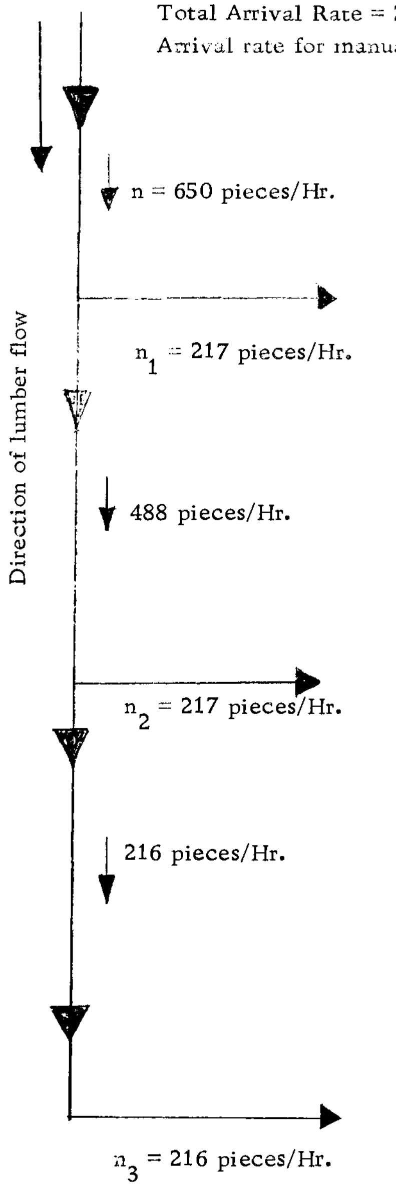
Output: $I_2 = 100 \log 6 = 258$

bits/Hr. 516
bits/sec. 0.16

$n = 400$ pieces/Hr.
$r = 24$ classifications

Figure 14. Input and output information process in the manual sorting chain. Mill 1, east side.

Total Arrival Rate = 21.6 pieces/min. of which assume 50% is sorted annually.
Arrival rate for manual sorting = 650 pieces/Hr.




CHAINMAN 1

Input information: $I_1 = 650 \log 21 = 2854$

Output information: $I_2 = 217 \log 7 = \underline{610}$

| | |
|---|---|
| bits/Hr. | 3464 |
| bits/sec. | 0.96 |

CHAINMAN 2

Input: $I_1 = (650-217) \log 14 = 1650$

Output: $I_2 = 217 \log 7 = \underline{610}$

| | |
|---|---|
| bits/Hr. | 2260 |
| bits/sec. | 0.68 |

CHAINMAN 3 (Last man)

Input: $I_1 = 216 \log 7 = 610$

Output: $I_2 = 216 \log 7 = \underline{610}$

| | |
|---|---|
| bits/Hr. | 1220 |
| bits/sec. | 0.39 |

n = 650 pieces/Hr.
r = 21 classifications

Figure 15. Input and output information process in the manual sorting chain, mill 2.

Table 6. Average information processing rates for lumber sorting jobs. Expressed in bits/sec.

| Type of sorting | Sawmill #1<br>100% Manual | Sawmill #2<br>40% Manual<br>60% Mechanical |
|---|---|---|
| First man on manual chain | 0.59 | 0.96 |
| Third man on manual chain | 0.27 | 0.39 |
| Sorter-tower operator | -- | 2.4 |
| Sorter-stacker operator | -- | 0.35 |

Mechanical Lumber Sorting

The manual sorting of lumber is being replaced by mechanical sorting which can be performed with edge sorters, tray sorters, and package sorters. For the purposes of the present study only tray sorters were investigated. Sorting in two mills was compared. In sawmill one (names were withheld at the request of the principals) sorting was 100 percent manual. In sawmill two, 60 percent of the lumber, in terms of volume expressed in thousands of board feet (fbm's), was sorted mechanically and the remaining 40 percent was sorted manually as in the past.

Mechanical tray sorters consist of conveyors that carry the pieces of lumber to trays each of which contain lumber of a specific dimension. Mechanical sensors, appropriately positioned on the chain, measure the length, width and thickness of each piece as it is carried through. The sensors are placed in order of increasing size. They are connected to a memory drum which records the size of the piece measured and actuates,in due time,the appropriate gate so as to carry all pieces of the same dimension to the same tray. The sorters surveyed for this study had 20-25 trays and, correspondingly, the same number of positions on the memory. The latter can be programmed for many combinations of length, width and thickness.

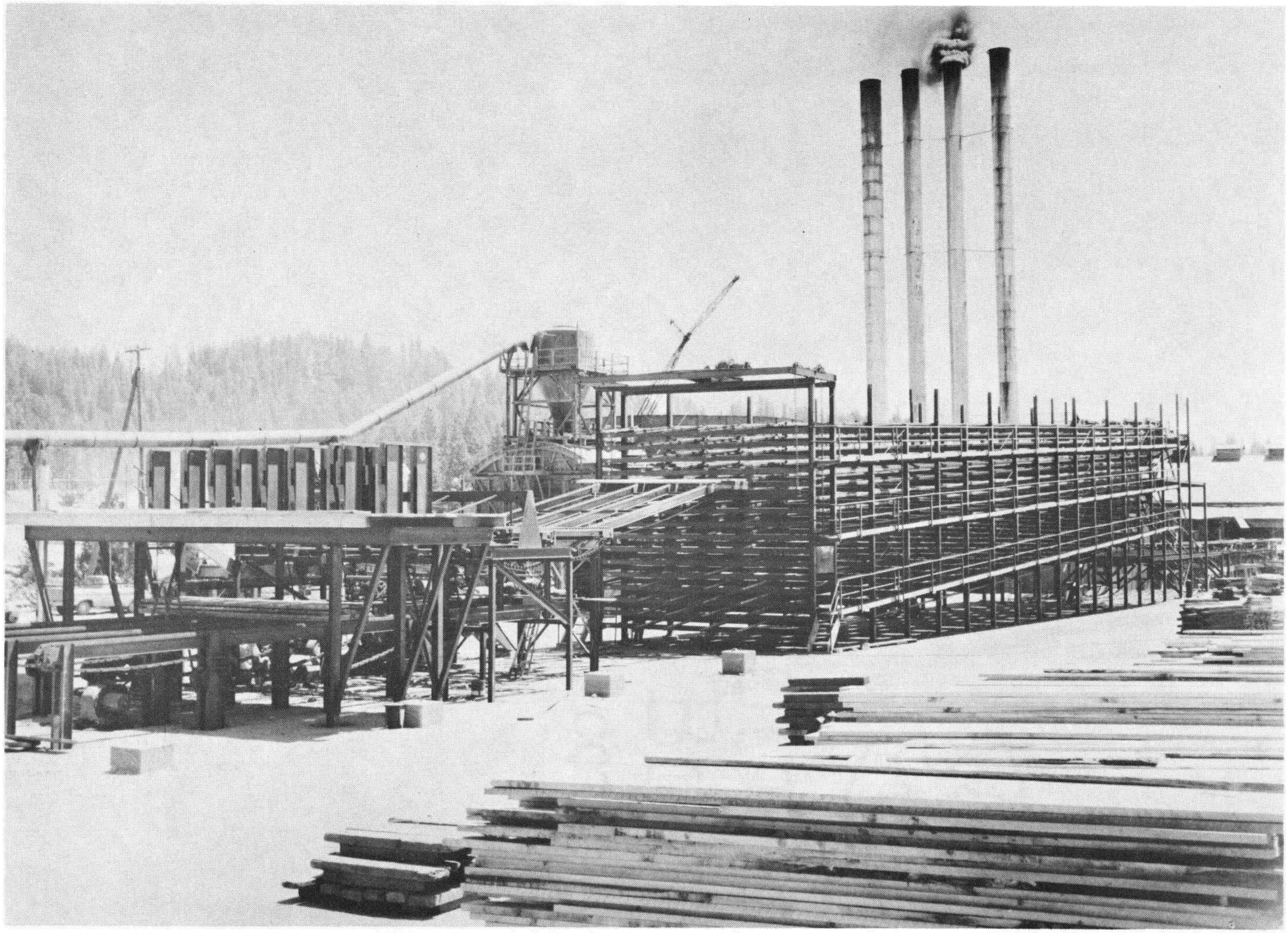


Figure 16. Overall view of mechanical sorting equipment. (Courtesy Moore Oregon Co.)

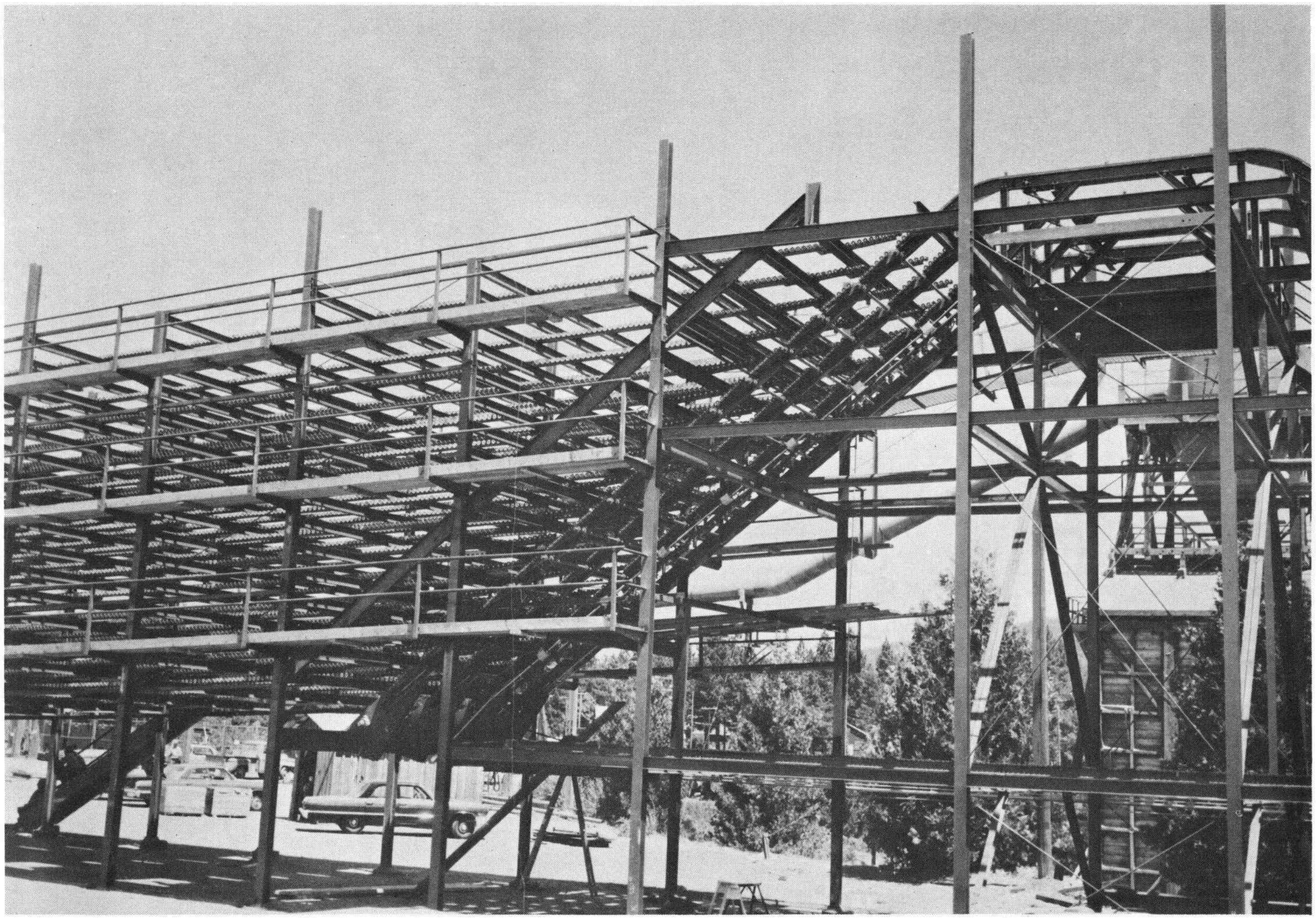


Figure 17. Partial view of mechanical sorting equipment. (Courtesy Moore Oregon Co.)

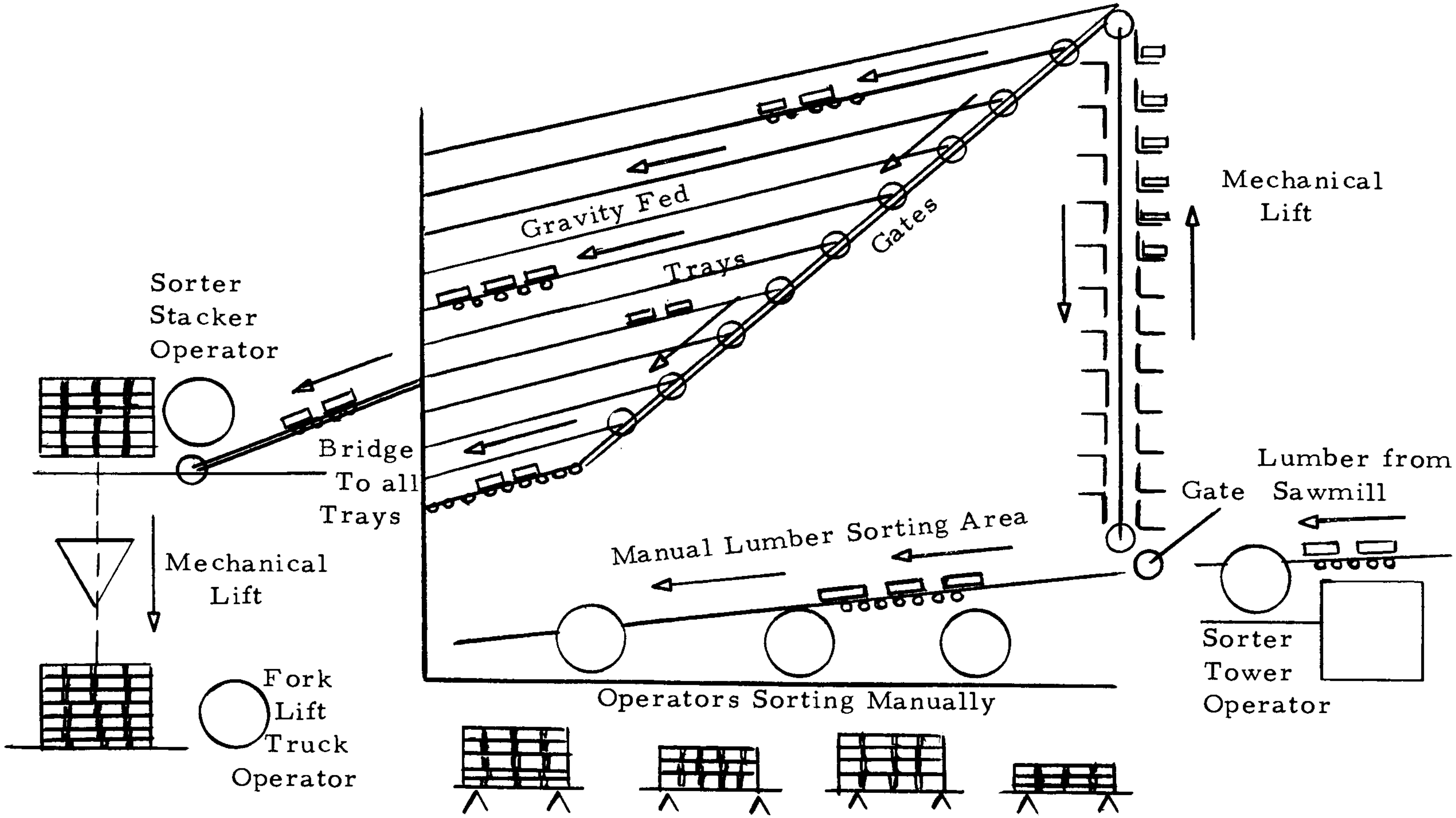



Figure 18. Schematic diagram of mechanical sorter.

The mechanical tray sorter is a considerable technological improvement over manual sorting. Figures 16 and 17 are photographs of a typical installation. Figure 18 is a schematic diagram showing the lumber flow through a mechanical sorter.

Data of volume sorted per unit of time show that the productivity of the mechanical sorters is at least twice as high as the productivity of manual sorting. The table below is a comparison of three mills and their respective output per man-hour.

Table 7

Productivity of Lumber Sorting in Three Mills

| | Type of Sorting | Productivity in Board-Feet/ Man-Hour |
|---|---|---|
| Sawmill 1 | 100% manual | 1560 |
| Sawmill 2 | 60% mechanical<br>40% manual | 3120 |
| Sawmill 3 | 100% mechanical | 3750[1] |

1 Productivity of this mill could be improved further. Figure shown is based on utilization of mechanical sorter at 60% of rated capacity.

Table A-1 gives the detailed characteristics of the three mills surveyed.

The introduction of the mechanical sorters obviously relieves men of the physical work of pulling lumber by hand. The content of work is also altered by the introduction of two new jobs which are required to operate the mechanical sorter. The work and mental content of these two new jobs - the 'sorter-tower operator' are analyzed below.

The Work of the Sorter-Tower Operator

The sorter-tower operator stands at the end of the mechanical conveyor that brings lumber from the sawmill, in a position just prior to the point where the lumber actuates the mechanical sensors. The sorter-tower operator monitors the flow of lumber to the sorter. If need be, he can stop all conveyors. The operator stands in front of a 20 button console which allows him to program the tray to which he desires a piece to be carried. He only actuates these buttons in case he wants to overrule the program for which the mechanical sensors have previously been set or when he wants to send a piece, whose dimensions do not agree with those already programmed, to one of the trays. The operator, in all cases, actuates a release pedal which allows the piece to enter the mechanical sorter and also a reject pedal to send a piece of lumber to the manual chain when desired. As was mentioned earlier, in the sawmill surveyed for this study, the mechanical sorter was being operated in conjunction with manual sorting. The mechanical sorter can only accommodate 20 sorting classifications. The chainmen sorted to another 22 classes, for a total of 42 different classifications.

Each piece of lumber arriving from the sawmill falls into one of the following five categories:

Case A: Occurs in two percent (2%) of total number. These are pieces for which the mechanical sensors have been programmed but which must be rejected because of visible defects. A reject mark may have been drawn by the grader-marker at a previous position.

Case B: Occurs in 50% of cases. These pieces have dimensions which have been programmed and require no action on the part of the sorter-tower operator except that they be released to be carried to the mechanical sorter trays.

Case C: Occurs in five percent (5%) of cases. Same as case B except the operator wants to ensure that the piece will be carried to the mechanical sorter and he, therefore, re-programs these pieces on the 20-button console.

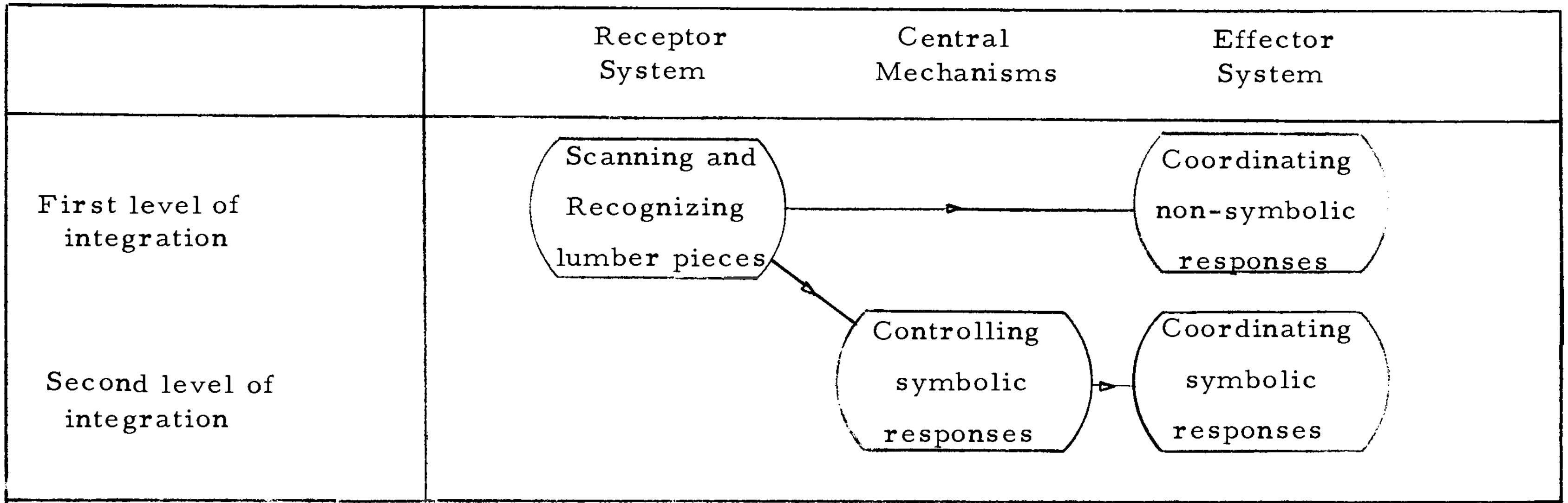
Case D: Occurs to 38% of the pieces. These pieces have not been programmed and they are allowed to proceed to the manual sorting area.

Case E: Remaining five percent (5%) of the total. These are pieces which have not been programmed and which the operator wants to program for mechanical sorting.

The integrative path and the information flow is shown on figure 19. Based on the fact that 60 percent of the lumber will be sorted mechanically, the operator must recognize these pieces among 20 different categories. The pieces which will be sorted manually represent another 22 different classifications. The information processed in the receptor system to effect this segregation is calculated to be 4. 37 bits/cycle. In all cases, the operator is required to release each piece by depressing a foot pedal, a 0-1 action which implies one bit/cycle. In 12 percent of all cases, (cases A, C, and E), the operator is either required to operate the 20-button console and program the pieces which must be carried by the mechanical sorter or he depresses the reject foot pedal to send the pieces to the manual sorting area, in total a choice involving 21 alternatives. The operation of the programming console was considered to involve a non-symbolic response involving the central mechanisms at the second level of integration. Programming each individual piece is of the nature of a discrete task requiring closed-loop control (Fitts and Peterson, 1964). The amount of information processed at the second level of integration results in 1.06 dubits per cycle or 2.12 bits/cycle. The total information processed per cycle equals 7.49 bits/cycle. Considering that the lumber arrival rate is 1224 pieces/hour, the average information processing rate for this operation is 2.38 bits/sec.

The relatively high information processing rate obtained for the sorter-tower operator is the result of the high lumber arrival rate. The sorter-tower operator's job can be classified among those of high cycle repetition rate but low entropy per cycle, both characteristics which will be discussed in length in chapter VII.

The job of the sorter-tower operator was likened by his supervisor to that of a piano player to the extent that both individuals must read a score of instructions in order to perform their function. The piano player reads notes. The operator identifies the marks on the lumber and acts accordingly. It is pertinent to recall the information processing rate obtained by Quastler and Wulff in forced-pace piano playing in the order of 22 bits/sec. and compare it against the industrial task rate of 2.4 bits/sec. The former is only valid for short spans of time, the latter must be sustained through long shifts.




| | Receptor System | Central Mechanisms | Effector System | Total |
|---|---|---|---|---|
| Amount of information processed | 0.60 log 20 = 2.59<br>0.40 log 22 = 1.78 | | 1.00 log 2 = 1.0 | |
| Sub-total bits/cycle | 4.37 | | 1.0 | |
| dubits/cycle | | 0.12 log 21 = 0.53 | 0.12 log 21 = 0.53 | |
| Total bits/cycle | 4.37 | 1.06 | 2.06 | 7.49 |

No. of cycles/hr. = 1224 pieces.

No. bits/hr. = 1224 x 7.49 = 9168 bits.

Average information processing rate = $\frac{9168}{3600}$ = 2.38 bits/sec.

Figure 19. Integrative path and information processing flow for sorter-tower operator (Mill 2).

The Work of the Sorter-Stacker Operator

The sorter-stacker operator is in charge of mechanically emptying the trays of the mechanical sorter. The lumber from the trays converges to his position via conveyors which push the pieces side by side. Figure 18 shows the location of the sorter-stacker operator. A tipple or bridge, which can be raised or lowered, allows each tray to be emptied in turn. The operator controls the operation of several chains which work end-to-end, end-rollers which straighten the lumber, the lumber stacker, a sticker-placer machine, an up-and-down package hoist and other auxiliary equipment to handle the package to a side position.

Contrary to the case of the sorter-tower operator, the sorter-stacker operator is not paced by the arrival rate of the lumber. Assuredly, he must proceed methodically to clear the lumber from each tray in turn or otherwise a bottleneck will occur when the trays are full. However, the capacity of the lumber-stacker and of the sticker-placer machines are such that the sorter-stacker operator can more than keep up with the rate at which the mechanical sorter brings lumber to the trays.

The mental content of the work performed by the sorter-tower operator was relatively high due to the continuous arrival of lumber to the sorter and the need to make choices and decisions regarding each piece in a short span of time. This is not the case for the sorter-stacker operator.

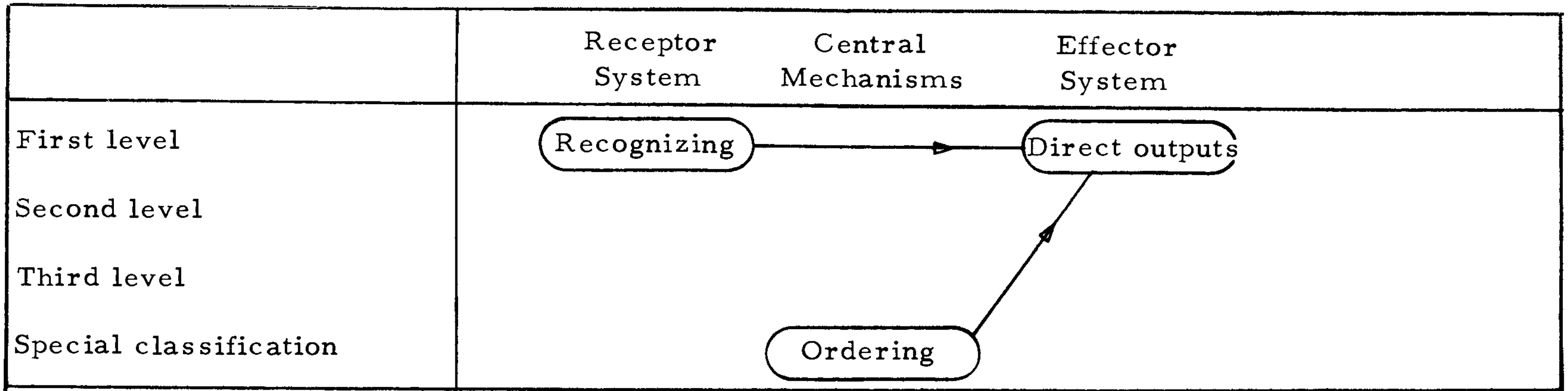
The sorter-stacker operator's work is of relatively low mental content. He does not have to concern himself with choices or alternatives. His decisions are limited to operating the right knobs at the right time so as to actuate chains, drives, clamps, and machines in an established and repetitive sequence to mechanically stack one layer of lumber over another. Figure B-1 shows a schematic of the type of button and knobs console from which the worker controls the operation. While he does not have to handle the lumber at any time, his work consists of ensuring that no jams occur, that the lumber is fed in layers evenly and that the machines operate adequately. While the mechanical sorter and its auxiliary equipment has removed the physical load of sorting lumber manually from a chain, it does not follow that the physical work has been completely eliminated. As a matter of fact, the sorter-stacker's job would be rated as relatively heavy work because the operator is required to climb into the sorter to clear jammed pieces, he walks over the boards to straighten the lumber or repair the machines, and, in general, performs any task required to assure the flow of lumber.

The analysis of mental therbligs in the task of the sorter-stacker operator is summarized in figure 20. The path of integrative behavior is limited to identifying alternatives to perform the outputs. Appendix C contains the list of the individual tasks performed, together with the selective entropy required for each motion per cycle. Selection of these alternatives takes place at the first level of integration and the outputs are considered non-symbolic. One hundred and forty bits are processed in each of the receptor and effector systems per cycle.

In addition, the work of the sorter-stacker operator is characterized by a definite sequence of tasks. He performs this sequence in a cycle which takes 15 minutes each time i. e. four cycles are performed per hour.

The sequence of tasks requires that the operator ask himself at the completion of each task: "What should I do next?". It is obvious that such introspection is unconscious in the case of overlearned sequences as the one performed by the sorter-stacker operator. It can be compared to the process which goes on continuously within the human communication system to monitor sequential tasks.

Where the sequence involves more than two tasks, feedback is essential to control the order in which the tasks are performed. We, therefore, introduce the mental therblig 'ordering' which involves the concept of order entropy presented in chapter III.




| Amount of information | Receptor System | Central Mechanisms | Effector System | Total |
|---|---|---|---|---|
| bits/cycle | 141[1] | 28.8 | 141 | |
| cycles/hr. | Four | | | |
| bits/hr. | 564 | 115 | 564 | 1243 |

Average information processing rate $= \frac{1243}{3600} = 0.35$ bits/sec.

[1] Refer to Appendix C for details.

Figure 20. Integrative path and information processing flow, sorter-stacker operation (Mill 2).

When dealing with a sequence, the total source entropy results from two factors, the conventional selective-source entropy already calculated as equaling 141 bits/cycle and the order source entropy which will be calculated below.

The sorter-stacker operator has to perform 12 consecutive tasks which must be repeated in a cycle. The order in which the tasks must be performed obviously becomes routine and, when overlearned, is probably devoid of cognitive control (Fitts and Radford, 1966). However, whether the mental process is conscious or unconscious the brain must retain, somehow, the order in which these tasks must be performed (Crossman, 1961).

The twelve tasks in the cycle are:

1. Choose one of twenty trays to empty.
2. Move the tipple into location.
3. Bring lumber forward.
4. Adjust thickness clamp depending on lumber size.
5. Adjust width level according to lumber size.
6. Advance one layer of lumber in lumber stacker.
7. Check operation of stick-placer machine.
8. Lower lumber stacker hoist with lumber package.
9. Operate roll-case forward.
10. Operate roll-case in reverse.
11. Operate lumber-stacker hoist up.
12. Load sticks in stick-placer machine.

Given that there are 12 items in the list, the order-source entropy is:

$H_2 = \log s!$ bits/list

where s = length of list = 12

and $s! = 4.79 \times 10^8$

$H_2 = 28.7$ bits/list.

The information processing rate, given that the list is performed four times per hour, is:

$I_2 = 4 \times 28.7 = 115$ bits/hour.

The total source entropy processed by the sorter-stacker operator is the sum of the selective-source entropy and the order-source entropy and results in an average information processing rate for this job of 0.35 bits/sec. This compares with the rate of 2.4 bits/sec. for the sorter-tower operator and the range of 0.59 to 0.96 bits/sec. obtained for the first man on the sorting chain.

The mental therblig 'ordering' which allows the sorter-stacker operator to maintain a consistent sequence among the tasks must be kept distinct from the function of relating. In ordering the operator assigns labels and position indicators to the various tasks which must be performed. It is assumed that even when the operator is proficient, the brain must scan registers the way a computer would in order to keep the order of the tasks straight. On the other hand, relating is the information process which fits an event to a totality of events and attempts to give significance to a portion of the job within the structure of the complete job. It can be said that the mental therblig 'ordering' is connected to the repetition of the sequence, whereas the therblig 'relating' is affected by the variability in the sequence.

## 2. The Grading of Lumber

Until recently grading of lumber has been done by trained and certified graders who exercised their judgement by appraising quality and strength from its appearance. The method is subject to human error and it is natural that mechanical methods of testing lumber have been tried.

Mechanical methods of grading lumber are called 'electro-mechanical stress rating' (EMSR) methods in that the allowable unit working stresses of each individual piece is established in a machine called a continuous lumber tester. As the Simpson Timber Company's manual explains: "The stress rating machine applies a force to the board, measures its resistance to deflection (or stiffness) and stamps it accordingly. Essentially each piece is tested and rated for its ability to sustain a given stress without failure or without deflecting beyond specified limits."

Figure 21 shows a schematic of the EMSR machine. The operational sequence of a board travelling through it is explained in Appendix D.

The significance of the mechanical stress grader for the present study is to assess the impact of mechanization on the work of the operator performing the grading function and to determine the information processing rate of the worker before and after the introduction of the machine.

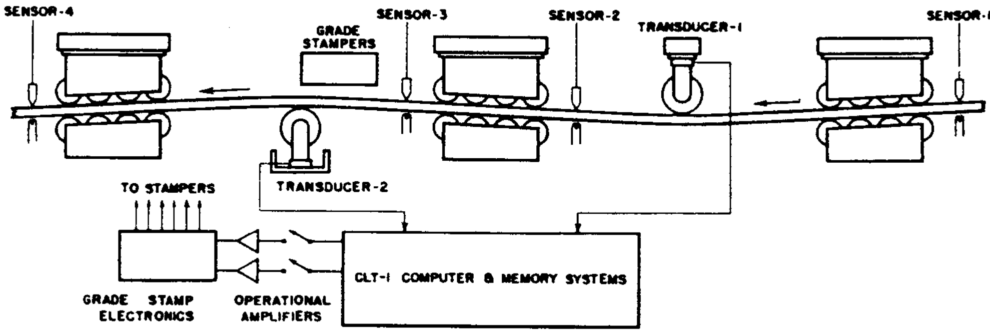
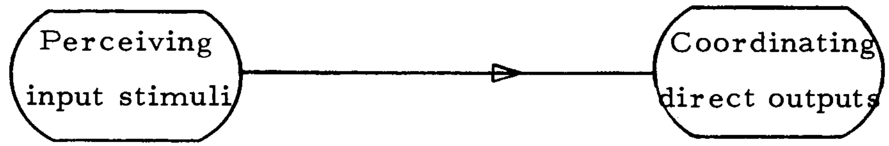



Figure 21. Schematic diagram of electro-mechanical stress-rating machine. (Courtesy Irvington Machine Works Inc.) See Appendix D for operating sequence.

## Grading Lumber Without the EMSR Machine

When no mechanical grader was available in sawmill four, two graders were needed to grade and mark dry lumber as it came from the planing mill prior to chain sorting. They graded lumber at the rate of 50 pieces per minute for both men or 25 pieces for each of them per minute. Grading consists of receiving input stimuli from the appearance of the wood and translating these inputs into responses. Each man was said to classify lumber into ten categories and because he looked at both sides of the board it can be assumed that the identification of a particular grade consists of recognizing one among 20 possible input stimuli. The output response consists of choosing one of ten different marks to stamp the graded lumber.

For purposes of calculating the information processing load of the lumber grader, the integrative behavior model was applied. Because this activity was repetitive and overlearned, the mental therbligs of perceiving and of coordinating non-symbolic responses at the first level of integration were applied. Figure 22 shows the integrative path and the information processing flow for each manual grader. The average information processing rate is equal to 3.2 bits/sec. for each grader.

| | Receptor System | Central Mechanisms | Effector System | |
|---|---|---|---|---|
| First level of integration |  | | | |

| Amount of information | | | | Total |
|---|---|---|---|---|
| bits/cycle | log 20 = 4. 32 | | log 10 = 3. 32 | 7. 64 |
| cycles/min. | 25 | | 25 | |
| bits/min. | 108 | | 83 | 191 |

Average information processing rate = 3. 2 bits/ sec.

Figure 22. Path of integrative behavior and information processing flow, lumber grader without EMSR machine, sawmill #4.

Grading Lumber With the EMSR Machine

It is a paradox that the addition of the stress grading machine has increased the manpower required to grade lumber in the sawmill surveyed. The lumber first goes through the machine and is stamped according to four (4) machine grades i. e. 2400 f, 2100 f, 1500 f and 1200 f. After the lumber comes out of the machine, it passes in front of three men. The two first individuals are classified as graders. They read the machine stamps on the piece of lumber, observe the appearance of the wood in terms of knots and defects and decide on a final grade for each individual piece. The last man is not a grader, he completes the work of the other two by placing a stamp which confirms some of the marks which the others place on the board. See diagram of grading procedure in figure 23.

Another aspect of this peculiar method of grading is very important for the purposes of the present study. It refers to the fact that the first grader does the bulk of the work. Hence, if the output of the stress grading machine is 50 pieces/minute, the first grader may process 34 pieces/minute, grade them and mark them and the second grader will grade the rest i. e. 16 pieces/minute. The first man on the line always works faster than the second. Every so often the two men exchange positions. The second position is to rest from the effort produced in the first one, and this is for good reason as will be apparent from our study of the mental content of this type of work.

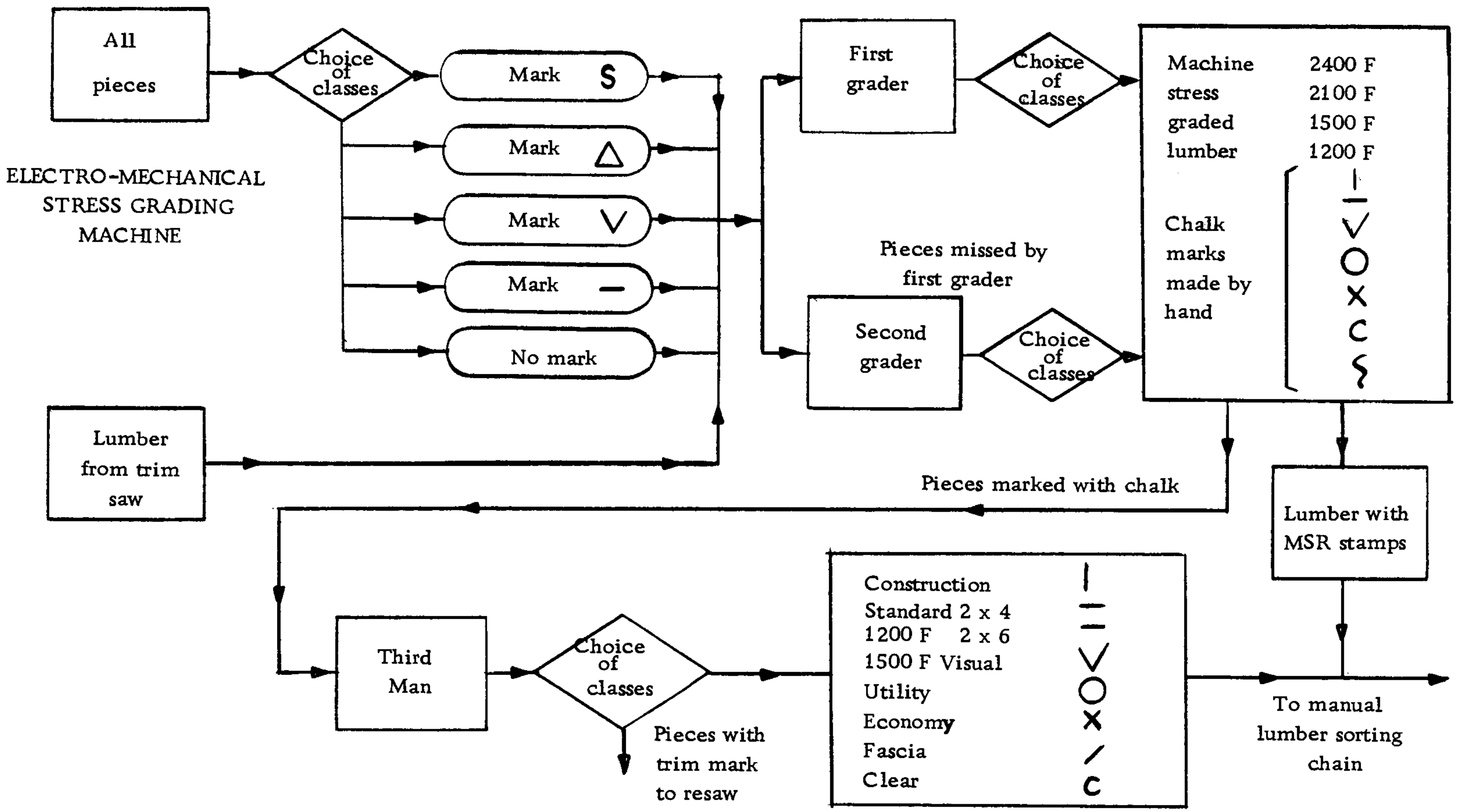



Figure 23. Flow diagram of lumber grading procedure with stress grading machine.

The existence of graders to back up the EMSR machine is only justified on the grounds that electro-mechanical stress rated lumber is still not accepted by the trade and, therefore, the sawmill must regrade the lumber manually after it has been graded mechanically. Obviously this is a backward step which may disappear in the future when the consumer gains confidence on the reliability of stress grading. To a technically oriented individual, stress grading should be more acceptable than manual grading in that the machine detects and measures the effects of wood characteristics which cannot be detected by visual means. Where appearance is not a factor such as in the production of structural members, the measurement of the allowable stresses should provide the desired classification regardless of the number of knots or other visual defects.

## Information Processing Load When Grading Lumber With EMSR Machine

Grading lumber manually after the machine has already graded it mechanically, increases the mental load of the graders as will be shown below.

Five additional input stimuli are added to the ten which the graders had to identify on each side of every piece when no EMSR machine was used. The EMSR machine adds five new input stimuli to the graders perceptual load: the four marks identifying the machine grades plus one classification bearing no mark.

The graders must choose among ten output grades as is the case without the EMSR machine. The following are the average and peak number of pieces which the three men were observed to process in their respective positions:

Table 8

Lumber Grading Rates, Mill Four

| | First Grader | Second Grader | Third Man |
|---|---|---|---|
| Average | 34 pieces/min. | 16 pieces/min. | 17 pieces/min. |
| Peak | 56 pieces/min. | | |

As in the case of grading without an EMSR machine, the integrative behavior model was applied to the three men. The integrative path and information processing flows are drawn up in figures 24 and 25. Calculations show that the following average and peak information processing rates are taking place:

Table 9

Information Processing Rates of Graders
Behind EMSR Machine, Lumber Mill Four

| | First Grader | Second Grader | Third Man |
|---|---|---|---|
| Average Rate bits/sec. | 4.5 | 2.1 | 1.4 |
| Peak Rate bits/sec. | 7.5 | | |

The peak rate was obtained when observing the grader working in the first position after a rest period and as he started processing lumber at the rate of 56 pieces/min., a speed which he sustained for only a few minutes.

| | Receptor System | Central Mechanisms | Effector System | |
|---|---|---|---|---|
| First level of integration | | | | |


| | Receptor System | | Effector System | Total |
|---|---|---|---|---|
| **1. Average processing rate** | | | | Total |
| bits/cycle | log 25 = 4.64 | | log 10 = 3.32 | |
| cycles/min. | 34 | | 34 | |
| bits/min. | 158 | | 113 | 271 |

Average information processing rate $= \frac{271}{60} = 4.5$ bits/sec.

| | Receptor System | | Effector System | Total |
|---|---|---|---|---|
| **2. Peak processing rate** | | | | |
| bits/cycle | log 25 = 4.64 | | log 10 = 3.32 | |
| cycles/min. | 56 | | 56 | |
| bits/min. | 260 | | 186 | 446 |

Peak information processing rate $= \frac{446}{60} = 7.5$ bits/sec.

Figure 24. Integrative path and information flow, 1st grader, mechanical grading. Average and peak processing rates.

| | Receptor System | Central Mechanisms | Effector System | |
|---|---|---|---|---|
| First level of integration | Perceiving input stimuli | → | Coordinating direct outputs | |
| **2nd Grader** | | | | Total |
| bits/cycle | log 25 = 4.64 | | log 10 = 3.32 | |
| cycles/min. | 16 | | 16 | |
| bits/min. | 74 | | 54 | 128 |
| Average information processing rate = 2.14 bits/sec. | | | | |
| **3rd Grader** | | | | |
| bits/cycle | log 6 = 2.58 1/ | | log 5 = 2.32 2/ | |
| cycles/min. | 17 | | 17 | |
| bits/min. | 44 | | 39 | 83 |
| Average information processing rate = $\frac{83}{60}$ = 1.4 bits/sec. | | | | |

1/ Do not count marks labelled "Fascia" and "Clear."

2/ Consider only 4 stamps and "trim mark."

Figure 25. Integrative path and information processing flow 2nd and 3rd Grader - mechanical stress grading.

## Average and Peak Information Processing Rates

Of all the processes studied for this thesis, stress grading was the only one that provides a close approximation to what can be termed 'maximum information processing rates' for an industrial operation.

The rate of 7.5 bits/sec. obtained in stress grading was only maintained for a very short period of time, a matter of a few minutes. The writer received the distinct impression that the mental load upon the operator was very high and that 7.5 bits/sec. can serve as a yardstick of high mental load for an industrial operation where the variability of the sequence is low but the rate of repetition of this sequence is high. This figure can be compared to the information processing rates obtained for the forced-rate task experiments performed in laboratory experiments such as piano-playing (22 bits/sec.), typewriting (17 bits/sec.), etc. reported in table 2.

Presumably, a rate of 7.5 bits/sec. could also be obtained in the performance of tasks where the rate of repetition of the sequence is low (i.e. the operation cycle is long) but where the variability of the sequence is high (i.e. the same sequence may never appear twice). An example of this type of situation can be witnessed in the work performed by the Kamyr digester operator, whose control function and information load will be taken up in section 4 of this chapter. To obtain peak rates in those cases presents practical difficulties because the worker was never observed as being pushed to his capacity.

Stress grading offers an example where the impact of technology raised the manpower requirements from two men to three and also increased the mental content of the work. The graders without the help of the EMRS machine processed an average of 3.2 bits/sec. The organization of work after the installation of the machine produced an imbalance. The first grader on the line saw his mental load increase to an average of 4.5 bits/sec., whereas the second grader on the line processed only 2.1 bits/sec. Among the two graders the average is still around 3.3 bits/sec., a figure similar to the rate obtained when the machine was not used.

It is obvious that neither the men nor the principals of the lumber mill in which this study was performed are aware of this situation. The graders were paid $3.22 an hour at the time of study, and it is believed that no extra compensation was given after the stress grading machine was installed.

Without a doubt, the situation where manual grading and machine grading are performed simultaneously will not last for very long and will not be available for further study again. However, the numerical values obtained for the average and for the peak information processing rates will gain significance because they are representative of jobs combining high mental content and high cycle rate.

## 3. The Production of Groundwood Pulp

### Processes by Which Wood Pulp is Produced

Most technical information on the production of wood pulp was obtained from Calkin and Witham (1957) and the Handbook of Pulp and Paper Technology (1964).

According to Calkin and Witham (1957, p. 11), wood constitutes the main source of cellulose fibers for paper,

> "the balance being made up from recovered waste paper (paper stock) and a small amount of other fibers, such as rag, jute, manila, straw, bagasse, depending on the availability of the supply. Wood consists of approximately fifty (50) percent cellulose, 30 percent lignin and the remainder hemicelluloses, pentosans and sugars. Lignin serves as a binder to hold the fibers together and must be removed to secure separation of those fibers if a product approaching cellulose is to be obtained."

There are various methods to produce pulp. The main ones cited by Calkin and Witham (1964) are: mechanical or groundwood pulp, soda pulp, sulfite pulp, sulfate (kraft) pulp, and semichemical pulps. Only processes related to the production of mechanical or groundwood pulp and with sulfate pulp were observed for the purposes of the present study. The basic principles involved will be described when relevant.

The production of groundwood pulp affords a dramatic comparison of the impact of technology on the skill requirements of old and new jobs.

Groundwood pulp is produced from logs by holding the wood against an abrasive mill-stone in a machine called a grinder. One of the earliest machines used for this purpose was a pocket-grinder where the wood was held against the abrasive surfaces by hydraulic pressure. While these machines are being quickly replaced by the disk refiners (see below), it was indeed fortunate for the purposes of the present study that hydraulic pocket-grinders were located and their operation observed.

The Handbook of Pulp and Paper Technology (1964, p. 236-257) gives a good account of the history of grinders and their development. Apparently, hydraulic pocket-grinders can still be purchased today. However, as will be described below, their productivity and method of operation are not in keeping with modern technology and present productivity requirements.

## The Operation of Hydraulic Pocket-Grinders and Grindermen's Mental Load

The grinders which are illustrated schematically in figure 26 usually have three or four pockets into which an operator, called the grinderman, introduces four foot long logs by hand. A grinderman usually handles two machines and ensures that all six pockets (in two three-pocket machines) are continually filled with wood, so that they operate continuously. In the oldest set-up observed, the logs were fed to the grinder operator on a flume. Of necessity, the grinderman worked under very adverse conditions due to the water spilled from the flume and due to the work itself, which consists solely of stoking logs into the grinder. In a relatively more recent installation, the wood is carried to the machines by an overhead conveyor which deposits one cord of wood at a time in front of the machine. From there, the grinderman's work consists of taking one piece or log at a time and feeding it into the machine. Depending on the size of the logs, he can place three to four pieces of wood in each pocket.

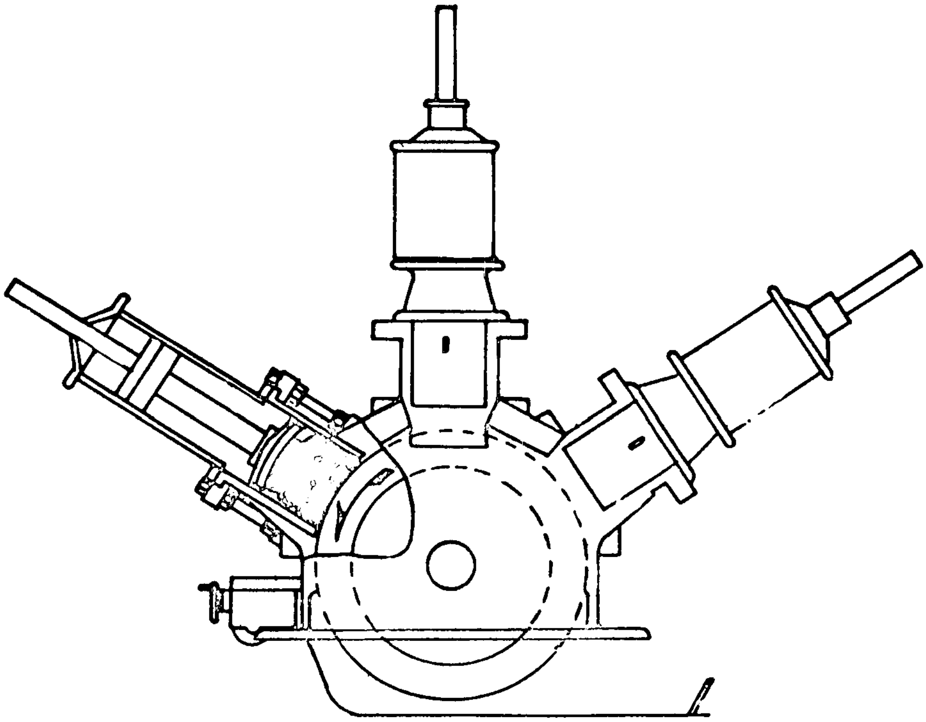


Figure 26. Schematic diagram of three pocket-grinder. (Cited in: Handbook of pulp and paper technology, 1964, p. 234)

The official description of the work to be performed, provided in the original job description in pulp mill one, reads as follows:

Company: Pulp Mill 1 Title: Grinderman

1. Operates two 2' grinders, three to four pockets each.

2. Takes wood out of flume to feed grinders.

3. Keeps slabs or slivers out from grinders. Knotty wood makes it difficult to keep pockets full.

4. Straightens out wood in flume, pulls out sinkers and cleans plug-ups.

5. Sorts out long, rotten, barky wood.

6. Signals sawmill or storage pile for wood as needed.

7. Cleans up bark.

In the two years which have elapsed while this study was being performed, the oldest grinders were scrapped. This study is based on three pocket grinders where the wood is delivered by carrier instead of by flumes.

Of all the operations observed for this study, the job of grinderman offered the least mental effort. Most of the work consists of physical effort spent in lifting and carrying logs from carrier to machine. The information processing, which could be detected in this type of work, involves:

a. Choice of one machine from two.

b. Recognition of whether machine pockets are empty or full.

c. Psychomotor task of applying or releasing hydraulic pressure to the pockets.

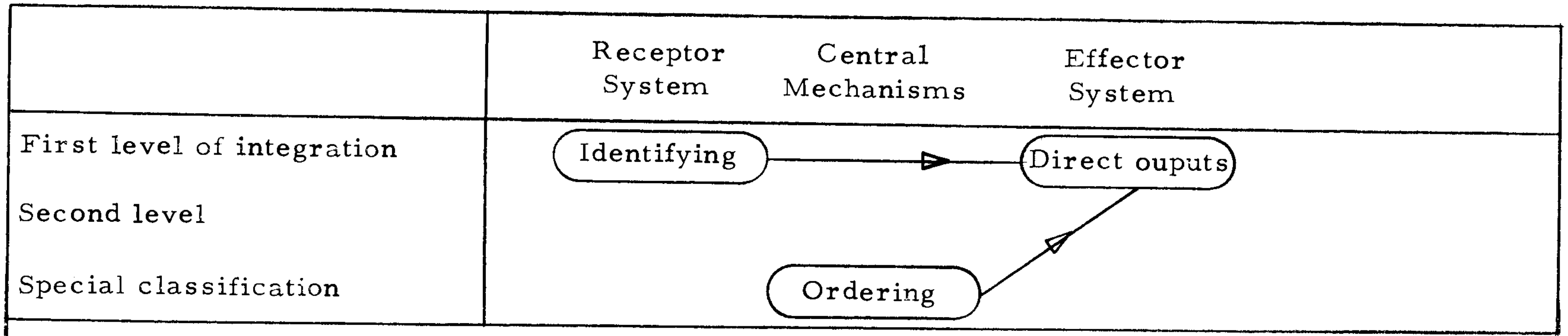
d. Psychomotor task of loading logs into pockets (Decision to load).

e. Changing log carrier when empty (only performed once every hour).

The grinderman's integrative path and information processing flow is analyzed in figure 27. Calculations are based on the following operational information:

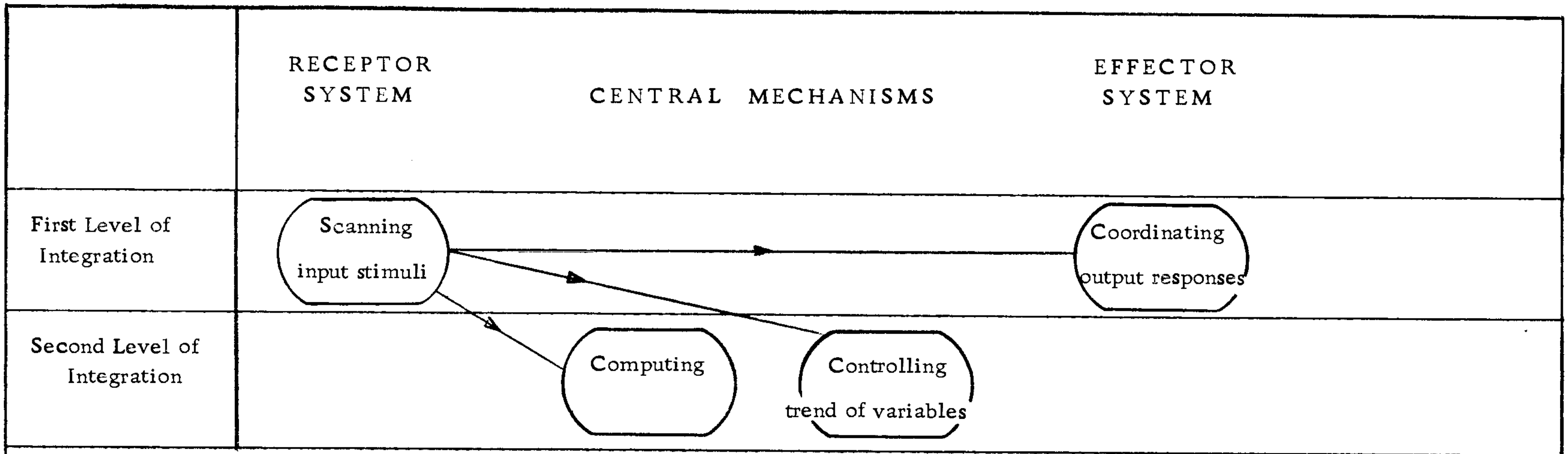
1. Each grinderman operates two machines.
2. Each grinder has three (3) pockets.
3. Wood consumption: 0.75 cords of wood/machine/hour.
4. No. of pieces: average of 90 logs/cord.
5. Load: three (3) logs per pocket.
6. No. of loads: 45 loads/hour.
7. Production or yield: 0.175 tons of stock/man hour.

The average information processing rate for the grinderman is 0.16 bits/sec., similar to the mental content of work of the last green chainman in sawmill one (see Chapter VI, Section 1). A similar calculation for the mental functions of the foreman of the groundwood pulp operation shows that, on the average, the mental content of his work is equivalent to 0.25 bits/sec. (see figure 28).




| Amount of information | Receptor System | Central Mechanisms | Effector System | Total |
|---|---|---|---|---|
| bits/cycle | 4 log 2 = 4 | 4, 6 | 4 log 2 = 4 | |
| No. of cycles/hr. | 45 cycles | | | |
| bits/hr. | 180 | 212 | 180 | |
| Plus extra operation | 2 | — | 2 | |
| Total information content | 182 | 212 | 182 | 576 bits/hr. |
| Average information processing rate | | | | 0. 16 bits/sec. |

Figure 27. Integrative path and information processing flow grinderman, groundwood pulp operation pulp mill 1.




| | | | | | |
|---|---|---|---|---|---|
| Amounts of Information | 180.6 bits/Hr. | 88 dubits/Hr. | 180.6 dubits/Hr. | 180.6 bits/sec. | Total |
| Equivalent bits/Hr. | 180.6 | 176.0 | 361.2 | 180.6 | 898.4 |

Average information processing rate $= \frac{898.4}{3600} = 0.25$ bits/sec.

Figure 28. Path of integrative behavior and information processing flow, foreman groundwood pulp mill operation, pulp mill 1.

The Operation of Chip Refiners

The production of groundwood by pulping logs on a stone is quickly becoming obsolete, as pulp is being produced from chips. Wood chips delivered to the mill by truck or produced on the premises from a chipping plant are washed to remove foreign material and pre-heated to soften them. They are then conveyed to a machine called the double disk refiner (see figure 29). This machine consists primarily of two heavy metal disks, which revolve at high speed and through which the chips are pumped at high pressure. The clearance between the 4 feet disks is controlled. The chips are converted into pulp as they are ground between the plates. The normal set-up consists of two double revolving disk refiners in parallel, followed by another disk refiner in series with the previous two, and finally a smaller 'pump through' refiner in series with the other three. Thus, four refiners are considered as working as one chip refining unit. In the pulp mill surveyed for the present study, refiners have been in operation since 1961. A more detailed description of the operations can be obtained from the Handbook of Pulp and Paper Technology (1964, p. 257-260) , from Robinson (1965) and Dobson (1966).

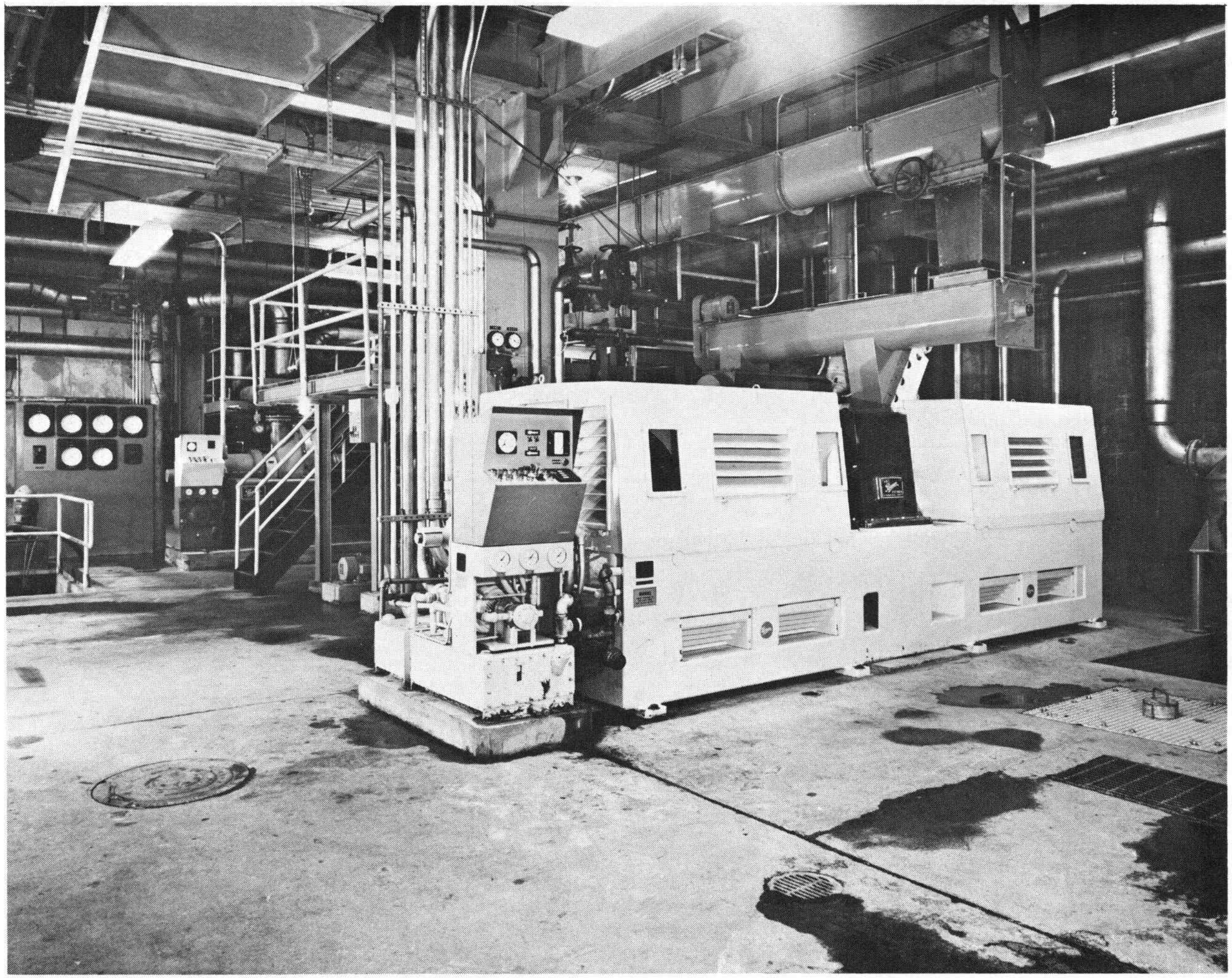


Figure 29. Double revolving disk refiner. (Courtesy Bauer Brothers Co.)

The following comparison of the productivity of grinder versus refiner groundwood pulp can be made:

Old Method:

Production: 150 tons of stock/24 hours.

Manpower requirements: (24 hr. periods)

| Pulp Mill | Man Hours |
|---|---|
| 4 Grindermen, 3 shifts | 96 |
| 1 Shift foreman, 3 shifts | 24 |
| 1 Monorail operator, 3 shifts | 24 |
| 1 Scoopmobile operator, 3 shifts | 24 |
| 1 Brightening operator, 3 shifts | 24 |
| Sawmill | |
| 13 Hourly workers, 1 shift | 104 |

New Method:

Production: 220 tons of stock/24 hours.

| Pulp Mill | Man Hours |
|---|---|
| 1 Lead chip refiner operator, 3 shifts | 24 |
| 1 #2 chip refiner operator, 3 shifts | 24 |
| Additional | |
| 1 Chip handling system operator, 1 shift | 8 |

The above figures show that the production of wood and its handling require a total of 152 man hours for every 24 hour period. In the new system, these men are replaced by only one man who takes care of the chip handling system on a one shift basis. In the old system, the production of pulp requires 144 man hours for 150 tons of stock produced in a 24-hour period which is equivalent to 1.04 tons/man hour. In the new system, the two refiner operators, on a three shift basis, produce 220 tons of stock equivalent to 4.58 tons/man hour. See table 10.

Table 10

Summary of Productivity Gains Obtained From Refiner Groundwood Pulp

| | Old Method Grinders | New Method Refiners |
|---|---|---|
| Productivity of Pulp Mill Only (tons of stock/man hour) | 1.04 | 4.6 |
| Overall Productivity, Including Preparation of Logs for Grinders (tons of stock/man hour) | 0.5 | 4.0 |

The above figures must be used with caution because in the overall productivity calculations for the new system (using refiners) the manpower required to produce chips is not included. The production of chips is usually not carried out on the premises, as they are bought as a by-product of sawmills. However, as more and more uses of chips are found and as more and more pulp mills convert to the direct use of chips, some pulp mills may have to produce chips in their own chipping plant (Robinson, 1965).

In the old method of producing stock with stone grinders, the work of the operator consisted solely in filling the pockets of the machine with wood. The work of the refiner operator is of a completely different nature. When the first installation of Bauer refiners took place in 1961, a refiner operator looked after two refiners, two deckers, knotters and a washing and bleaching system equipment which was estimated to be worth about $350,000. Nowadays, the refining system comprises four refiners, consistency regulators, centricleaners, an impressafiner, blending equipment and Cowan screens in addition to the knotters, washing and bleaching systems. All of this equipment is valued at five times the figure of the initial investment. There is still only one operator in charge.

For practical purposes, the refiner operator does not have to perform any physical work except walking around from machine to machine and observing that every piece of equipment under his supervision operates as expected. In another set-up observed by the writer, the equipment was spread over a wide area and on two different stories. Thus considerable walking was required. In a newer set-up, all machines, controls, instruments and panel boards have been consolidated in a small area. Whereas this had reduced the physical effort of the operator, it may be conducive to boredom and may result in less reliable vigilance on the part of the operator.

Information Processing Load of the Refiner Operator

As shown in the integrative path diagram of the refiner operator (see figure 30), the following mental therbligs have been identified:

1. Scanning of inputs - first level.
2. Computing of test results - second level.
3. Controlling trend of variables - second level.

4. Relating inputs - third level.
5. Outputs non-symbolic - first level.
6. Outputs symbolic - second level.
7. Ordering of sequences - special level.

Scanning of Inputs

Appendix E gives a list of the instruments and variables monitored by the operator. An instrument reading was interpreted as equivalent to reducing to zero the uncertainty of which particular pointing setting would take place. Thus if an instrument has ten (10) graduations, the entropy involved in one reading is $\log_2 10 = 3.32$ bits/reading. This calculation is in agreement with our definition of the expected amount of information in a message which would reduce the existing degrees of freedom to zero. See Chapter III. It assumes, as before, that the probabilities of each pointer setting are the same. For the purposes of our calculations, this assumption is sufficient.

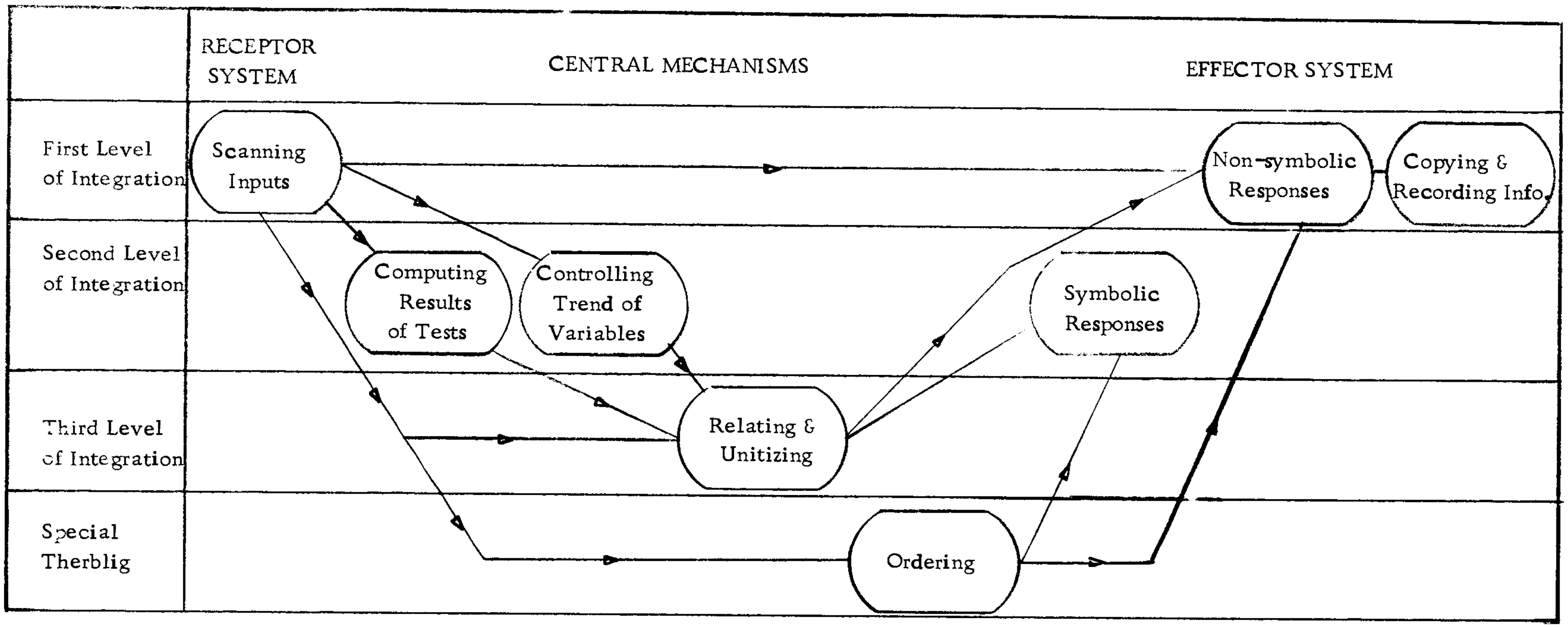



Figure 30. Path of integrative behavior, refiner operator, pulp mill 1.

It was assumed also that the operator performed the scanning of variables four times in one hour. Amount of information scanned per cycle = 490 bits.

## Controlling of Variables

The operator scans his controls and instruments to obtain information on the processes, whose trends he must monitor. These processes include the system which delivers chips to the refiners, the washing of chips, the operation of the refiners, the deckers, screens, brightening equipment, etc.

Given the scanning of variables, controlling their trends involves the same inputs. Behavior has been set to take place at the second level of integration and the information processed in dubits/cycle represents twice the amount of transmission of the first level. Amount of information transmitted per cycle = 490 dubits or 980 bits. As for the scanning of inputs, it was assumed that this mental therblig was performed four times each hour.

## Relating

Because the processes are not independent of each other, a malfunction in any part of the system will affect the others.

Relating is the mental therblig which clearly identifies higher degrees of mechanization and automation. Of all the jobs reviewed in this study to this point, none involved the mental therblig of relating. We may recall emphasizing that the sorter-stacker operator was responsible for performing a sequence of tasks which was repeated over and over again. This was also true of the green chain men, of the sorter-tower operator and of the lumber graders. On the other hand, the refiner could face 'variability in the sequence' i. e. the trend of a variable may start to change in an unforeseen direction. Correcting this malfunction requires behavior of a higher degree of integration than when the sequence of events is repeated. The amount of information processed has been set in the model at three times the amount of information transmitted at the first level of integration. Amount of information transmitted per cycle = 490 tribits or 1470 bits. For the purpose of computing the information processing rate, it will be assumed that relating was only performed once each hour. The effects of performing this function more often will be considered below.

Ordering

Three different lists of tasks were performed in a definite order and, therefore, this therblig was included in the computation. Amount of information transmitted per cycle = 264 bits.

Responses

The writer did not have an opportunity to observe the refiner operator when any action, other than recording the values of the process variables, was necessary. As a result, the type of action which would be required in cases of breakdown or of change had to be assumed. In case of normal operation it was assumed that 490 bits/cycle were transmitted to perform non-symbolic responses and 490 dubits/cycle to perform symbolic responses.

Total information transmitted, refiner operator, normal operation:

| | |
|---|---|
| Scanning, 4 times/hour | 1860 bits/hour |
| Computing | 474 |
| Controlling, 4 cycles/hour | 3920 |
| Relating, 1 cycle/hour | 1470 |
| Ordering | 264 |
| Symbolic responses | 980 |
| Non-symbolic responses | 490 |
| Recording (non-symbolic response) | 490 |
| Total bits/hour | 9948 |
| Average information processing rate bits/sec. | 2.8 |

For more details on these figures see figure 31.

| Scanning Inputs | | Computing Results of Tests | Controlling | Relating | Ordering | Symbolic Responses | Non-symbolic Responses | Recording |
|---|---|---|---|---|---|---|---|---|
| 1) Control instruments | | | | | | | | |
| log 24 = 4.58 | | | Same inputs as in scanning | Same inputs as in scanning | log 22! = 69 | Based on scanning inputs | Based on scanning inputs | Same inputs as in scanning |
| log 10 = 3.32 | | | | | log 14! = 40 | | | |
| log 555 = 9.1 | | | | | log 10! = 23 | | | |
| 3 log 60 = 17.7 | | | | | | | | |
| log 200 = 7.64 | | | | | | | | |
| 2 log 40 = 10.64 | | | | | | | | |
| 6 log 50 = 15.92 | | | | | | | | |
| log 20 = 4.32 | | | | | | | | |
| log 30 = 4.91 | | | | | | | | |
| 3 log 100 = 19.9 | | | | | | | | |
| log 36 = 5.17 | | | | | | | | |
| Sub-total bits/cycle | | 237[a] | | | 132 | | | |
| one machine 103 | | | | | | | | |
| four machines 412 | | | | | | | | 412 |
| Bits/cycle | 412 | | | | 264 | | | |
| 2) Two settings/Hr. | 18 | | | | | | | 18 |
| 3) Foxboro Charts/check/Hr. | 60 | | | | | | | 60 |
| Sub-total bits/cycle | 490 | | | | | | 490 | 490 |
| Sub-total dubits/cycle | | 474 | 490 | | | 490 | | |
| Sub-total tribits/cycle | | | | 490 | | | | |
| Total bits/cycle | 490[a] | 474 | 980 | 1470 | 264 | 980 | 490 | 490 |

[a] See details Appendix E

Figure 31. Information processed by refiner operator, pulp mill #1.

In this instance, the average information processing rate may not be a good indication of the operator's load because his job is to detect abnormal conditions and to deal with them when they occur. The information processing rate of 2. 8 bits/sec. calculated above only reflects the performance of duties when all is well. The mental load, when a malfunction occurs, will concentrate the effort in a short period of time, while the emergency is dealt with. The ability of the operator to deal with this peak rate will depend on whether the amount of information which he must process in this short time does not exceed the capacity of the human communication channel.

For sake of argument, we can assume the following: if a malfunction occurs, in order to locate it and decide what appropriate response is necessary, the operator would have to scan the values of most of his instruments, check (control) their trend and 'relate' this information. These mental therbligs would involve the following amounts of information:

| | |
|---|---|
| Scanning | 490 bits |
| Controlling | 980 |
| Relating | 1470 |
| Total Bits | 2940 |

If we assume, additionally, that the peak capacity of the human communication channel is about seven to eight bits/sec. and that in case of emergency the operator could operate at this rate, he would require say six minutes, to perform the above therbligs. See also figure 44.

This is a relatively long time considering that when a malfunction occurs, it may occur suddenly. The writer witnessed a situation, in another location, in which the machines ground to a halt and did not give enough time for the control operator to react. The above approach is claimed to be useful in systems analysis and design to compare the reaction times of the individual and the requirements of the system. As systems grow more complex, the system designers claim to give the operator enough instrumentation to check the normal trend of the variables and to detect trouble when it arises. However, they should also compare the built-in lags and inertia characteristics of the system to determine whether they are compatible with the informational demands required from the human beings who must control them. The above considerations agree with those expressed by Van Court Hare, Jr. (1967, p. 148) who discusses the requirements which must be met in matching a system and a controller:

> "To obtain complete control of a system the analyst or controller must have three abilities:
>
> 1. At least as many distinct available alternatives as the system can exhibit (or equivalently, the ability to work longer or faster with coded equivalents);
> 2. The precisely correct set of alternatives within the set available to counter those generated by the system (or equivalently, the precisely correct translating ability);
> 3. The processing ability to use these distinct actions (or their coded equivalents) at a rate at least equal to the system to be controlled (or such that the information generated by the controller per unit of time equals that generated by the system)."

The model of integrative behavior, postulated in this study, provides a measure of the average information processing requirement of an industrial job. It can also be used, as shown in the last two pages, to calculate the reaction time required by the system to process the information which it generates.

### 4. The Production of Sulfate (Kraft) Pulp

According to Calkin and Witham (1957, p. 14),

> "Wood chips are cooked in a liquor containing approximately equal parts of caustic soda and sodium sulfide. The name 'sulfate' stems from the fact that chemical losses are replaced with sodium sulfate or sulfur which is reduced to sulfide in the recovery process."

The sulfate pulping process is meant to remove the lignin which binds the cellulose fibers in the wood. Wood and liquor are "cooked" in a steam heated pressure vessel termed the "digester". After the cooking process is completed, the mixture is blown to a tank where the chips disintegrate. The pulp consists of loose fibers of wood which are separated from the spent cooking solution called black liquor (Handbook of Pulp and Paper Technology, 1964, p. 171). The cooking solution of chemicals is recovered in various ways while the pulp is screened to remove uncooked knots and other undesirable materials. The pulp is then sent directly to the paper machines or treated for special purposes prior to being made into paper.

In the present study, the cooking process was of main concern. To give an idea of where the cooking process fits into the overall process of making sulfate pulp, the flow diagram of the Kraft pulping process is shown in figure 32. The piece of equipment designated as the digester will be the center of attention in the sections which follow. This is where the pulp is cooked with the liquor.

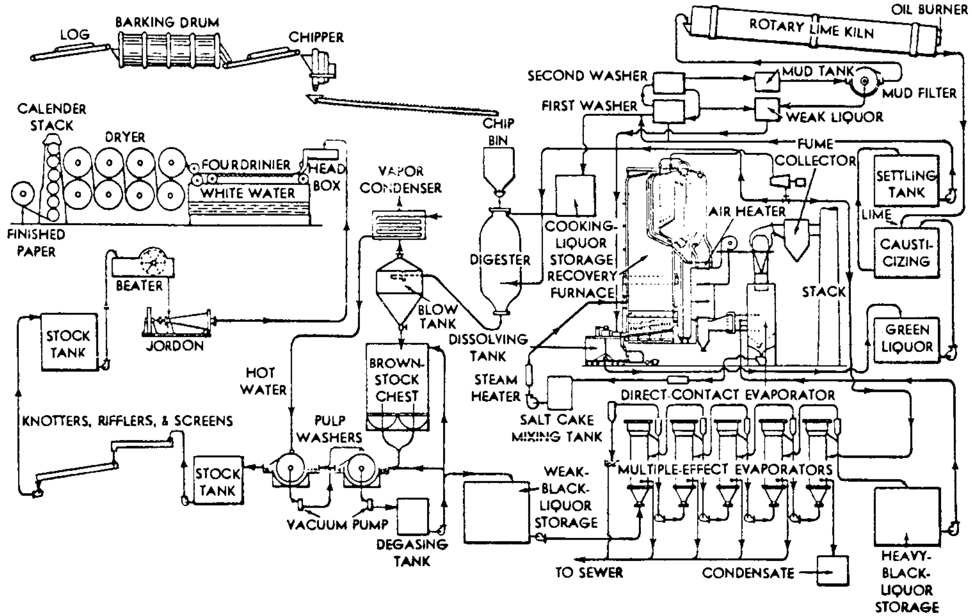



Figure 32. Flow diagram of the kraft pulping process.
(Cited in: Handbook of pulp and paper technology, 1964, p. 171)

Two methods of cooking sulfate pulp will be considered and compared, namely the batch digester and the continuous digester with and without process control computer.

Cooking Kraft Pulp Using a Batch Digester

The batch digester is a one-piece steel vessel designed to withstand high pressure. The Handbook of Pulp and Paper Technology (1964, p. 174) cites a common size being 12 feet in diameter and 45 feet long equivalent to a volume of about 4,000 cubic feet. Figure 33 shows the schematic of a batch digester for kraft. Screen chips are weighed and conveyed into the digester from the chips silos or storage. The amount of chips is carefully monitored by weightometer. Valves to allow white and black liquor to enter the digester are opened. Control valves, set by the operator, monitor the required amount of liquid chemicals required in the digester. Once the proper charge of chips and liquor have been metered, the digester is closed with a pressure valve and the cooking cycle begins as the loaded digester is brought to the appropriate temperature and pressure by the injection of steam. Once the desired temperature and pressure levels have been reached (range of pressure: 100-135 psi; range of temperature: 170-176 degrees C. ), these conditions are maintained for about one hour or more depending on the type of pulp required. When the cooking cycle is considered complete, the digester pressure and temperature are brought down and the charge is blown into a tank after which the liquor and the pulp are separated.

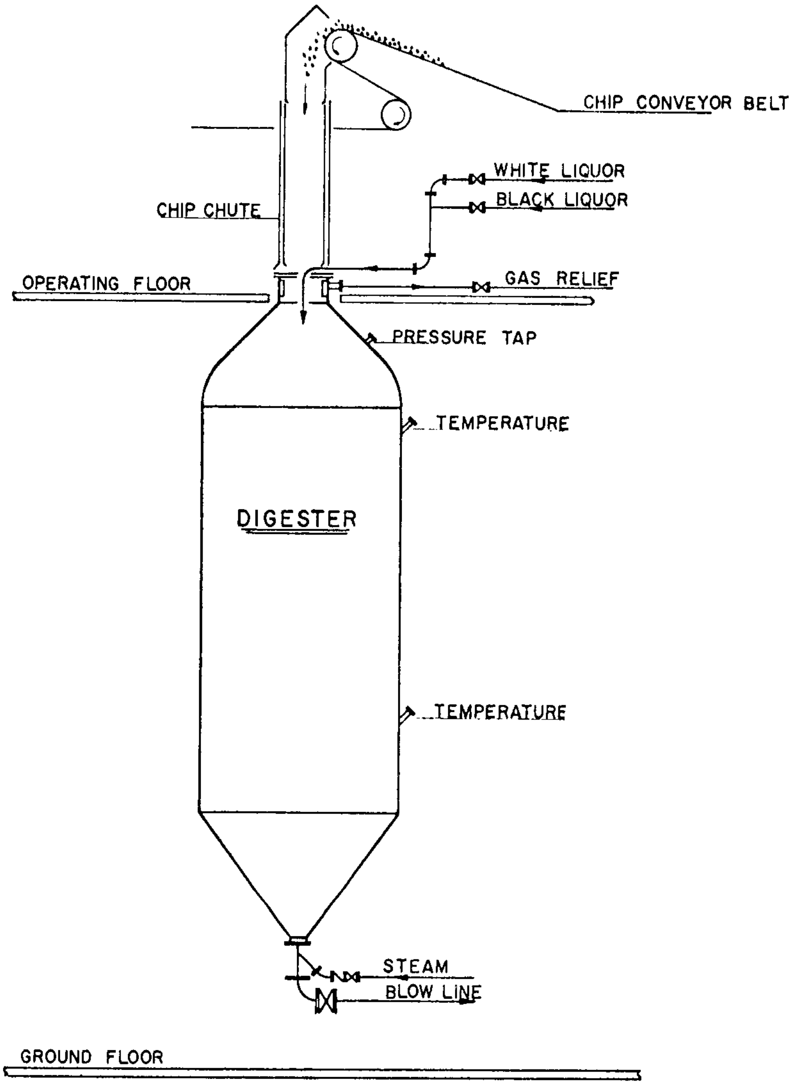



Figure 33. Batch digester for kraft pulp. (Cited in: Handbook of pulp and paper technology, 1964, p. 175)

The Handbook of Pulp and Paper Technology (1964, p. 173) gives the following typical digester charge:

| | |
|---|---|
| Chips, bone dry basis | 25 tons |
| Moisture content of chips | 50 percent |
| Water in chips | 6, 000 gallons |
| Volume of digester | 3, 900 cubit feet |
| Volume of cooking liquor | 14, 500 gallons |
| Black liquor in cooking liquor | 4, 500 gallons |
| White liquor in cooking liquor | 10, 000 gallons |
| Active alkali in white liquor | 0. 78 lb/gallon |
| Total active alkali | 7. 800 lb. |
| Tons pulp produced | 12 tons |
| Active alkali per tons of pulp | 650 lbs. |
| Active alkali basis of dry wood | 15. 6 percent |

The amount of total alkali consumed is a direct function of the amount of wood consumed. The ratio of wood to alkali is an important variable in the process which affects the yield (Handbook of Pulp and Paper Technology, 1964, p. 176).

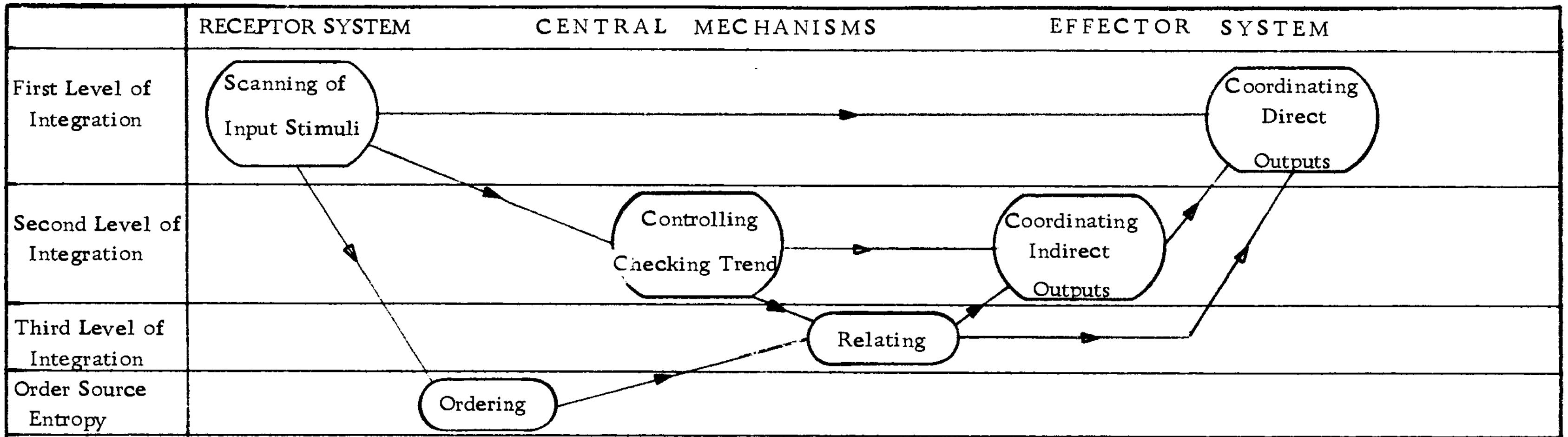
Our concern will turn now to the work involved in operating the batch digester and to the operators who are in charge of performing the required tasks. In the installation studied, two operators looked after seven batch digesters which were charged and discharged in cycle. The cook is the senior worker to whom the cook's helper reports.

The Work of the Cook's Helper

The main responsibility of the cook's helper consists of filling the digester with the proper charge of chips and chemicals (liquor). In the installation visited for this project, seven digesters are filled in cycle. After the filling procedure for one digester is completed, the cook seals the vessel and proceeds to apply steam to raise temperature and pressure. After the cooking cycle is completed, the contents of the digester are blown out into a tank and the filling procedure started anew.

Appendix F shows in detail the steps followed by the cook's helper to accomplish the filling procedure. He manually controls the flow of chips which arrive by conveyor. The flow of white liquor, black liquor and knots is also controlled manually although once the required amount is set, an automatic valve system meters the quantity desired. The cook's helper starts and stops the chip conveyor several times during the process to fill the digester to capacity.

Figure 34 shows the integrative path and information processing flow attributed to the cook's helper. His information functions mostly comprise the scanning of input stimuli and the checking of variables. Little or no relating can be detected. His job requires him to perform direct responses. The total information transmitted per cycle amounts to 523 bits/cycle. It was estimated that the working cycle took only 15 minutes which would mean an average information processing rate of 0. 58 bits/cycle. If on the other hand, the average




| | | | | | | |
|---|---|---|---|---|---|---|
| | 2 log 20 = 8.64[a] | | 2 (log 20) = 8.64 | 2 log 20 = 8.64 | | |
| | 3 log 3 = 4.74 | | | | 3 log 3 = 4.74 | |
| | log 55 = 5.78 | log 30! = 120 bits/sec. | log 55 = 5.78 | log 55 = 5.78 | 2 (log 55) = 11.6 | |
| | 18 (log 2) = 18.0 | | | | 4 log 20 = 17.2 | |
| | 3 log 5 = 7.0 | | | | 18 (log 2) = 18.0 | |
| | 10 (log 4) = 20.0 | | | | 3 log 5 = 7.0 | |
| | log 160 = 7.3 | | log 160 = 7.3 | | 10 log 4 = 20.0 | |
| | log 280 = 8.1 | | log 280 = 8.1 | | log 300 = 8.3 | |
| | 2 log 55 = 11.6 | | 2 log 55 = 11.6 | | | |
| | log 286 = 8.2 | | log 286 = 8.2 | | | |
| | 3 log 300 = 25.0 | | 3 log 300 = 25.0 | | | |
| | 124.4 | | 74.6 | 14.4 | 86.8 | |
| | bits/c. | | dubits/c. | tribits/c. | bits/c. | |
| Total bits/cycle | 124.4 | 120.0 | 149.2 | 43.3 | 86.8 | 523.7 |

[a] For details see Appendix F.

Average information processing rate (1) Cycle takes 15 mins. $\frac{523}{15 \times 60} = 0.58$ bits/sec.

(2) Based on 2.1 cycles/Hr. $\frac{523 \times 2.1}{3600} = 0.31$ bits/sec.

Figure 34. Path of integrative behavior, cook's helper, batch digester, pulp mill #2.

rate were to be calculated on the basis of the number of cycles performed per hour, (2.1 times per hour) the average information processing rate would only be 0.31 bits/sec.

The Work of the Cook, Batch Digester

The cook is the senior worker in charge of the operation of the batch digesters. He supervises the work of the cook's helper and at the same time performs several tasks. In the first place, he takes over from the helper as soon as the latter has completed the filling procedure. He places a lock in the digester aperture, checks that the appropriate liquor valves are closed and opens the steam valve to allow steam into the vessel. The cooking cycle consists of bringing the digester to an established temperature and pressure and keeping it there for about an hour. The cook's main job consists at all times of checking the automatic controls which maintain temperature and pressure in the digester. Once the cooking cycle is over, the blowout procedure consists of emptying the digester into the blow tank. Again the main concern is to ensure at all times that control is exercised on the steam valves and on the state of the process. Like a stationary engineer, the cook's concern is for safety, as the digester operates at about 80 psi and 300 degrees F.

The Information Processing Flow of the Cook, Batch Digester

The path of integrative behavior for the work performed by the batch digester cook can be established on the basis of the tasks which he performs. See Appendix G.

The following mental therbligs are involved:

1. Scanning, as it concerns the input stimuli.

2. Computing (calculation of the digester charge).

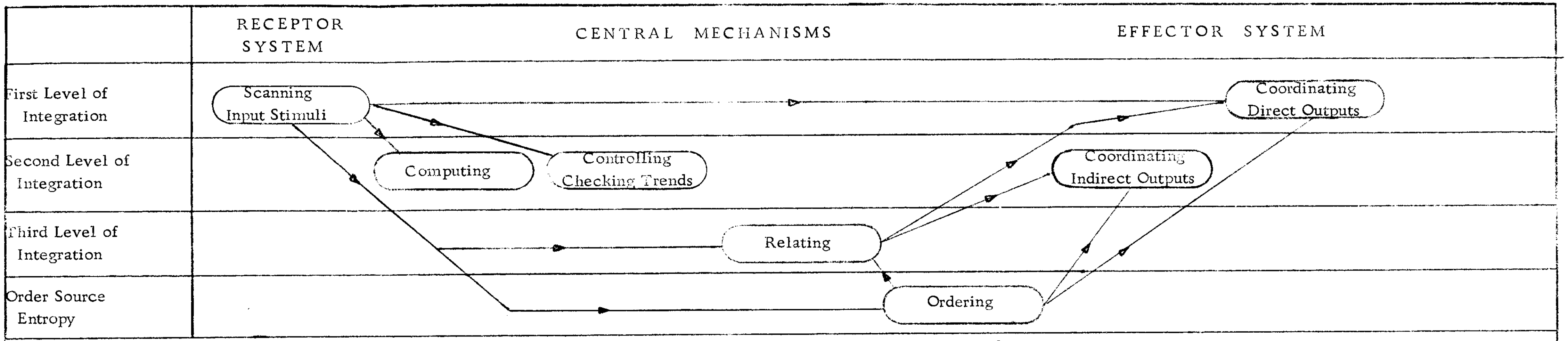
3. Controlling i. e. checking the trend of the process variables.

4. Relating i. e. predicting the course of the process on the basis of an understanding of the relationship among the variables.

5. Coordinating symbolic and non-symbolic responses, including keeping records.

6. Ordering the items of a list or sequence of tasks.

In this case, the simplified version of the integrative behavior model was applied. See Figure 35. Given that the operator scans 84 bits/cycle, the mental therbligs of computing, controlling and of relating contribute 581 bits/cycle. Ordering represents 194 bits/cycle. These four therbligs are performed in a span of ten minutes. The partial information processing rate calculated on the basis of these therbligs is equal to 1. 3 bits/sec. If all the therbligs are taken into account and averaged out over the total cycle of about 28 minutes, an average information processing rate of 0. 7 bits/sec. is obtained.




5 x log 65 = 30.1
5 x log 45 = 27.1
2 x log 20 = 8.64
log 70 = 6.13
2 x log 20 = 8.64
log 10 = 3.32
bits/c 83.9

2(log 17!) = 96
2(log 15!) = 81
2(log 7!) = 17
bits/c 194

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | log N = 84.0[1/] bits/cycle | log N = 84.0 dubits/cycle | log N = 84.0 dubits/cycle | log N = 84.0 tribits/cycle | 194 bits/cycle | log N = 84 dubits/cycle | Total bits/cycle |
| Equivalent bits/cycle | 84.0 | 168.0 | 168.0 | 252.0 | 194.0 | 168.0 | 1034 |

Average information processing rates (1) Based on therbligs in central mechanisms performed in 10 mins. $= \frac{782}{10 \times 60} = 1.3$ bits/sec.

Based on 2.1 cycles/Hr. all therbligs $= \frac{1034 \times 2.1}{3600} = 0.7$ bits/sec.

[1/] See Appendix G

Figure 35. Path of integrative behavior and mental therbligs, cook, batch digester.

The Continuous Digester

The cycle of events which take place in the batch digester can be performed continuously in the continuous digester. Thus, instead of loading each vessel and cooking in batches, the mass of chips are fed with the cooking liquors at the top and the pulp is extracted at the bottom in a continuous stream. The first commercially successful continuous digester was built by Kamyr, Inc. in 1950. One of these units was surveyed for the present study. According to the Handbook of Pulp and Paper Technology (1964, p. 176), the use of continuous digesters provides lower capital investment per unit of product, reduced labor costs, reduced maintenance costs as well as lower operating costs.

The following processes take place continuously in various sections of the digester, a diagram of which is shown in figure 36.

Wood chips are fed from the chip bin to a horizontal steaming vessel where trapped air is removed. The chips are discharged into the vessel and cooking liquor is used to flush the chips and seal the feeder. The chips and the liquor enter the separators at the top of the cooking vessel. The chips are carried through the digester at a rate established by the amount of cooked chips which are discharged at the bottom of the vessel, and by the interplay of complicated by-pass valves, extraction valves and counter flows which can be used to speed or slow down the mass of chips going through the digester. In the impregnation zone, the chips are allowed to impregnate the cooking liquor in a 240 degrees F

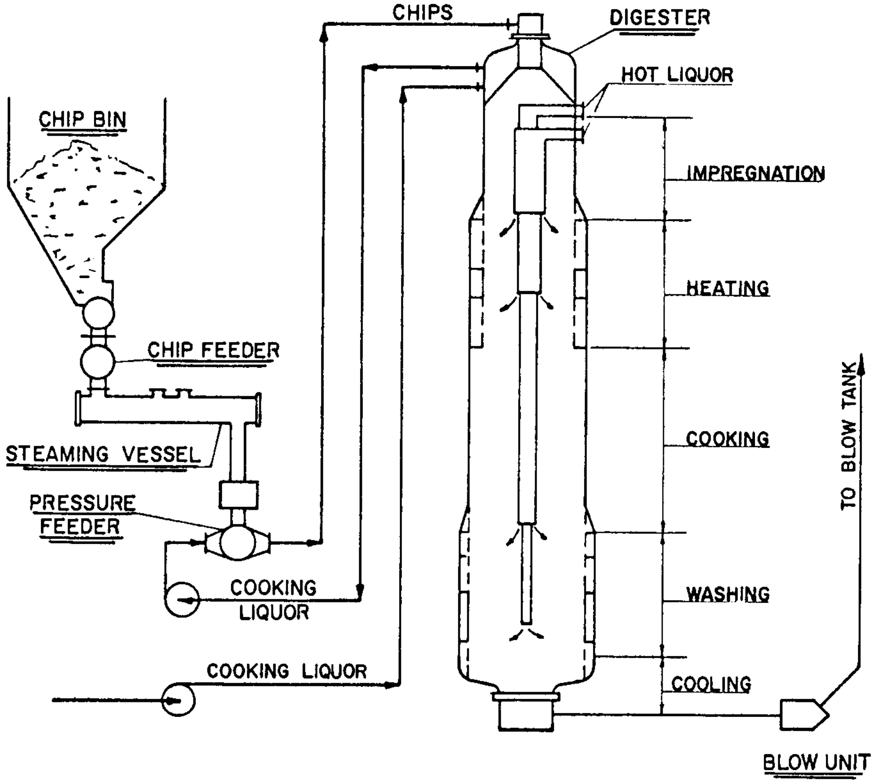



Figure 36. Kamyr continuous digester. (Cited in: Handbook of pulp and paper technology, 1964, p. 177)

zone. In the next zone, the cooking zone, the temperature is raised to 330 degrees F in various stages and the liquor is allowed to react with the chips. The strength of the liquor and its temperature determine the type of kraft pulp which is being produced. In the washing zone, the chips are washed through weak black liquor and finally through a cool wash liquor at about 200 degrees F. At the bottom of the digester, the mass of chips is discharged in blow tanks in a manner similar to the ones used to empty the batch digesters. The same blow tanks may be used. The whole process described above is carried out under pressure. The internal pressure of the digester is maintained at 165 psi.

The chemistry of continuous digesting does not differ considerably from the batch digester process. What is considerably different is the scale of the operation, the type of equipment used and the complexity of the system.

Seven batch digesters produce an average of 18 tons of pulp per hour. The continuous digester produces more than 25 tons of pulp hourly. The book value of the seven batch digesters is in the order of less than $200,000, whereas the Kamyr digester and auxiliary equipment is valued at more than $2 million. These costs are typical for this type of installation.

The continuous digesting operation employs two men who are housed in a control room from which they monitor the progress of the process. The senior operator is called 'Kamyr continuous digester operator'. His assistant is called 'assistant Kamyr operator'. In theory, the senior operator supervises the work of his assistant. In practice, each is concerned with his own portion of the system.

To give an idea of the scope of these men's operation, the following is a broad list of the equipment for which they are responsible:

The Kamyr operator is responsible for: the Kamyr digester, two washers, two steaming vessels, two high pressure feeders, two low-pressure feeders, two chip meters, six liquor heaters, one thick stock pump, one consistency regulator. The Kamyr assistant is responsible only for the washing and screening equipment but the list of which reads as long as the one given above. The main difference between the work of the Kamyr operator and his assistant and the work of the batch digester cook and his helper is that the latter are physically in contact with the equipment which manufactures the product. They see the chips and the cooking liquors as they fill the batch digesters. They seal the vessels by activating valves with their own hands. On the other hand, the Kamyr digester is operated from an isolated remote control room by a maze of complicated instrumentation and controls. The following is a list of the instrumentation in one half of the control room which are the concern of the Kamyr operator. The Kamyr assistant operator is in charge of as many instruments in the second half of the control room.

24 G. E. Type 540-31 controllers

11 Flowmeters

12 Recorders

31 Ammeters

58 On-off controls

4 Increase-decrease controls

10 Speed controls

4 TV cameras

10 Flow diagram lights

14 Alarm board lights

14 Totalizers

In addition, the Kamyr operator must remain informed on the status of processes preceding and following his own, as well as on any occurrence which might have an effect on the progress of his operation. By contrast, the cook in the batch digester is to a certain extent more isolated from the rest of the system although it would be wrong to say that he is completely independent.

One of the most important instruments upon which the Kamyr operator relies to maintain control over the process is the G. E. Type 540-31 controller. An explanation of its function is pertinent.

### The G. E. Type 540-31 Controllers

These are remote adjustment analog set-point controllers. Their main function is to automatically maintain a flow or a pressure at the value which is preset as a 'set-point'. The controllers form part of what is called an instrument control loop which comprises the pipeline through which the flow occurs, a measuring device which measures the flow (probably a flowmeter), a control valve, the

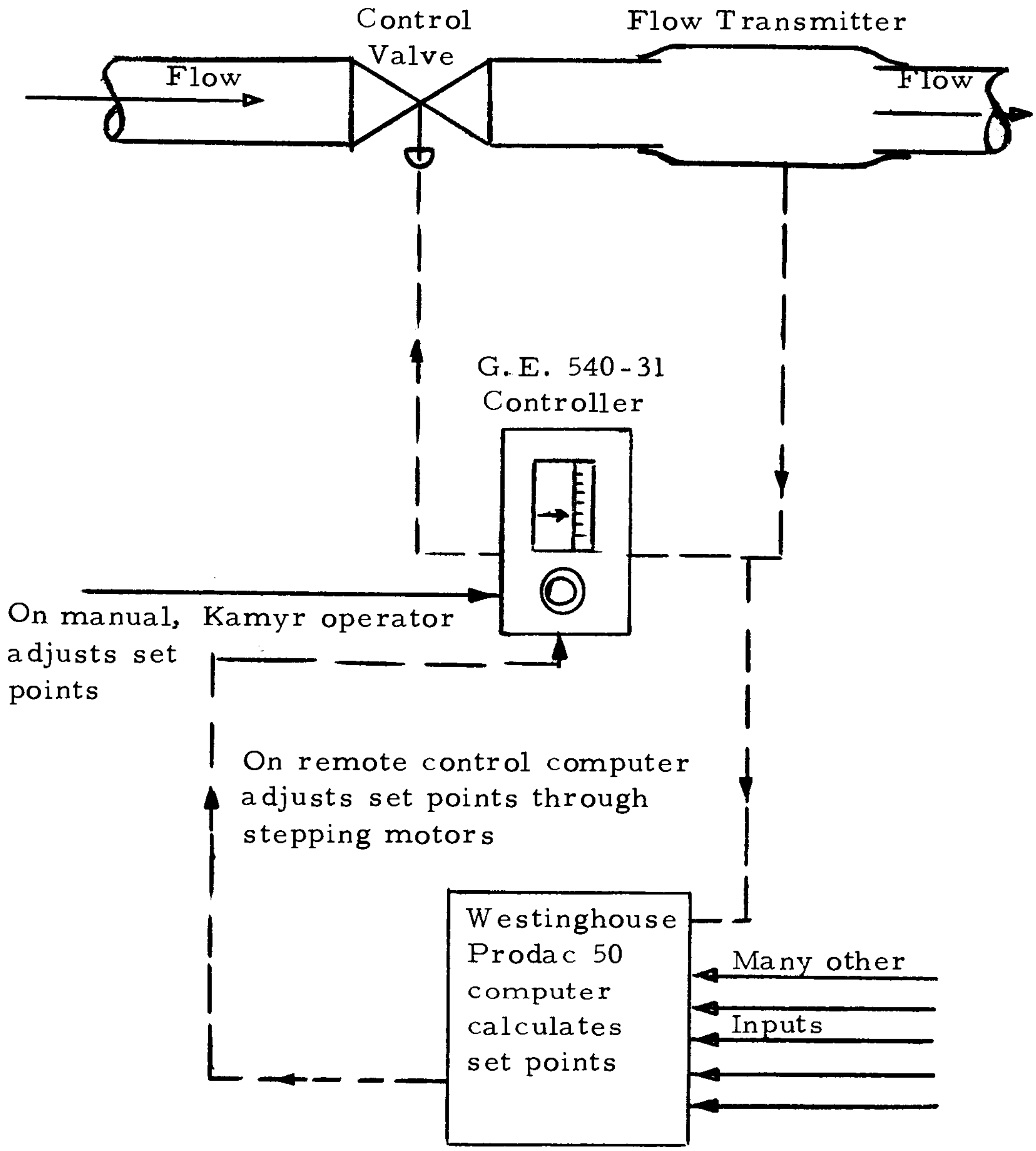



Figure 37. Schematic diagram of instrument loop, Kamyr Digester, pulp mill 2.

controller itself and an operator. A diagram of an instrument loop is shown in figure 37. By manipulating the valve the operator can manually maintain the flow at the required level, or he can set the desired flow level on the controller (establish a set-point) in which case the controller will automatically control the opening of the valve by comparing the reading from the flowmeter and the set-point.

There were 24 controllers and 24 instrument loops in the system studied for this project[2]. This number could, of course, vary depending on the system. Of those 24 loops, the following 12 were considered most important:

1. Chip meter, side 1.
2. Chip meter, side 2.
3. White liquor flow.
4. Upper heater temperature to digester, hot side.
5. Lower heater temperature to digester, hot side.
6. Extraction zone flow.
7. Second stage temperature from digester.
8. Washing zone flow.
9. Lower washing flow temperature to digester, hot side.
10. Counter wash flow.
11. Outlet device speed.
12. Blow line flow.

---

[2] It is felt that the approach used here is general enough that identification of the concern where this study was conducted is not important.

The Process Control Computer

Purposely, no mention was made of the process control computer until now. This is to emphasize that automatic control of the process can be achieved without it. This is an important point often missed when the use of a computer is raised.

The computer used in the installation visited was a Westinghouse Corporation Prodac 50. The auxiliary equipment comprises a teleregister input-output station and an output typewriter reader.

The function of the process control computer is to replace the operator in setting and resetting the set-points in some of the important instrument loops. The computer is programmed to calculate what the value of each variable should be in the process it controls. This calculation is based on several inputs which, of course, differ for each variable considered. The quality of the product and the yield of the process depends on the sophistication of the process control programs used.

The computer receives signals from control instruments which have been converted from analog to digital form. The digital numbers are processed by the computer which calculates the value of the set-point in question. The new value of the set-point is compared with the value calculated previously. If a difference exists, a signal is sent to a stepping motor which adjusts the set-point on the controller which in turn repositions the valve to its new required setting. It is pertinent to mention that the computer calculates new values for each set-point every three minutes and every ten seconds interrogates whether the actual value of the variable in the process differs from the calculated set-point. In case it does, a signal is sent via the controller to reposition the valve setting.

Source Entropy in Instrument Loops: The Computer

In order to calculate the set-points, the computer receives inputs from several instruments. The calculation can be regarded as choosing one value among all the possible ones which may be obtained. In a simple case, the setting for the chip meter only depends on the production rate desired. If there are 14 possible values which the production rate can assume, the expected entropy per setting can be taken as log 14 = 3.8 bits. It is the amount of information required to reduce the uncertainty as to which value will prevail to zero. In the case of a set-point, which depends on more than one variable, the expected entropy will be much larger. As an example:

| Instrument Loop | Variables Entering Calculation | Number of Possible Values For Each Variable |
|---|---|---|
| White liquor flow | Changes in desired K No. | 200 |
| | Changes in white liquor test | 80 |
| | Changes in black liquor test | 100 |
| | Production rate | 14 |

In calculating the set-point for the white liquor instrument loop the computer is choosing one value from the matrix of possible values. The dimension of this matrix is $200 \times 80 \times 100 \times 14 = 2.24 \times 10^7$ alternatives. The expected entropy = 24.4 bits/cycle or setting. A calculation of the total entropy for 12 instrument loops indicates that the computer processes 450 bits each time a calculation of set-points is performed. Table H-1 is a summary of instrument loop entropy as calculated by the computer.

Source Entropy in Instrument Loops: The Operator Without Computer

When the operator does not have a computer to calculate the set-points he has to arrive at a suitable setting by himself. The idea of choosing a value from the matrix of the possible alternatives is a fruitful model to conceptualize the operator's mental process.

In a simple case such as setting the chip meter, the operator relies on the production rate of which 14 different values have been established. Thus the operator, as well as the computer, processes 3.8 bits/setting. In instrument loops which depend on more than one variable, the assumption will be made that the operator's matrix of alternatives is simplified by considering a lesser number of variables, a smaller number of alternative values for each variable and a different degree of accuracy. In the case of the white liquor flow instrument loop, the following matrix is used (This determination was made in conversations with personnel involved in the plant in this operation):

| Instrument Loop | Variables Entering Calculation | Number of Possible Values Considered |
|---|---|---|
| White liquor flow | Chip meter settings | 9 |
| | Active alkali test | 8 |
| | Production rate | 14 |

Size of matrix of possible alternatives = 9 x 8 x 14 = 1008 alternatives. Expected entropy = 9.96 bits/setting. The total instrument loop entropy calculated for 12 set-points which are continuously being reviewed is 60 bits/cycle as shown in Table H-2.

In addition to accuracy and size of matrix, the other fundamental difference between the operator's performance and the computer's is the interval at which these computations are performed. In the case of the computer, we recall, the set-points are recalculated every three minutes and the comparison between the actual and the set point value performed every ten seconds. We shall consider the scanning rate of the operator in a paragraph to follow.

Total Entropy Generated by the Control Room Instrumentation Panel

The control room of a Kamyr digester is very different from a laboratory setting where the information assimilated by a subject can be tested, by displaying a limited number of stimuli at a time. Osborne, Quastler, Tweedell and Wilson (1955), Senders and Cohen (1955) and Senders (1955) report on attempts to measure the amount of information transmitted from complex displays and instrument readings. Unfortunately, none of these methods proved applicable to our industrial setting.

As a start, the total potential information which could be obtained from the panel board instrumentation was calculated. Figure 38 shows that if the operator could embrace and scan all these instruments, the information transmitted by the source would be in the order of 363 bits/cycle.

| Type of Display | Entropy bits/cycle |
|---|---|
| 24 Controllers (assume 20 graduations can be read at any one time) | 35 x log 20 = 104.0 |
| 17 Flowmeters (20 divisions) | 17 x log 20 = 73.4 |
| 12 Recorders (depends on variation of variable. From exhibit I-4) | = 20.9 |
| 31 Ammeters (2 alternatives) | 31 x log 2 = 31.0 |
| 58 On-Off Controls | 58 x log 2 = 58.0 |
| 4 Controls to INC-DEC Flows | 4 x log 2 = 4.0 |
| 10 Speed Controls | 10 x log 20 = 43.2 |
| 4 TV Cameras (Indicate whether to INC or DEC flows) | 4 x log 2 = 4.0 |
| 10 Flow Diagram Lights | 10 x log 2 = 10.0 |
| 14 Alarm Board Lights | 14 x log 2 = 14.0 |
| Potential Source Entropy Generated | bits/cycle = 362.5 |

Figure 38. Source entropy generated by Kamyr digester instrumentation.

On the basis of the simplified model postulated in Chapter V, we can assume:

Number of mental therbligs at first level of integration = 3
(Here, an additional therblig at this level was assumed)

Number of mental therbligs at the second level = 2

Number of mental therbligs at third level = 1

Total amount of information processed is:

| Information at First Level | | Information at Second Level | | Information at Third Level |
|---|---|---|---|---|
| (log N) x 3 | + | (log N) x 2 | + | (log N) x 1 |
| in bits/cycle | | in dubits/cycle | | in tribits/cycle. |

(log N) x 3 + 2x (log N) x 2 + 3 (log N) = 10 (log N) bits/cycle.

Given that log N = 363 bits/cycle, we can calculate the average information processing rate assuming the following scanning rates:

a. If the operator performs all functions ten times/hour (or every 6 minutes):

Average information processing rate =

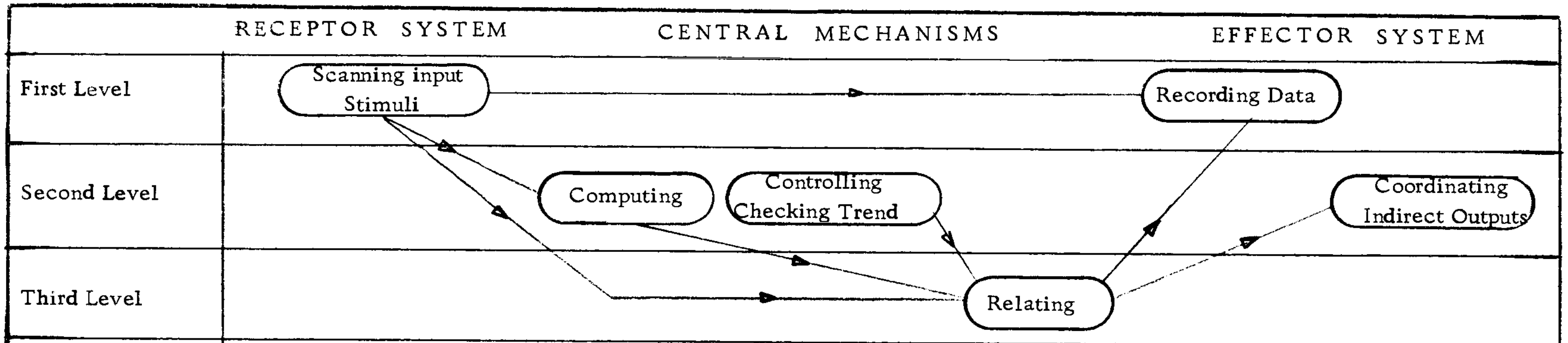
$$\frac{363 \times 10 \times 10}{3600} = 10 \text{ bits/sec.}$$

b. If the operator performs all functions five times/hour (or every 12 minutes):

Average information processing rate =

$$\frac{363 \times 10 \times 5}{3600} = 5 \text{ bits/sec.}$$

The above calculations show that it is doubtful that the operator could scan all the instruments on the panel each time he looks at it. Seven to eight bits can be considered the upper limit for the average capacity of the human channel, as evidenced by results surveyed in this study. As a matter of fact, we also know that "the information value of certain signals changes as skill develops" and that the skilled operator learns to gauge the status of the process by only monitoring key variables (Annett and Kay, 1956 & 1957). According to Kay (1957): "The operator learns that he does not have to pay equal attention to all signals but that some are more significant than others." As a result, Figure 39 was drawn showing how the various mental therbligs were applied selectively to each classification of instrument and control. This information was gleaned from the records available in the mill.




| | | | | | | |
|---|---|---|---|---|---|---|
| 24 Controllers | Check whether within set-points | Calculate set-points | Yes | Calculate set-points | Copy set-points (once/Hr. | Establish set-points |
| 17 Flowmeters | Check those not connected to controllers | No | Yes | Only those not connected with controllers | Copy Reading | No |
| 11 Recorders | Yes | No | Yes | Yes | Copy Reading | No |
| 31 Ammeters | Yes | No | 2 Altern. | No | Only a few readings. | No |
| 58 On-off Controls | No | No | No | No | No | Yes, when starting digester |
| 4 Controls Inc-dec | Only chip supply system | No | Only chip supply system | No | No | Yes, for chip supply system |
| 10 Speed Controls | Yes | No | A few | No | A few | Same |
| 4 TV Cameras | Yes (5 min. intervals) | No | Yes | Yes | No | No |
| 10 Flow Diagram Lights | Yes | No | Yes | Yes | No | No |
| 14 Alarm Panel Board Lights | Will light automatic | No | No | No | No | No |

Figure 39. Selective performance of mental therbligs, Kamyr digester operation without computer.

The Integrative Behavior of the Kamyr Operator Without the Process Control Computer

It is interesting to calculate and compare the average information load of the Kamyr operator in situations with and without computer control. Fortunately, information in this regard was available in the mill visited.

The main difference, resulting from having a process control computer, resides in the automatic computation of the set-points. In the installation surveyed for the present study, the instrumentation included 24 controllers. The computer only relieved the operator of the work of establishing set-points for nine of those 24 controllers, as the remaining 15 were still manually set.

The computation of the set-points is deemed to involve the mental therbligs 'computing' at the second level of integration and 'relating' at the third level, apart from scanning the value of the variables and of setting the controls themselves. To determine a set-point, the operator must not only choose one value from the matrix of all possible alternatives, but he must first build a conceptual model of the operation in order to understand which variables will have a bearing on the particular instrument loop. This information function requires a high degree of skill and a great deal of experience.

The total information load can be calculated in two steps. First, the amount of information transmitted in all mental therbligs except computing and relating set-points can be calculated as it applies to each set of instruments and controls. See figure 40. This

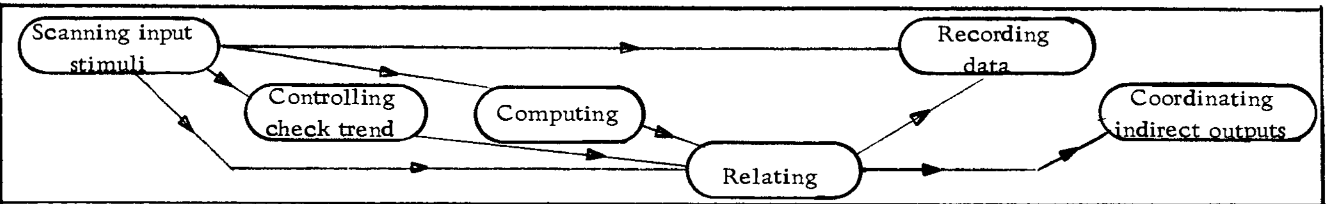
| | | | | | | |
|---|---|---|---|---|---|---|
| First Level<br>Second Level<br>Third Level |  | | | | | |
| Units | Bits | Dubits | Dubits | Tribits | Bits | Dubits |
| 24 Controllers | 19.3[a] | 19.3[a] | See Table 12 | See Table 12 | 19.3 | 19.3 |
| 17 Flow-meters { 5 not connected to controllers | 60 log 20[b] | 60 log 20[b] | No | 60 log 20 | 60 log 20 | - |
| 12 connected | - | - | | | - | - |
| 11 Recorders | 9.7[c] | 9.7[c] | - | 9.7 | 9.7 | - |
| 31 Ammeters | 12 x 31 log 2 | 12 x 31 log 2 | - | 12 x 31 log 2 | 4 x log 20 | - |
| 58 On-off Controls | - | - | - | - | - | 58/24 log 2[f] |
| 4 Inc-Dec Controls | 12 log 2[d] | 12 log 2 | - | 12 log 2 | - | 12 log 2 |
| 10 Speed Controls | 12 x 10 x log 2 | 12x10 log 2 | - | 12x10x log 2 | - | 7 x 12 log 2 |
| 4 TV Cameras | 4 x 12 log 2 | 4 x 12 x log 2 | - | 4 x 12 x log 2 | - | - |
| 10 Flow Diagram Lights | 12 x 10 log 2 | 12 x 10 log 2 | - | 12 x 10 log 2 | - | 12 x 10 log 2 |
| 14 Alarm Panel Board Lights | 0.25 x 14 x log 2[e] | 0.25 x 14 x log 2 | - | 0.25 x 14 x log 2 | - | - |
| | 963.7 bits/Hr. | 963.7 dubits/Hr. | | 944.4 tribits/Hr. | 295.5 bits/Hr. | 246.9 dubits/Hr. |
| bits/Hr. | 963.7 | 1927.4 | | 2833.2 | 295.5 | 493.8 |
| | | | | | Total bits/Hr. | 6513.6 |

Figure 40. Information processing flow Kamyr digester operator, without computer, pulp mill 2

Notes to Figure 40.

a Data from Table I-3, based on audits of continuous signals

b Assumes 12 scans/Hr.

c Data from Table I-4, based on audits of continuous signals

d Chipbin level system

e Assume one alarm every 4 hrs.

f 58 controls set once every 24 hrs.

load amounts to 6514 bits/hour.

Then, the amount of information transmitted in computing and relating set-points can be estimated. This load will depend on the rate at which these therbligs are performed per hour. Three different rates will be assumed below to arrive at the average information processing rates. Computing involves 60 dubits/cycle and relating 60 tribits per cycle based on the source entropy calculated in a preceding section for 12 instrument loops. As a result, based on an average entropy of 25 bits/set-point/cycle, an equivalent 600 bits/cycle will be transmitted when calculating and relating 24 set-points. See table below:

Table 11

Amount of Information Transmitted in Computing and Relating Set-Points for Instrument Loops

| | Computing Therblig | Relating Therblig | Total |
|---|---|---|---|
| 12 Instrument Loops[1] | 60 dubits/cycle | 60 tribits/cycle | |
| Average Per Loop | 5 dubits/cycle | 5 tribits/cycle | |
| Total Equivalent Entropy Per Loop | 10 bits/cycle | 15 bits/cycle | 25 bits/c |

[1] See Appendix H-2.

Table 12 shows the final computation of total information content and average information processing rates for three different intervals of instrument loop settings. If controllers are reset every three minutes, the average information processing rate is 5.2 bits/sec. If they are set 12 times per hour the mental content is 3.8 bits/sec. in the average, and it is 2.8 bits/sec. when they are reset every ten minutes.

Table 12

Operation Without Process Computer Aided Control: Total Information Transmitted and Average Information Processing Rates of Kamyr Operator Based on Three Different Setting Intervals

| Time Intervals at Which Set-Points are Calculated cycles/Hr. | Total Information Content in Computing and Relating Therbligs bits/Hr. | Total Info. Content Other Therbligs bits/Hr. | Total bits/Hr. | Average Information Processing Rates bits/sec. |
|---|---|---|---|---|
| 20 cycles/Hr. (every 3 min.) | 600 x 20 = 12,000 | 6514 | 18,654 | 5.2 |
| 12 cycles/Hr. (every 5 min.) | 600 x 12 = 7,200 | 6514 | 13,714 | 3.8 |
| 6 cycles/Hr. (every 10 min.) | 600 x 6 = 3,600 | 6514 | 10,114 | 2.8 |

The Integrative Behavior of the Kamyr Operator With the Process Control Computer

When working with a computer, the following differences in work load take place:

1. The Kamyr operator is relieved of the burden of calculating and setting the set-points for nine computer controlled instrument loops. We recall that the computer recalculates these set-points every three minutes. The Kamyr operator is still left with 15 manually set controllers to monitor.

2. Of the 17 flowmeters, 12 are related to controllers which are computer controlled.

3. Three of the ten speed controls are computer controlled.

4. The Kamyr operator must manually enter data in the computer program by operating the input-output teleregister;

5. He receives output of status and entries by typewriter output reader.

In order to calculate the total information load, we proceed in a manner similar to the preceding section. First, we calculate the total information content of all therbligs, excluding computing and relating the 15 manually controlled set-points.

The mental therbligs which apply to the Kamyr operator's activities when operating with the process computer are shown in Figure 41. The total informational load can be calculated in three steps:

1. Calculate the information transmitted when performing all mental therbligs, excluding those involved in computing and relating the set-points of controllers not under computer control.

2. Calculate the amount of information involved in the therbligs of computing and relating 15 manually set controllers, based on the entropy of 25 bits/cycle per instrument loop. See Table 11.

3. Assume three different intervals for resetting of control points for manually set controllers.

Based on the above procedure, the total information load of the Kamyr operator, when monitoring the process with computer, is of 4.3, 3.4, and 2.8 bits/sec, depending whether 3, 5 or 10 minute intervals for set-point calculation are assumed (see Table 13). These average information processing rates should be compared to those obtained by a similar computation for conditions of no computer assistance (see Table 14).

These results show the following:

For short set-point intervals (3 to 5 minutes), the operator is relieved of some informational load because of the computer. However, this assistance appears to be less effective if one assumes that the operator resets control points less often (intervals of 10 minutes or more). The additional burden of information generated by the input and output computer units offsets the advantages provided by the computer taking over nine controllers and three speed controls.

Notes to Figure 41.

[1] From Exhibit I-3, based on audit of continuous signals

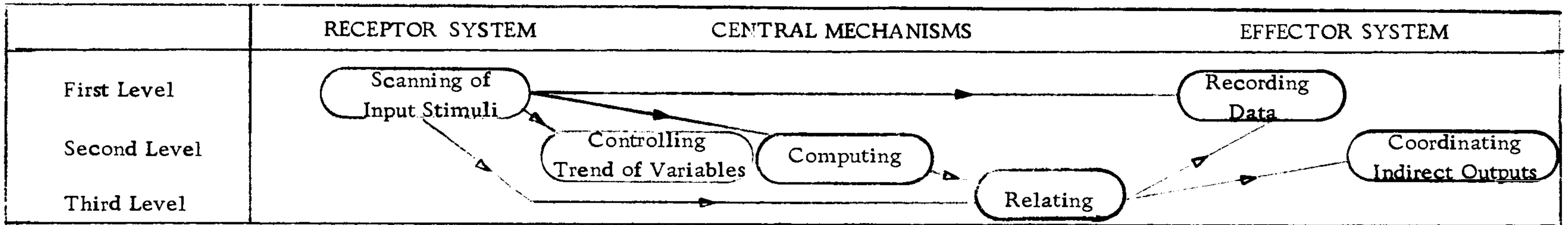
[2] Based on 12 scannings/Hr.

[3] From Exhibit I-4, based on audit of continuous signals

[4] Input, one variable every 1.7 Hrs.

[5] 4 Times/Hr., 30 variables, 4 digits/var.

[6] 58 controls set once every 24 Hrs.




| Units | Bits | Dubits | Dubits | Tribits | Bits | Dubits |
|---|---|---|---|---|---|---|
| 9 Computer set Controllers | | Computer Set and Controlled | | | | |
| 15 Manually Set Controllers | 10.5 1/ | 10.5 1/ | See Table 13 | See Table 13 | 10.5 | 10.5 |
| 12 Flowmeters, Var. Computer Controlled | | | Variables Computer Controlled | | | |
| 5 Flowmeters, Var. Not Comp. Controlled | 5 x 12 log 20 2/ | 5 x 12 log 20 | - | 5 x 12 x log 20 | 5 x log 20 | |
| 11 Recorders | 8.90 3/ | 8.90 | - | 8.90 | 8.90 | |
| 31 Ammeters | 12 x 31 log 2 | 12 x 31 log 2 | - | 12 x 31 x log 2 | 4 log 20 | |
| 58 On-off Cont. | | | | | | 58/24 log 2 6/ |
| 4 Inc-Dec Cont. | 12 log 2 | 12 log 2 | - | 12 log 2 | - | 12 log 2 |
| 3 Computer Cont. Speed Cont. | | | - | | | |
| 7 Manual Speed Controls | 7 x 12 x log 2 | 7 x 12 log 2 | - | 7 x 12 x log 2 | - | 7 x 12 x log 2 |
| 4 TV Cameras | 4 x 12 x log 2 | 4 x 12 log 2 | - | 4 x 12 x log 2 | - | - |
| 10 Flow Diagram Lights | 10 x 12 x log 2 | 10 x 12 log 2 | - | 10 x 12 log 2 | - | 10 x 12 log 2 |
| 14 Alarm Panel Board Lights | 0.24x14 x log 2 | 3.5 log 2 | - | 3.5 log 2 | - | - |
| Console Input to Computer | 10 x log 900 = 5.7 4/ | — | - | 10 log 900 4/ | - | 10 log 900 4/ |
| Typewriter Output Reader | 30 x log 1000 5/ | 30 x log 1000 | - | 30 x log 1000 | - | - |
| | 1221.3 bits/Hr. | 1221.3 dubits/Hr. | | 1210.8 Tribits/Hr. | 58.3 bits/Hr. | 234.6 dubits/Hr. |
| bits/Hr. | 1221.3 | 2442.6 | | 3632.4 | 58.3 | 469.2<br>Total bits/Hr. 7,823.8 |

Figure 41. Path of integrative behavior and information processing flow, Kamyr operator with computer, not including therbligs related set-points.

Table 13. Operation with process controlcomputer: Total information transmitted and average information processing rates of Kamyr operator, based on three different setting intervals.

| Time interval to calculate set-points mins or cycles/Hr. | Total information content in computing and relating therbligs | Total information content other therbligs bits/Hr. | Total bits/Hr. | Average information processing rates bits/sec. |
|---|---|---|---|---|
| 20 cycles/Hr. (every 3 minutes) | 375 x 20 = 7,500 | 7,824 | 15,324 | 4.3 |
| 12 cycles/Hr. (every 5 minutes) | 375 x 12 = 4,500 | 7,824 | 12,324 | 3.4 |
| 6 cycles/Hr. (every 10 minutes) | 375 x 6 = 2,250 | 7,824 | 10,074 | 2.8 |

Table 14. Comparison of average information processing rates of Kamyr operator for conditions with and without process computer control.

| Interval between instrument loop set-points calculations Mins. | Average information processing rates | |
|---|---|---|
| | Without computer bits/sec. | With computer bits/sec. |
| Every 3 minutes or 20 times/Hr. | 5.2 | 4.3 |
| Every 5 minutes or 12 times/Hr. | 3.8 | 3.4 |
| Every 12 minutes or 5 times/Hr. | 2.8 | 2.8 |

The above results are deceiving and do not show the important advantage of having the process control computer.

With the computer, the variability of the process is much greater than when the operator controls the adjustment of all the set-points. This is the conclusion reached in a collateral study of the waveforms of important variables with and without computer control. The method used to measure the variability of the process is the method suggested by Nadler and Seidel (1966) and discussed in Chapter IV. We recall this method was based on the analysis of waveforms and the calculation of the entropy transmitted per unit of time on the basis of the formula:

$$I = n \log N$$

where n is twice the number of inflection points F and N is the number of significant levels found in the waveform per unit of time. An analysis and comparison of the analog signals generated with and without computer show that with the computer the number of inflection points F and the number of levels N is larger than without computer. In other words, the variability of the process is larger with computer control i. e. the process is allowed to vary within broader limits. As a consequence, the total entropy generated is larger. See Table 15. However, with the computer the operator's informational load is smaller, a result which we have already shown.

Table 15

The Increased Variability (Entropy) of the Kamyr Digester Process Operated With Process Control Computer, Pulp Mill Two

| | Operation Without Computer | Operation With Computer | |
|---|---|---|---|
| | Operator bits/Hr. | Operator bits/Hr. | Computer bits/Hr. |
| Entropy Processed by Operator and by Computer | 34.5 | 11.7 | 35.1 |
| Total System Entropy[1] | 34.5 | 46.8 | |

[1] Based on data of 100 hours of study on waveforms. See Table I-1.

With computer, the process yield is improved. This can be directly attributed to the fact that the computer can operate closer to optimization points. By himself, the operator is afraid to push the digester to its ultimate capability. Also, it can be presumed that by using the computer program, the optimum relationship among the variables can be approached more systematically and more consistently. The mental capacity of the operator in this regard is, of course, limited.

# VII. ANALYSIS AND DISCUSSION OF FINDINGS

Figure 42 is a summary tabulation of all the information processing rates obtained during the present study.

## Repetition Cycle Rate Versus Variability of Sequence in the Mental Content of Work

The average information processing rates calculated with the model of integrative behavior show that high mental content can be the result of two different aspects of the nature of work:

a. The repetition rate of the operations cycle; and

b. The degree of variability of the sequence.

These concepts were defined by Annett and Kay (1956).

The relatively high average information processing rates obtained for jobs such as the sorter-tower operator and the lumber graders are the result of high rates at which their operation cycle is repeated. On the other hand, high information rates can also be obtained for jobs where the information content per cycle is very high,and where the cycle rate must be considered nil because the operation is continuous.

In order to bring out the difference between the cycle repetition rate and the degree of variability of the sequence, these two components of the information processing rates are tabulated, separately, in Figure 43. At one extreme, the grading of lumber requires 8 bits/cycle but at peak performance more than 3300 grading cycles are performed per hour. At the other extreme, the Kamyr operator processes more than 13,000 bits/Hr. (no distinct cycle of operation can be assumed to exist).

The mental content of work i. e. the total demand it makes upon the worker should appropriately take into account both the complexity of the job, as measured by the entropy per cycle, and the number of times the operation has to be performed in a given period of time. Each of these two elements - entropy per cycle and repetition rate - can be evaluated separately. They define different skill requirements. The high repetition rate with low entropy per cycle may be an operation which can lend itself to further mechanization. It requires from the operator a relatively high proportion of physical to mental load. On the other hand, the process with high entropy and practically non-existant cycle only requires mental effort and no physical effort. Its inherent variability may be fruitful ground for further automation.

In summary, high information processing rates can point the way to further mechanization or further automation depending whether they can be attributed to a high repetition rate or a high entropy content per cycle.

| LOWER LEVELS OF TECHNOLOGY | bits/sec. | HIGHER LEVELS OF TECHNOLOGY | bits/sec. |
|---|---|---|---|
| **LUMBER SORTING, MANUAL CHAIN** | | **LUMBER SORTING, MECHANICAL SORTING** | |
| Typical, 1st man on chain, Mill #1 | 0.59-0.96 | New Jobs: Sorter-Tower Operator | 2.38 |
| 2nd man on chain | 0.42-0.63 | Sorter-Stacker Operator | 0.35 |
| 3rd man | 0.27-0.39 | | |
| **GRADING OF LUMBER, NO M/C ASSISTANCE** | | **GRADING OF LUMBER WITH EMSR M/C** | |
| Grader, no machine assistance | 3.2 | 1st Grader with E.M.S.R. M/C assist. | avg. 4.5 |
| | | | peak 7.5 |
| | | 2nd Grader | avg. 2.1 |
| | | 3rd Man | avg. 1.4 |
| **PRODUCTION OF GROUNDWOOD PULP, GRINDER** | | **PRODUCTION OF GROUNDWOOD PULP, REFINERS** | |
| Grinderman, 3 pocket grinder | 0.16 | Refiner Operator | avg. 2.8 |
| Foreman | 0.25 | | |
| **PRODUCTION OF KRAFT PULP, BATCH DIGESTER** | | **PRODUCTION OF KRAFT PULP, CONTINUOUS DIGESTER** | |
| Cook's helper | 0.31-0.58 | | |
| Cook | 0.7 -1.3 | | |

PRODUCTION OF KRAFT PULP, CONTINUOUS DIGESTER

| Kamyr operator Assuming setting of controller set-points | without computer bits/sec. | with computer bits/sec. |
|---|---|---|
| every 3 mins. | 5.2 | 4.3 |
| every 5 mins. | 3.8 | 3.4 |
| every 10 mins. | 2.8 | 2.8 |

Figure 42. Summary of all information processing rates obtained during study.

| | Degree of Variability of Sequence | Rate of Repetition of Sequence | Job No. |
|---|---|---|---|
| **LUMBER SORTING, MANUAL CHAIN** | bits/cycle | cycle/Hr. | |
| 1st man, sorting chain | 20.9-16.0 | 100-217 | (1) |
| 2nd man | 15.1-10.4 | 100-217 | |
| 3rd man | 9.7- 5.7 | 100-217 | |
| **GRADING OF LUMBER, NO M/C ASSISTANCE** | | | |
| Grader | 7.6 | 1500 | (2) |
| **PRODUCTION OF GROUNDWOOD PULP, GRINDER** | | | |
| Grinderman | 12.6 | 45 | (3) |
| Foreman | 898.4 | 1 | (4) |
| **PRODUCTION OF KRAFT PULP, BATCH DIGESTER** | | | |
| Cook's helper | 524 | 2.1 | (5) |
| Cook | 1034 | 2.1 | (6) |

| | Degree of Variability of Sequence | Rate of Repetition of Sequence | Job No. |
|---|---|---|---|
| **LUMBER SORTING, MECHANICAL SORTER** | bits/cycle | cycles/Hr. | |
| Sorter-tower operator | 7.5 | 1224 | (7) |
| Sorter-stacker operator | 311 | 4 | (8) |
| **GRADING OF LUMBER, WITH EMSR M/C** | | | |
| 1st grader, with M/C | avg. 7.96 | 2040 | (9) |
| | peak 7.96 | 3360 | (10) |
| 2nd grader with M/C | avg. 7.96 | 960 | (11) |
| 3rd man | avg. 4.9 | 1020 | (12) |
| **PRODUCTION OF GROUNDWOOD PULP, REFINER** | | | |
| Refiner operator | 2487 | 4 (avg.) | (13) |
| **PRODUCTION OF KRAFT PULP, CONTINUOUS DIGESTER** | | | |
| Kamyr operator | | | |
| Without process control computer* | 13,714 | less than 1 | (14) |
| With process control computer | 12,324 | less than 1 | (15) |

* Assumes setting set-points every 5 minutes

Figure 43. Breakdown of information processing rates in terms of degree of variability and rate of repetition of sequence.

## The Mental Content of Work and the Levels of Technology

The impact of technology on the various processes chosen for study can be analyzed by comparing the typical jobs which represent different levels of mechanization.

### Sorting of Lumber

The job of the lumber chainman is typified in Table 16 where various attributes of the system and context of work are described. The most striking feature of this type of work is the limited scope of the activities performed. Previous studies (van Gigch, 1967) have emphasized the physical and work measurement aspects of this work by developing a mathematical model of the system and the mental aspect had been set aside. The present study shows that the mental load of the sorting operator cannot be neglected. The informational load of each operator depends, of course, on the position he has on the chain, on the arrival rate of the lumber and on the number of loads for which he is responsible. It is estimated that he processes between 15 to 20 bits per sorting cycle. By contrast, the new job of sorter-tower operator only requires 8 bits/cycle. Taken on a per cycle basis, the mental load of the new operator appears to be lower than for the sorting chainman. However, the high repetition cycle rate makes the sorter-tower operator's total informational load more demanding than for the sorting man. The effect of this repetition rate on the total mental load is also apparent in the case of the grader's work.

Table 16. Comparison of lumber sorting at two levels of technology.

| | Manual sorting chairman | Sorter-tower operator |
|---|---|---|
| System in charge | Can only be said to be in charge of the loads of lumber . | Consists of the mechanical conveyors and memory system which operates gates and trays. He can start and stop the equipment from his central console. |
| Control functions | Only concerned with the destination of boards of lumber travelling on the conveyor | Concerned with the operation of the whole system as well as relating outstanding customer orders to incoming lumber. |
| Main nature of tasks | Pulls lumber from conveyor | Controls flow of lumber through his position by activating foot pedals and gate controls. |
| Sequence of activities | Limited to a few motions | Limited to a few tasks. |
| Repetition rate | Depends on lumber arrival rate and number of loads. Repetition rate can be relatively high | Depends on lumber arrival rate. Repetition rate is usually higher than for manual sorting systems. |
| Timing of tasks | Rigid | Rigid and dictated by machine requirements. |
| Variability of sequence | Almost nil | Almost nil. |
| Mental therbligs | Involves coordinating input stimuli with appropriate response. Overlearned with practice | Only involves scanning of input and direct outputs. Limited feedback is required. |
| Levels of integration | Only involves mental therbligs at first level of integration. Mental content of each cycle is higher than for the sorter tower operator | Mental content of each cycle is very low. |
| SUMMARY | | |
| Repetition rate, cycles/hr. | 100-217 | 1224 |
| Entropy per cycle, bits/c. | 16.- 20.9 | 7.5 |
| Information processing rate bits/sec. | 0.59- 0.96 | 2.4 |

Grading of Lumber

Grading of lumber with the EMSR machine or continuous tester may be a technological advance but all the benefits which could be derived from it are nullified by the addition of three men to the line. A discussion of the reasons for this set-up are not within the scope of this study.

The system of having three graders re-grade the machine graded lumber can only be temporary. Therefore, a comparison of the two levels of technology (with and without the stress grading machine) is not appropriate. Nonetheless, the study of the mental content of graders provided important results.

The graders were found to work at very high rates of performance, paced by the output of the EMSR machine. Consequently, they had to process the boards of lumber and grade it at what seemed to be impossible speeds. The lumber arrival rate reached 56 pieces per minute and, on that basis, a peak information processing rate of 7.5 bits/sec. was calculated. The average sustained rate was found to be 4.5 bits/sec. Thus, the mental content of this type of work is relatively high. It would have been appropriate to determine the level of errors which accompanied these rates. Equivocation lowers the entropy transmitted by a source. However, this information was not obtained.

Production of Groundwood Pulp

A better assessment of the impact of technology of the mental content of work can be obtained from the comparison of the jobs chosen for review in the pulp mills.

The grinderman and the refiner operator truly represent different generations in the historical development of groundwood pulp. It was, indeed, fortunate to see them at work side by side. The attributes of the job and work systems are compared in Table 17.

The grinderman's job is slowly being phased out and replaced by that of the refiner operator. The transition step is very big. The average information processing rate of the grinderman is 0.16 bits/sec., the lowest of all jobs surveyed in this study. This confirms the low mental demand made on this type of operator. On the other hand, the refiner operator is asked to process 2.8 bits/sec., on the average, under normal operation conditions. In all probability, a malfunction would make additional informational requirements on the operator which were not assessed. As shown in Table 17, the information content of the grinderman's work cycle is very small (12.6 bits/c) when compared to the information flow transmitted by the refiner operator (2,490 bits/c). The production of groundwood pulp from chips is a continuous process. No operation cycle can be measured. The operator repeated certain activities each hour. To that extent, a round of tasks could be identified.

Table 17. Comparison of groundwood production at two levels of technology.

| | Grinderman | Refiner operator |
|---|---|---|
| System in charge | Consists of two machines and inputs and outputs directly related to operation | Consists of a process with different types of machines and equipment feeding products into one another at different stages of manufacture. |
| Control functions | Oversees the conversion of the material fed into the machines | Same as the grinderman, except that scope of operations is larger. Must monitor the operation of different types of equipment. |
| Main nature of tasks | To accomplish a series of tasks which are repetitive | Work can best be described in terms of broad responsibilities to keep process running turning out the required output. |
| Sequence of activities | Sequence is fixed | Sequence difficult to establish. |
| Repetition rate | Higher than refiner operator | Low |
| Timing of tasks | Rigid and pre-established | Flexible and at the discretion of operator. |
| Variability of sequence | Sequence involves few variables. Vary within narrow range. Information content of cycle is low | Sequence involves many variables. Involves decisions within broad ranges. Information content of cycle is high. |
| Mental therbligs | Only involves scanning of input stimuli and coordinating direct responses | Involves all types of mental therbligs. |
| Levels of integration | Only involves mental therbligs at first level of integration | Information processing is heavily weighed toward higher levels of integration due to the complexity of mental requirements. |
| SUMMARY | | |
| Repetition rate, cycles/hr. | 45 | 4 |
| Entropy per cycle, bits/c. | 12.6 | 2,487 |
| Information processing rate bits/sec. | 0.16 | 2.8 |

Production of Kraft Pulp

The batch digester operator processes an average of 0. 7 bits/sec. and in certain cases his information processing rate goes up to 1. 3 bits/sec. This is considerably lower than the informational load placed on the Kamyr digester operator, who, without the computer assistance, transmits about 3. 8 bits/sec. Because no operation cycle can be identified, the high rate is solely due to the information content and not to repetition rate, as was the case for the graders.

The Kamyr operator's job had the highest information content per cycle of all the jobs surveyed. This was obviously the result of the large entropy generated by the displays, which the operator used to gain knowledge of the state of the system. The calculation of information processing rates for operation with and without computer shows that the computer, to a certain extent, reduces the mental content of the job. However, the computer only relieves the operator of a very small portion of the total information processing load (9 controllers and 3 speed controls). As a matter of fact, it was shown that the computer increases the variability of sequence i. e. with computer control the process is allowed to vary within broader limits. The computer, indeed, controls the increased entropy which results. However, the operator must always back the computer and stand by in case a malfunction occurs. In this case, the operator must take over and operate the process without the computer. A comparison of the jobs of producing kraft pulp at two levels of technology is given in Table 18.

Table 18. Comparison of kraft pulp production at two levels of technology.

| | Batch digester operator (cook) | Kamyr digester operator |
|---|---|---|
| System in charge | Operates seven batch digesters. Operator is in direct contact with the equipment. Can see the inputs and outputs to his system | Overlooks the operation of an integrated system of related processes. Does not have direct contact with inputs and outputs except through readings of gauges. |
| Control functions | Manipulation of the equipment is direct | Operates the equipment by remote control through controllers, speed controls, buttons and the like. |
| Nature of tasks | To accomplish a repetitive sequence of tasks | Operator has no established sequence of tasks to perform. However, in order to maintain control over the process he carefully checks in turn all important variables and their respective trends. |
| Sequence of activities | Sequence is fixed | No established sequence except in starting and closing down. |
| Repetition rate | Low, due to the nature of the process. But fixed. | No repetition. |
| Timing of tasks | Rigid and pre-established | Controlled by themarch of the process. |
| Variability of sequence | Sequence involves relatively few variables the values of which must always be the same in each cyle. Relatively low entropy per cycle. | Operator is faced with a situation which in a continuous state of flux. Information content is high because uncertainty prevails. |
| Mental therbligs | Involves therbligs at first and second levels of integration. Relating is not prevalent | Informational load is mainly concentrated in higher levels of integration although informational load from scanning of input stimuli is high due to the amount of instrumentation dealt with. |
| SUMMARY | | |
| Repetition rate, cycles/hr. | 2.1 | - |
| Entropy per cycle, bits/c. | 1,034 | 13,714 |
| Information processing rate bits/sec. | 0.7-1.3 | 3.4-3.8 |

## The Mental Content of Work and Average Versus Peak Information Processing Rates

At first,it may appear unreasonable to obtain information processing rates for the stress grading job which are higher or of the same order of magnitude as those obtained for the Kamyr digester operator. However, it is important to point out that the peak information processing rate obtained for the grader of 7. 5 bits/sec. can be considered close to the maximum rate which can be obtained for this type of work. It is the highest rate which individuals can reach for brief moments, a matter of minutes, in the context of industrial operations. The average rate of 4. 5 bits/sec. was sustained for longer periods of time, perhaps half-hour stretches. When the average rate was obtained, it was also felt that the operator was working hard and that the high lumber arrival rate was pushing him to perform close to his physical and mental capacity.

The information processing rate obtained for the Kamyr digester is an average rate but does not represent a maximum. The operator is responsible for monitoring the process and ensuring that the equipment is running adequately. To keep the process within normal bounds, the operator exercises a watchful eye over the trend of every variable. Because trends take a certain time to develop and because the design of the control system provides the operator with advance signals, he is in a position to anticipate and take measures to counteract impending changes. The maximum rate for an operator such as the Kamyr operator can be simulated (see next section) but would be difficult to obtain in the industrial setting. It would occur in times of emergencies when the operator would have to take action caused by a sudden malfunction.

For industrial purposes, it is important to know both the average and the peak information processing rates of each job against which the mental capacity of individual operators can be evaluated. Maximum rates, where obtainable, can be used as standards to compare the mental content of jobs and the mental load of workers.

## The Mental Content of Work and the Speed of Response

The model of integrative behavior affords a method to calculate the total amount of information which workers in industrial settings must face during the normal course of their work. It can also be used to calculate the information requirements and the times required to transmit information prior to obtaining a response. These calculations are shown in Figure 44. As was intuitively obvious, response times[3] increase with the complexity of the system which must be handled. When the operator has only one machine to control, as is the case of the grinderman in the groundwood pulp mill, only a fraction of a minute is required to handle the hypothetical informational load created by a malfunction. As the system grows in complexity, the response times increase. The batch digester cook would require one minute, the refiner operator in the kraft pulp mill

[3] Response times are not to be confused with reaction times presented in chapter III, p. 30. Reaction times are minimum times required by the central mechanisms to operate upon the presentation of simple stimuli, whereas response times are related to the total times required by the individual to organize a response to inputs.

six minutes, and the Kamyr digester operator would need 12 minutes to cope with the situation. Whereas these figures are simulated, the concept of calculating the time required to handle the information load, in times of malfunctions, is of the utmost importance to system designers, engineers and managers alike. In actual fact, operators such as the refiner operator in the groundwood pulp mill or the Kamyr digester operator are really hired to handle the situations when the automatic portion of the control system cannot operate. Even if he is idle the rest of the time, he justifies his wage when he can prevent a breakdown or when he averts further damage. The control equipment is really designed to control the process under normal circumstances. When the situation leaves normal bounds, the control system rings the alarm and the operator must take over.

The use of the process control computer, in many respects, paradoxical because it allows the process to fluctuate more widely than when the operator manually adjusted the set-points on all the controllers. In addition, the computer increases the informational load of the operator because of the additional information generated by the input and output units. Finally, when the process wanders beyond certain pre-established limits, the computer rings the alarm and the operator must take over as if no computer existed. The computer cannot be justified in terms of the possible relief of informational load which it may provide to the Kamyr operator. On the other hand, it probably pays for itself many times over because of the increased yield which can be obtained in the cooking process. No figures on this improvement were available in the mill surveyed.

| | Grinderman<br>groundwood pulp<br>From Fig. 27 | Refiner Operator<br>groundwood pulp<br>From Fig. 31 | Cook<br>Batch Digester<br>kraft pulp mill<br>From Fig. 35 | Kamyr Digester<br>kraft pulp mill<br>From Fig. 40 |
|---|---|---|---|---|
| Scanning therblig | 4 | 490 | 84 | 964 |
| Controlling therblig | 8[1] | 980 | 168 | 1928[2] |
| Relating therblig | 12[1] | 1470 | 252 | 2892[2] |
| Total bits | 24 | 2940 | 504 | 5784 |
| Response time based on max capacity of 7.5 bits/sec. | 3.2 secs | 6 mins say | 1 min say | 12 mins say |

[1] Added here for purposes of comparison on the basis of log N dubits and log N tribits respectively.

[2] Does not include entropy of controllers, figures are therefore underestimated.

Figure 44. Calculation of simulated response times for four different work systems.

## The Mental Content of Work and Compensation

Compensation is usually a function of prevailing rates in the industry or in the community and is dictated, in part, by the demands of the labor market and, in part, by the content of the work. The compensation for the jobs analyzed in this study are no exception.

It was, indeed, fortunate that many of the jobs under study here have been analyzed and rates of compensation agreed upon on the basis of an official job evaluation plan developed by the Pacific Coast Association of Pulp and Paper Manufacturers (PCAPPM). The companies and the unions give their joint blessing to this plan which is quite elaborate. Details of the plan can be obtained from Tedford (1964). It is sufficient for our purposes to explain that the content of each job is evaluated on the basis of several components, the values of which determine the total steps of the job above a base rate. Some of the elements considered in this determination are the following:

a. Education

b. Experience

c. Judgement

d. Working Conditions

e. Amount of responsibility for material produced, for equipment and for personnel supervised.

Each element is studied separately and points are awarded within each element category. Finally, the grand total of points determines the number of steps, above a base line, at which the job analyzed can be placed relative to the other jobs in the scale.

For our purposes, the element of 'judgement' offered most interest as it is the one which represents most closely mental content. According to Tedford (1964, p. 30):

> "Judgement, the third of the skill factors, expresses the requirement of the job which demands that the worker be able to meet new and emergency situations as they arise. Broadly, judgement as it is used in job analysis embodies initiative and ingenuity. For simplicity one term is used. Special intelligence is also embodied, but the term judgement expresses intelligence and is probably more commonly used by people in industry.
>
> "The requirement for judgement is brought about by job complexity not because of complexities which can be overcome by experience, but because of decisions involving a variety of ever changing situations.
>
> "Simple, highly repetitive, short cycle jobs require very limited experience and practically no judgement; whereas complicated, quick mental action situations call for judgement, initiative and ingenuity. Frequency and intensity of mental activity determine the importance of the feature or characteristic of the job."

As an example, the credit in steps or fraction of credits which are given in evaluating the judgement required by the batch digester operator are based on the following criteria:

1. How many grades are cooked.

2. How many species are cooked (If species are cooked separately, more judgement credits are given. ).

3. Size of the operation (tons per day).

4. Number of batch digesters (Extra credits if the size of the digesters differs. ).

5. Method of circulation used.

6. Whether bleachability standards have to be met or not.

7. Whether turpentine decantor system is used.

8. Number of cooking cycles per day.

The above list reveals that judgement is primarily based on the amount of 'variety' with which the operator must deal in his operation and that this concept is very close to the amount of entropy used in the present study to measure mental content. This similarity was tested by tabulating, for the jobs for which the Association had evaluations, the credits in steps awarded for judgement. See Table 19. These figures were then plotted against the average information processing rates obtained for each job during the present study. . The following linear relation between the judgement element and the information processing rates as defined here was found to be (see Figure 45):

$$y = 1.53\ x$$

where x = judgement points as established by the PCAPPM and y = average information processing rates.

It provides added support and significance to the values obtained in our study. Plotting the average information processing rates versus hourly pay rates, Figure 46, shows that pay rates do not bear a direct relationship to the mental content of work, a conclusion which is obvious.

In the PCAPPM plan, jobs which must be analyzed are first compared to similar jobs in processes found in the industry:

> "Job rates for new processes in the modern wood preparation plants were developed by relating the old and new skills, responsibilities and working conditions." ..... "To emphasize, most processes within the pulp and paper industry have counterparts in many plants. In these cases the pattern is possible to find. The composite wage scales in these plants reflect the prevailing wage of the pattern of wages. This is the guide under our plan for obtaining fair wage position relationships." (Tedford, 1964, p. 22).

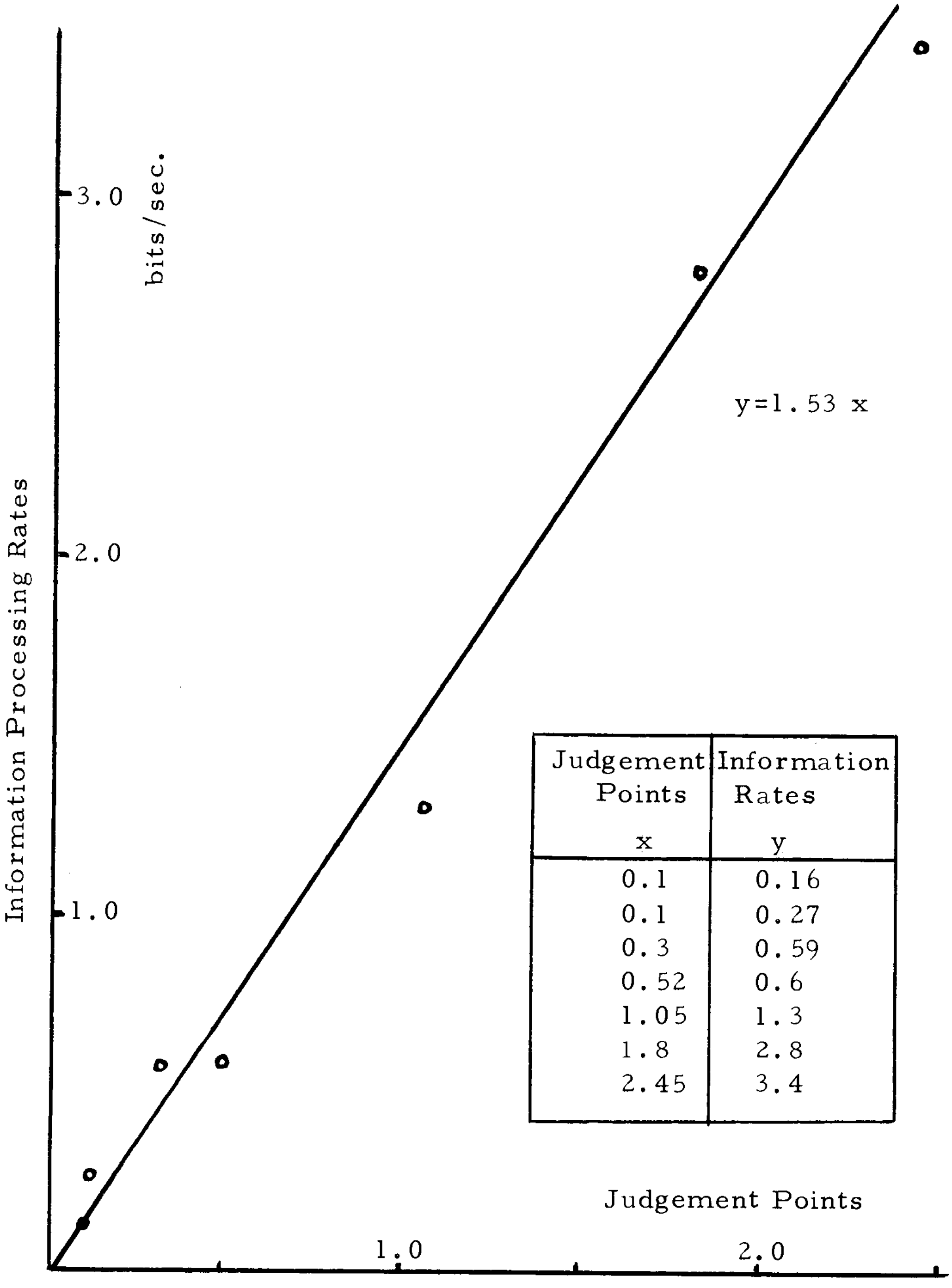
The above approach may be sensible from a labor relations point of view but does not allow jobs to gain their proper wage level on the basis of physical and mental skills and independently of market pressures. It should be an accepted reality of our economic system that wages are set, at least in part, by competitive forces and that they cannot always be held as completely equitable rewards for skill.

Table 19. Tabulation of pay-rates, judgment points and information processing rates of jobs surveyed.

| | Hourly pay rates $/hr. | Judgment points from PCAPPM job evaluation plan[1] | Average information processing rates bits/sec. |
|---|---|---|---|
| Lumber Mills | | | |
| Conveyor operator (chainman) | 2.75 | 0.1 | 0.27 |
| Head conveyor operator | 2.85 | 0.3 | 0.59 |
| Sorter-tower operator | 2.60 | n.a. | 2.4 |
| Sorter-stacker operator | 2.60 | n.a. | 0.35 |
| Grader, no stress-grading machine | 3.22 | n.a. | 3.2 |
| Grader, with stress-grading machine | 3.22 | n.a. | 4.5 |
| Pulp Mills | | | |
| Grinderman, groundwood pulp | 2.85 | 0.1 | 0.16 |
| Shift foreman, groundwood pulp | 3.315 | n.a. | 0.25 |
| #2 chip refiner operator | 3.11 | 1.25 | -- |
| Lead chip refiner operator | 3.42 | 1.80 | 2.8 |
| Cook's helper, batch digester | 2.90 | 0.52 | 0.6 |
| Cook, batch digester | 3.625 | 1.05 | 1.3 |
| Operator, continuous digester | 3.935 | 2.45 | 3.4[2] |
| Assistant operator, c/d. | 3.21 | 1.23 | -- |

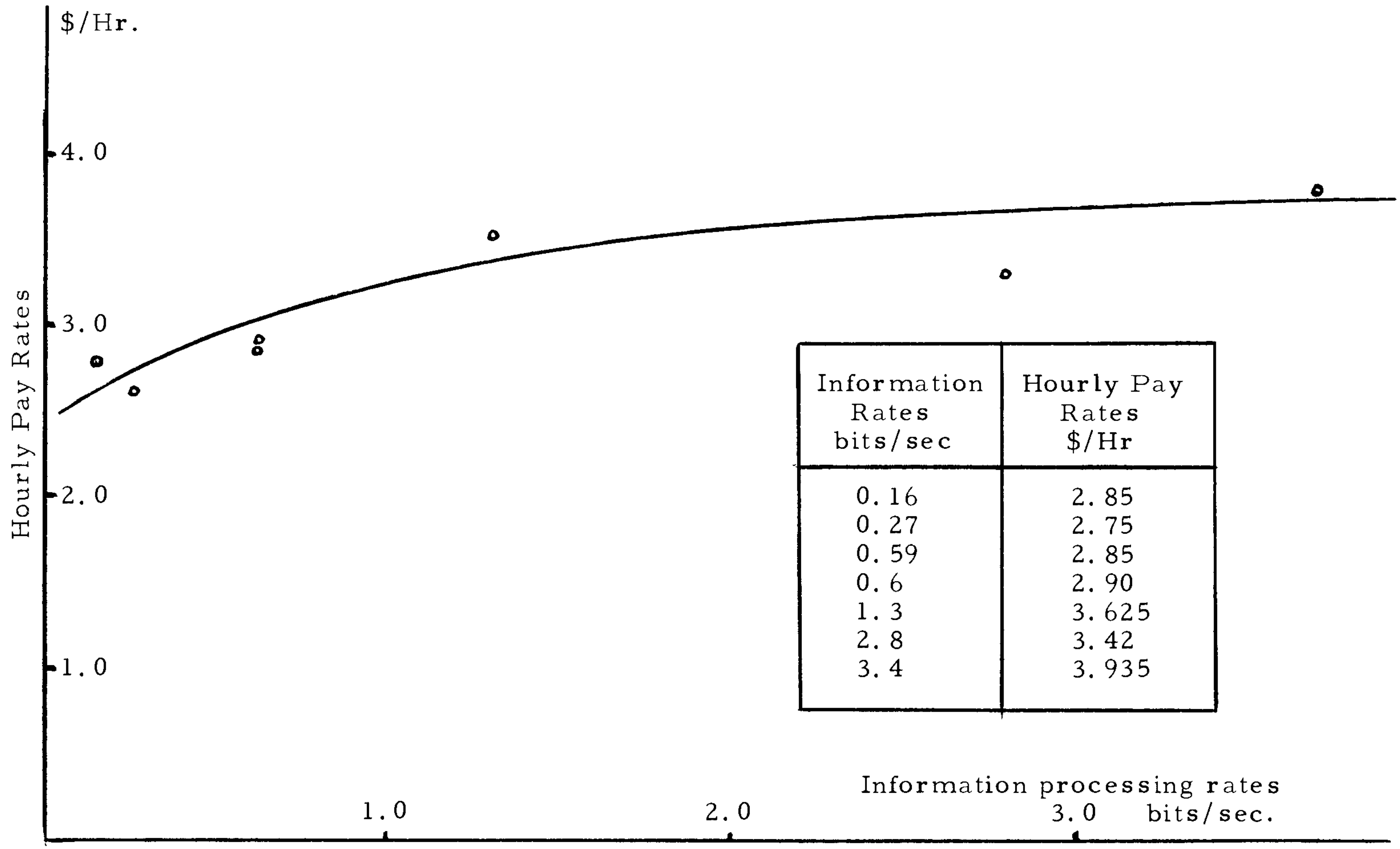
[1] Industrial Job Analysis, Portland, Oregon, Pacific Coast Association of Pulp and Paper Manufacturers.

[2] With computer and setting control points at 5 mins. intervals.




| Judgement Points x | Information Rates y |
|---|---|
| 0.1 | 0.16 |
| 0.1 | 0.27 |
| 0.3 | 0.59 |
| 0.52 | 0.6 |
| 1.05 | 1.3 |
| 1.8 | 2.8 |
| 2.45 | 3.4 |

Figure 45. Regression line between judgement points of Pacific Coast Association of Pulp and Paper Manufacturers' job evaluation plan and information processing rates.




| Information Rates bits/sec | Hourly Pay Rates $/Hr |
|---|---|
| 0.16 | 2.85 |
| 0.27 | 2.75 |
| 0.59 | 2.85 |
| 0.6 | 2.90 |
| 1.3 | 3.625 |
| 2.8 | 3.42 |
| 3.4 | 3.935 |

Figure 46. Information processing rates versus hourly pay rates.

## The Mental Content of Work and Training

Training and the management of learning is a field in itself, thus beyond the scope of this study. However, some of the subjects covered are related to the subject of 'knowledge of results' and 'skilled performance' treated by Annett and Kay (1956 and 1957). Their papers treat, in particular, the type of cues which a trainer must give to his trainee to hasten the process of learning. This is an important field of industy if the training of operators for difficult and complex jobs,such as those resembling the Kamyr digester operator, is to become a deliberate science. At present too much of the traditional 'on-the-job training' is used,where the neophyte is usually left to his own devices hoping that he will acquire enough 'experience' by trial and error.

Annett and Kay (1956 and 1957) point out that the trainee needs two types of information to learn:

a. Knowledge of results, and

b. Knowledge of performance.

'Knowledge of results' refers to information provided in terms of end scores, numerical results, test numbers, output yield figures, etc. These are usually easy to get but they do not tell the operator where and how to amend his performance to obtain better results. This is where 'knowledge of performance' is required.

'Knowledge of performance' is more difficult to acquire, the more complex of the system. In cases where the 'variability of the sequence' (entropy) is inherently high, it becomes all the more difficult to discern and separate the important cues from those which are valueless.

The skilled operator has learned which are which and, thus,

> "the skilled man is responding to fewer cues than the unskilled. Since his variability (in the sequence) is less, ..... he provides himself with fewer signals and at the same time reduces the information load since so many events are now predictable" (Annett and Kay, 1956).

Industry and the individuals who are training the operators to handle complicated equipment and systems should investigate more thoroughly how to provide 'knowledge of performance'. It is the opinion of the writer that this is a neglected area and that operators are left to acquire this kind of knowledge on their own devices. Consequently, the informational load of trainees is much higher than those of skilled operators who have learned to discard irrelevant signals and know where to eliminate redundancy. The question to answer is whether, in many situations, the informational load required of unskilled operators (in the sense of those lacking the 'knowledge of performance') is beyond their informational processing capacity. After facing one of these harrowing experiences, the trainee refuses the promotion to his new job and prefers to 'freeze' in his old job which is not as nerve wrecking or mentally exhausting.

The approach used in this study to measure the mental content of work identifies the mental therbligs which are performed in each particular job. The function of the trainer is to recognize the individuals whose endowments can most likely be developed to handle the informational load of the job and to work with the trainee so as to increase his information processing capacity.

# VIII. CONCLUSIONS

The results obtained in this study were based on the following premises:

## The Use of Information Theory and Communication Theory

1. Information Theory provides useful concepts which can be used to measure the mental content of work in industrial operations.

2. The Theory of Communication provides an analogy for the human communication system in the context of which the information processes of the worker can be identified and studied.

3. Information processes at different levels of integration provide the conceptual structure to study the complexity of the worker's mental load.

## The Model of Integrative Behavior

1. The mental load imposed upon an individual can be related to the integrative behavior which the performance of his job demands of him.

2. The worker performs mental therbligs which are information processes which take place in the human communication system.

3. Four levels of integration can be defined depending upon the complexity of the information processes involved.

4. The performance of a task requires that the information processes be organized along a path of integrative behavior which describes the relationships of the mental therbligs in the human communication system.

5. The amount of information processed or transmitted is the average of expected amount of information, in the Information Theory sense, which is required to reduce the prevailing uncertainty (entropy) to zero.

6. The mental content of work in industrial operations can be compared and measured by the amount of information processed in the performance of mental therbligs, at four levels of complexity, in terms of bits, dubits, tribits and quabits or their bits-equivalent.

The following conclusions can be drawn from the findings of the last chapter:

1. As the levels of mechanization and automation increase in industry, workers are increasingly assigned the work of supervising processes and monitoring their progress. The physical effort involved is practically nil and, therefore, work measurement methods fail to provide measures of performance.

2. The model of integrative behavior shows that mental therbligs can be used, like the therbligs of work measurement, to identify the elements of the mental work done.

3. As the level of complexity of a job increases, mental therbligs of higher levels of integration are prevalently used. To handle complexity, the operator must learn to integrate the information obtained from his environment with his own knowledge of the situation. The operator is continually surveying the set of possible alternatives to make decisions on what ought to be done. Because the process is in a continuous state of flux, there is no fixed sequence of events. This leads to the concept of variability of the sequence

which was borrowed to describe 'variety' in the process states.

4. The mental content of work can be measured in terms of the information processing rates, determined in the context of the model of integrative behavior. The rate of 7.5 bits/sec., obtained for the lumber grading operator paced by the continuous testing machine, can be considered close to the maximum capacity of the human communication channel in industrial jobs.

5. The informational loads of existing systems and systems to be designed can be evaluated against the rate of 7.5 bits/sec., in order to assess the ability of the operators to supervise the process.

6. In every job two types of situations must be considered: Situations of normalcy and emergency situations. The average information processing rates reflect the informational load under normal conditions. The peak rates indicate loads sustained for short periods of time, such as those prevailing at the time of equipment malfunctions. Results of the study suggest that operators are hard pressed to cope with the informational loads imposed upon them by the system in times of emergencies. Process control computers add to the mental load of the operator, unless they are designed to complement the work of the operator when the normal limits of the process are surpassed.

7. The model postulated here allows the measurement of response times i.e. the times required to produce a coordidinated output at the reception of complicated inputs. Our study shows that, as systems grow in complexity, the speed of response is reduced because the entropy of the system is larger. This relationship should cause concern at a time when it is desirable

that the operator react faster to any malfunction, due to the high investment in equipment. The operator's response time, no doubt, will depend upon whether he has in store automatic actions which he can readily summon in case of alarm. The new processes being installed have very high variability of sequence and the operator may not be in a position to know exactly what to do in every emergency situation.

8. Further insight into the skill requirements of the job can be obtained by breaking the information processing rates into its own components i.e. the repetition rate and the entropy processed per cycle. Newer jobs at higher degrees of mechanization and automation have a tendency to show high entropy per cycle and low repetition rates; indeed, continuous processes have no distinct cycle.

9. Understanding jobs by the information processes which they require provides new insights into the mechanism and substance of the learning and training process. The operator trainee requires both 'knowledge of results' and 'knowledge of performance' in order to understand the relationship among the variables in the process. To a large extent, 'learning' consists of eliminating redundancy in the information obtained from the system. Proper training involves matching the information capacity of the individual with the informational demand of the system.

10. Wage plans and compensation rates have never been established solely on the basis of work and effort expended. The methods of work measurement have their shortcomings but at least they provide a sound foundation for the evaluation of physical work.

Now that the shift from physical to mental effort is pronounced, methods such as those developed here to measure the mental aspects of work become indispensable. They should complement other job evaluation techniques in providing equitable remuneration for the new jobs of the plant of tomorrow.

## Extensions and Further Research

Further research should be conducted along the following lines:

### The Ranking of Jobs

The model developed here should be applied to other jobs in a variety of industries to compare their mental content. Of particular importance, these methods should be expanded to anticipate the mental demands for the new jobs of the automated factory. Job complexity needs to be probed further to establish measures of entropy for different jobs in the same industry and comparable jobs across different industries.

### The Worker's Total Contribution

The present study was limited to evaluating the mental content of work. Now that a methodology has been established in this direction, it is necessary to combine it with the traditional work measurement techniques. It would be useful to measure the total contribution of the worker, in terms of therbligs as traditionally defined and primarily concerned with overt motions, and the mental therbligs defined here to evaluate information processing.

## Stress and Emergencies

At the moment, the operators are left to rely on their own ingenuity to handle emergency situations which arise in complicated systems: witness the power blackouts and the possible failures of airline pilots. The approach presented in this study opens the way to a determination of the entropy displayed by a system's instrumentation. Plant simulators, like airplane and astronaut capsule simulators, can be built. The information surges created by malfunctions could be simulated and calculated to determine whether individuals are capable of handling them. As it is, the process control computer reviewed in the present study gives up when certain limits are passed, at the very time when it would be most valuable as a process controller.

## The Design of Systems

The above considerations lead to the desirability of building into the system auxiliary sub-systems which could help the operator handle the extra informational requirements which can occur in cases of abnormal operation. It is not enough to determine mathematically the conditions of stability of a system. One must also consider the consequences of the system's instability upon the individual controller and provide him with the suitable means to cope with it.

# BIBLIOGRAPHY

Annett, J. and H. Kay. 1956. Skilled performance. Occupational Psychology 30:112-117.

________________. 1957. Knowledge of results and skilled performance. Occupational Psychology 31:69-79.

Barnes, R.M. 1963. Motion and time study: design and measurement of work. New York, John Wiley and Sons. 739 p.

Blauner, R. 1964. Alienation and freedom: the factory worker and his industry. Chicago, University of Chicago. 222 p.

Bridgman, P. W. 1922. Dimensional analysis. New Haven, Yale University. 113 p.

Bright, J. R. 1958. Automation and management. Boston, Harvard University. 270 p.

Calkin, J. B. and G. S. Witham. 1957. Modern pulp and paper making. New York, Reinhold. 549 p.

Clapham, J. C. and T. A. Lambe. 1961. An operations - research approach to lumber sorting. Forest Products Journal 11: 181-184, 320-323.

________________. 1963. The sorting of sawmill lumber. Journal of the Operations Research Society of America 11:502-518.

Costello, T. W. and S. S. Zalkind. 1963. Psychology in administration: a research orientation. Englewood Cliffs, N. J., Prentice Hall. 500 p.

Crossman, E. R. F. W. 1953. Entropy and choice time: the effect of frequency unbalance on choice response. The Quarterly Journal of Experimental Psychology 5:41-52.

________________. 1956. The information-capacity of the human operator in symbolic and non-symbolic control processes. In: The application of information theory to human operator problems, ed. by J. Draper. [Kent, England]. p. 4-18 (Ministry of Supply. Report no. WR(D)2/56).

________________. 1960. The information - capacity of the human motorsystem in pursuit tracking. The Quarterly Journal of Experimental Psychology, part 1, 12:1-16.

________________. 1961. Information and serial order in human immediate memory. In: Fourth London Symposium on Information Theory, ed. by C. Cherry. Washington, D. C., Butterworth. 476 p.

________________. 1964. Information processes in human skill. British Medical Bulletin 20:32-37.

________________. 1965. European experience with the changing nature of jobs due to automation. In: The requirements of automated jobs: final report and supplement of North American Joint Conference, Washington, D. C., 1964. Paris, Organization for Economic Cooperation and Development. p. 161-185.

Crossman, E. R. F. W., S. Laner, S. Caplan and L. E. Davis. 1966. Evaluation of skills, profiles and job content due to technological change, methodology and pilot results from the banking, steel and aerospace industries. Berkeley, University of California, Department of Industrial Engineering and Operations Research. 102 p. plus appendices.

Dobson, T. W. 1966. Mechanical pulp today. Paper presented at the First Newsprint Conference, Technical Section, Canadian Pulp and Paper Association, Vancouver, B. C., September 27th - 29th.

Epstein, L. T. 1957. A proposed measure for determining the value of a design. Journal of the Operations Research Society of America 5:297-299.

Felton, W. W., E. Fritz and G. Grier, Jr. 1951. Communication on measurements at the Langley Air Force Base during November-December 1951. Washington, D. C. 85 p. (U. S. Air Research and Development Command. Human Resources Research Laboratories. Report no. 31.)

Fitts, P. M. 1954. The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology 47:381-391.

Fitts, P.M. and J.R. Peterson. 1964. Information capacity of discrete motor responses. Journal of Experimental Psychology 67:103-112.

Fitts, P.M. and M.I. Posner. 1967. Human performance. Belmont, California. Wadsworth. 162 p.

Fitts, P.M. and B.K. Radford. 1966. Information capacity of discrete motor responses under different cognitive sets. Journal of Experimental Psychology 71:475-482.

Fitts, P.M. and C.M. Seeger. 1953. S - R compatibility: spatial characteristics of stimulus and response codes. Journal of Experimental Psychology 46:199-210.

Fritz, E. L. and G.W. Grier. 1955. A study of information flow in air traffic control. In: Information theory in psychology, ed. by H. Quastler. Glencoe, Illinois, The Free Press. p. 232-243.

Garner, W.R. 1953. An informational analysis of absolute judgments of loudness. Journal of Experimental Psychology 46: 373-380.

Garner, W.R. and H.W. Hake. 1951. The amount of information in absolute judgments. Psychological Review 58:446-459.

Gore, W.C. 1960. Information theory. In: Operations research and systems engineering, ed. by C.D. Flagle, W.H. Huggins and R.H. Roy. Baltimore, Johns Hopkins. p. 583-608.

Gregg, L. W. 1966. Human - factors engineering. In: Industrial psychology, ed. by B. von Haller Gilmer. New York, McGraw-Hill. p. 338-369.

Hake, H.W. and W.R. Garner. 1951. The effect of presenting various numbers of discrete steps on scale reading accuracy. Journal of Experimental Psychology 42:358-366.

Handbook of pulp and paper technology. 1964. New York, Reinhold. 537 p.

Hartley, R.W. 1928. The transmission of information. Bell System Technical Journal 17:535-550.

Hick, W.E. 1952. On the rate of gain of information. Journal of Experimental Psychology 4: 11-26.

Holmes, W.G. 1945. Applied time and motion study. Rev. ed. New York, Ronald Press. 383 p.

Kay, H. 1957. Information theory in the understanding of skills. Occupational Psychology 31: 218-224.

Klemmer, E.T. and F.C. Frick. 1953. Assimilation of information from dot and matrix patterns. Journal of Experimental Psychology 45: 15-19.

Little, Arthur D. 1965. Analysis of automation potential by means of unit operations. Washington, D.C., U.S. Department of Labor, Office of Manpower, Automation and Training. 122 p.

Miller, G.A. 1953. What is information measurement? American Psychologist 8: 3-11.

_______________. 1956a. Human memory and the storage of information. Transactions of the Institute of Radio Engineers, Professional Group on Information Theory IT-2: 129-137.

_______________. 1956b. The magical number seven, plus or minus two: some limits to our capacity for processing information. Psychological Review 63: 81-97.

Nadler, G. 1963. Work design. Homewood, Illinois, R chard D. Irwin. 837 p.

Nadler, G. and M.J. Seidel. 1966. The measurement of information in a continuous process. The Journal of Industrial Engineering 17: 150-156.

Osborne, J.W., H. Quastler, K.S. Tweedell and K.V. Wilson. 1955. Human performance in information transmission. Part III. Flash recognition - scale reading. Urbana, University of Illinois. 68 p. (Report R-68)

Pierce, J.R. and J.E. Karlin. 1957. Reading rates and the information rate of a human channel. Bell System Technical Journal 36: 497-516.

Quastler, H. (ed.) 1955. Information theory in psychology, problems and methods. Glencoe, Illinois, The Free Press. 436 p.

Quastler, H. and V. Wulff. 1955. Human performance in information transmission. Urbana, University of Illinois. 44 p. (Report R-62)

Richards, D. L. and J. Swaffield. 1953. Measurement of communication rate of a speech link. In: Communication theory, ed. by W. Jackson. New York, Academic Press. 532 p. (Cited in: Quastler, H. and V. Wulff. 1955. Human performance in information transmission. Urbana, University of Illinois. p. 59. (Report R-62) )

Robinson, S. J. 1965. Production of groundwood from chips. The Technical Association of the Pulp and Paper Industry, Journal 48: 48A-51A.

Ross, D. K. 1960. Information concepts in work analysis. Ph. D. thesis. Saint Louis, Missouri, Washington University. 202 numb. leaves.

______________. 1961. Information content analysis. The Journal of Industrial Engineering 12: 267-275.

Sanford, F. H. 1965. Psychology: a scientific study of man. 2d ed. Belmont, California, Wadsworth. 627 p.

Seidel, M. J. 1963. The human decision requirements in a process using information techniques. Master's thesis. Saint Louis, Washington University. 69 numb. leaves.

Senders, J. W. 1955. Man's capacity to use information from complex displays. In: Information theory in psychology, ed. by H. Quastler. Glencoe, Illinois, The Free Press. p. 360-364.

Senders, V. L. and J. Cohen. 1955. The effects of sequential dependencies on instrument reading performance. In: Information theory in psychology, ed. by H. Quastler. Glencoe, Illinois, The Free Press. p. 282-290.

Shannon, C. E. and W. Weaver. 1949. The mathematical theory of communication. Urbana, University of Illinois. 125 p.

Simon, H. 1960. The new science of management decision. New York, Harper and Row. 50 p.

Simpson Timber Company. n. d. EMSR Simpson electro-mechanical stress-rated structural lumber. In: Simpson electro-mechanical stress-rated lumber manual. Seattle. p. 501-507. (File No. 19-B)

Schroder, H. M., M. J. Driver and S. Streufert. 1967. Human information processing. New York, Holt, Rinehart and Winston. 224 p.

Tedford, J. M. 1964. Industrial job analysis. Portland, Pacific Coast Association of Pulp and Paper Manufacturers. 60 p.

Van Court Hare, Jr. 1967. Systems analysis: a diagnostic approach. New York, Harcourt, Brace & World. 544 p.

van Gigch, J. P. 1967. Operations analysis of lumber sorting. Unpublished report presented in partial fulfillment of requirement in a course in operation analysis, Professor W. Engesser, Dept. of Mechanical and Industrial Engineering. Corvallis, Oregon State University. 40 numb. leaves.

Welford, A. T. 1960. The measurement of sensory-motor performance: survey and reappraisal of twelve years' progress. Ergonomics 3: 189-230.

Wiener, N. 1954. The human use of human beings. 2d rev. ed. New York, Doubleday. 200 p.

# APPENDICES

Table A-1

Characteristics of Three Sawmills Surveyed

| | Sawmill 1 | Sawmill 2 | Sawmill 3 |
|---|---|---|---|
| Type of sorting | Manual | 50% Manual<br>50% Mechanical | 100% Mechanical |
| Total volume per month in million bd-ft | 2.5 | 5.0 | 6.0 |
| No shifts/ day | one | two | two |
| Manpower<br>Manual chain | 8 men<br>1/2 each side | 3 men | --- |
| Mechanical chain | | 2 men | 5 men |
| Chain speed ft/sec. | 0.5 | 2.2 | 1.8 |
| Lumber arrival rate in no. of pieces/min. | 7.5 | 21.6 | 19.6 |
| Total Number of sorting classifications | 67 | 22, manual<br>20, mechanical | 25, mechanical |
| Sorting classes/man in active sorts | 6.0 | 7.0 | --- |
| Productivity in bd-ft/man hr. | 1560 | 3120 | 3750. |
| Average information processing rates in bits /sec: | | | |
| First man on chain | 0.59 | 0.96 | --- |
| Third man on chain | 0.27 | 0.39 | |
| Sorter-tower operator | --- | 2.4 | |
| Sorter-stacker operator | --- | 0.35 | |

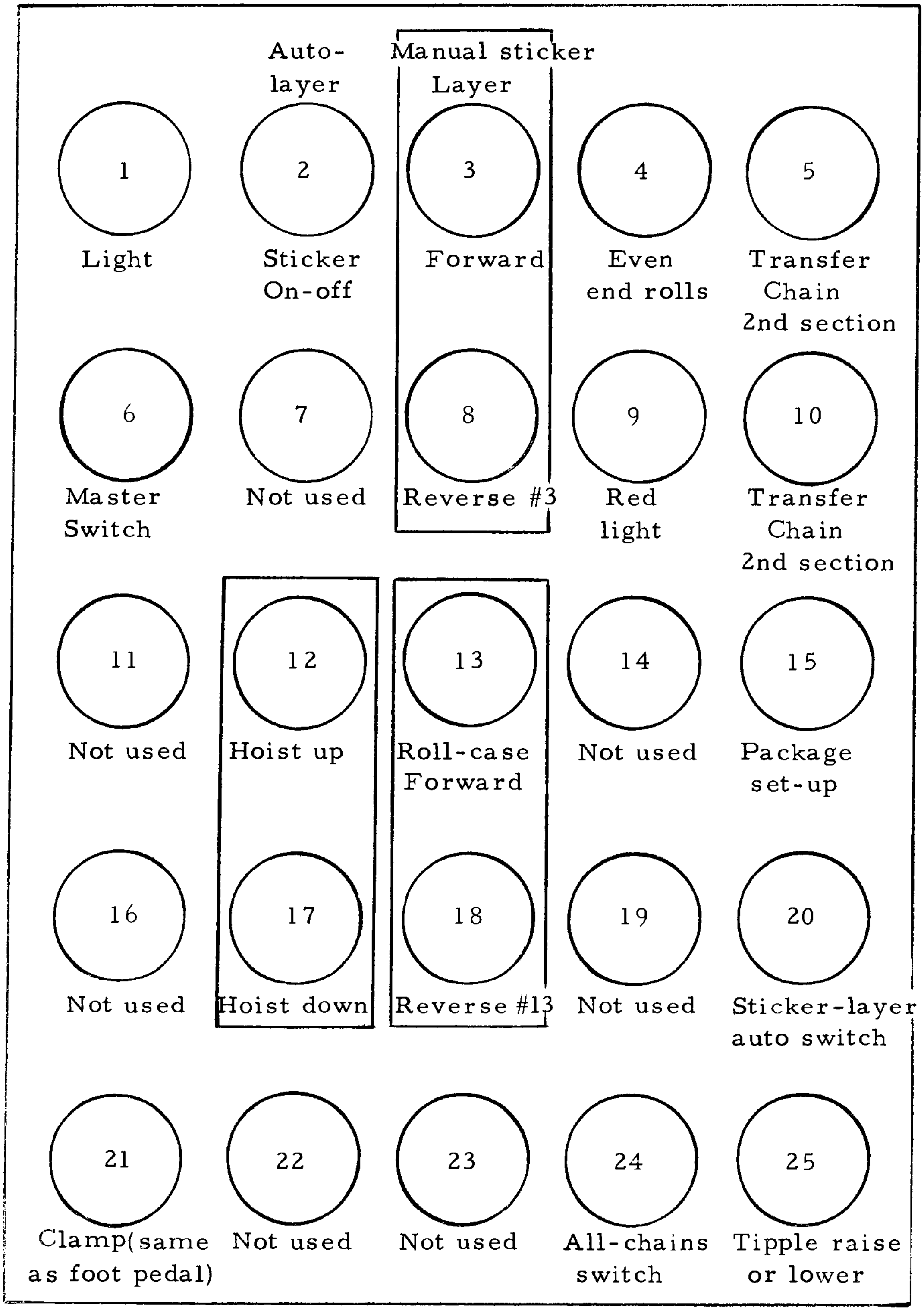



Figure B-1. Schematic diagram of control console for sorter-stacker operator, mechanical sorter, lumber mill 2.

Calculation of entropy for tasks performed by sorter-stacker operator, mechanical sorter, mill 2.

| | | |
|---|---|---|
| 1. | Choose one of 20 trays to empty | log 20= 4.3 |
| 2a. | Move tipple into location | log 2= 1.0 |
| 2b. | Push one of 20 buttons on console | log 20= 4.3 |
| 3. | Bring lumber forward | |
| | Actuate all chains Switch 24[1] | log 25= 4.64 |
| | and rollers Switch 4 | log 25= 4.64 |
| 4. | Start and stop chains and rollers if lumber does not advance properly. Assume done 3 times. | 3 log 25=13.9 |
| 5. | Adjust thickness clamp (10 positions) | log 2+ log 10= 4.32 |
| 6. | Adjust width level | log 2+ log 8= 4.0 |
| 7. | Advance one layer forward (actuate 2 switches to advance) | 2 log 25+ log 2=82.4 |
| 8. | Release layer with foot pedal (Stick placer operates automatically) Go to 7 and repeat for 8 layers | |
| 9. | Actuate hoist down Switch 17 | log 24= 4.6 |
| 10. | Actuate roll case forward Switch 13 | log 25= 4.6 |
| 11. | Actuate roll case reverse Switch 18 | log 25= 4.6 |
| 12. | Actuate hoist-up Switch 12 | log 25= 4.6 |
| | Total bits/cycle | 141.0 |

[1] Refer to Figure B-1.

# APPENDIX D

## OPERATIONAL SEQUENCE OF THE CONTINUOUS LUMBER TESTER

Cited from Simpson Timber Company, Simpson

Electro-Mechanical Stress-Rated Lumber Manual,

American Institute of Architects (A.I.A.) File No.

19-B, p. 501-507.

Explanations below refer to Figure 21 of the text.

The Operation Sequence of a Board Traveling Through the CLT-1 Occurs as Follows:

1. Light source for photo-electric Sensor #1 is interrupted, alerting the portion of the electronic system concerned with the first section.

2. Powered clamp-up roll section feeds board into the machine and firmly holds the board in a manner to delete any transmission of tail-end whip or vibration past this point.

3. Board passes Sensor #2 alerting second section.

4. Board enters second powered roll section and is induced to deflect.

5. Board passes Sensor #3 full arming first section and activating Transducer #1.

6. Transducer #1 reports readings at six-inch intervals to Capacitor Storage bank. As each reading is fed into Capacitor Storage, the total readings are stored.

7. Final powered roll section induces opposite deflection.

8. Board passes Sensor #4 fully arming second section and activating Transducer #2.

9. Transducer #2 also reports readings at six-inch intervals to Capacitor Storage bank, and these readings are stored as they are infed.

10. As tail end of board leaves Sensor #1, light source is resumed, accumulated information is held in storage, and Transducer #1 ceases recording.

11. As board leaves Sensor #2, the combined storage readings from both Transducer #1 and Transducer # 2 are transmitted from storage to the electronic system which activates the Stamp corresponding to the proper grade.

12. Grade printer actuates and prints proper grade.

13. As board leaves Sensor #2 electronics system is reset and ready for next sequence.

14. A counter for each grade and a totalizer for all grades is provided. A separate total counter for reject is also supplied.

Calculation of entropy for tasks performed by refiner-operator, groundwood pulp mill

## Part I. Scanning Input Stimuli

| | |
|---|---|
| Time of day | log 24=4.58 |
| Feeder setting | log 10=3.32 |
| Plate clearance | log 555=9.1 |
| Hydraulic pump pressure psi | log 60=5.9 |
| Opening pressure psi | log 60=5.9 |
| Closing pressure psi | log 60=5.9 |
| Lubrication oil temp. | log 200=7.64 |
| Indicated load. Main motor | log 40=5.32 |
| C.E.T. Control End Motor | log 50=5.64 |
| C.E.M. Control End Bearing (inboard) | log 50=5.64 |
| C.E.R. Control End Bearing (outboard) | log 50=5.64 |
| F.E.M. Feed end motor | log 50=5.64 |
| F.E.R. Feed end bearing (inboard) | log 50=5.64 |
| F.E.T. Feed end bearing (outboard) | log 50=5.64 |
| Feeder Load (percent of motor load current) | log 20=4.32 |
| Feeder Speed (not working) | ----- |
| Strip chart (one per m/c). Shows amount of load on refiner | log 40=5.32 |
| Control Valve setting | log 30=4.91 |
| Water (gallons per minute) | log 36=5.17 |
| Chip bin speed "N" | log 100=6.64 |
| Chip bin speed "S" | log 100=6.64 |
| Surge bin speed | log 100=6.64 |
| One machine Sub Total | 103 |
| Four machines bits /c | 412 |

| | |
|---|---|
| Plus two settings: STP Setting log 500=9.1 | |
| Zinc Hydr. setting log 500=9.1 | 18.2 |
| Plus entropy Foxboro Chart. See part II | 59.5 |
| Total bits/cycle | 489.7 |
| say | 490 |

Exhibit E. (continued)

Part II. Scanning Inputs. Foxboro Charts

| | | |
|---|---|---|
| 1. | R.W.W. level | log 25=4.64 |
| 2. | R. Sum level | log 15=3.91 |
| 3. | 412 Sump level | log 15=3.91 |
| 4. | R Knotter chest level | log 10=3.32 |
| 5. | Book grade | |
| | 5.1 | log 8=3.00 |
| | 5.2 | log 4=2.00 |
| 6. | R Sump consistency | |
| | 6.1 | log 60=5.91 |
| | 6.2 | log 40=5.32 |
| 7. | Mag. -Stock flow | log 50=5.64 |
| 8. | Not operating inside Foreman's room: | — — |
| 9. | Brightness tower consistency | log 30=4.91 |
| 10. | Slivers pump | log 50=5.64 |
| 11. | Not used | — — |
| 12. | White water (make up to refiners) | log 50=5.64 |
| 13. | #1. W.W. Make up refiners | log 50=5.64 |
| | | Total bits/cycle = 59.5 |

Exhibit E. (continued)

Part III. Freeness Test. Mental Therblig: Computing

| | |
|---|---|
| Fill container with stock | |
| Place in stainless steel container | |
| Stir | |
| Look at temp. Thermometer reading | |
| graduated 0-20 | log 20= 4.32 |
| Let water run out | |
| Pour in beaker | |
| graduated to 250 | log 250= 7.96 |
| Read chart (matrix: 700 x 30) | =14.3 |
| Dry sample on hot plate | |
| Weigh mgs (scale) | |
| Read chart (matrix: 700 x 30) | =14.33 |
| Ordering. 10 items/list | log 10!=23.0 |
| Sub Total bits/cycle | 63.91 |
| Say | 64.0 |

Part IV. Total of Tests

| | |
|---|---|
| 1. Decker Freeness test, downstairs | 64.0 |
| 2. Decker Freeness test, lab. | 64.0 |
| 3. Decker Freeness test, upstairs | 64.0 |
| 4. A.T. Mullen test [reading =34.3] | log 343= 8.45 |
| 5. A.T. Tear Test Lab [reading: 103] | log 1030=10.0 |
| 6. A.T. Brightness Lab [reading: 56.6] | log 566= 9.2 |
| 7. Test #1 [reading 49.4] | log 494= 8.74 |
| 8. Test #2 [reading 49.4] | log 494= 8.74 |
| Total bits/cycle = | 237.14 |
| Say | 237 |

# APPENDIX F

Entropy of tasks performed by Cook's Helper, Batch Digester, Kraft Pulp Mill 2

| Tasks | Entropy bits/cycle |
|---|---|
| Open large gate valve (one out of three) for white liquor (no flow yet) | log 3=1.58 |
| Open large gate valve (one out of three) for black liquor (no flow yet) | log 3=1.58 |
| Open large gate valve (one out of three) for knots (no flow yet) | log 3=1.58 |
| Calculation of Appropriate Charge (See Cook's responsibilities) | |
| Set Foxboro Chart to appropriate quantities (may be Cook's responsibilities) | |
| a) volume of white liquor Chart #898402[1] | log 55=5.8 |
| b) volume of liquor and knots Chart #89445[1] | log 20=4.32 |
| c) volume of black liquor Chart #898402[1] | log 20=4.32 |
| Controls will automatically monitor right amount in filling | |
| Filling Digester | |
| Turn buzzer on (warning) | log 2=1.0 |
| Reset Weightometer to zero | 3 log 5=6.96 |
| Turn feeder and belts on | |
| Usually running 2 belts and 2 feeders per belt | |
| Have choice of 4 belts. | |

| | |
|---|---|
| Must decide which belts to run | log 4=2.0 |
| Then turn on 2 feeder per belt | log 2=1.0 |
| (one for #3 bin, another for #4 bin) | |
| Measure 16 tons of chips | |
| Once belts and feeders running, wait until meter registers 16 tons | log 160=7.32 |
| Turn liquor feed to automatic | |
| Start liquor feed | |
| a) White liquor | |
| b) Knots | |
| c) Black liquor | |
| (All three may not be applicable) | |
| When Chip Meter shows 28 tons | log 280=8.13 |
| Shut off all 4 feeders | log 4=2.0 |
| (4 buttons) keep 2 belts running | |
| Look at mirror to see when chips stopped | log 2=1..0 |
| Set White Liquor Feed to 100 cu. ft. | log 55=5.78 |
| to flush line out. (See previous page) | |
| Turn automatic liquor feed button | log 2=1.0 |
| Start liquor feed, will feed 100 cu. ft. and stop automatically | |
| Start feeders again | log 4=2.0 |
| Recall choice of 4 belts with 2 feeders per belt | |
| Set White Liquor Feed to complete filling procedure. Recall already have 100 cu. ft. | |
| Turn liquor feed button to auto | log 2=1.0 |
| Start liquor feed | |
| a) White liquor | log 2=1.0 |
| b) Black liquor (if any) | log 2=1.0 |

Filling Procedure (continued)

| | |
|---|---|
| c) knots | log 2=1.0 |
| White liquor flow indicated by lights. Green indicates flow into digester; red: tank refilling<br>Buzzer indicates knots in | |
| Turn knots flow off on panel | log 2=1.0 |
| Run to gate valve near digester to close knots valve | log 2=1.0 |
| Stop chips feed at 28.6 tons | log 286=8.16 |
| Check inside digester with flashlight to determine how full | log 2=1.0 |
| Start 4 feeders on | log 4=2.0 |
| Stop 4 feeders | log 4=2.0 |
| 3x (Check level inside digester) | 3(log 2)=3.0 |
| Start 4 feeders | log 4=2.0 |
| Stop 4 feeders | log 4=2.0 |
| Check on panel board to determine how much white liquor left to be filled | log 2=1.0 |
| Start 4 feeders | log 4=2.0 |
| Check chip meter all the time | log 300=8.25 |
| Turn off 2 feeders. Two still on | log 4=2.0 |
| Turn off 2 feeders | log 4=2.0 |
| Red light on panel indicates all white liquor is in digester | log 2=1.0 |

Filling Procedure (continued)

| | | |
|---|---|---|
| Operator goes to close two gate | log | 3=1.58 |
| valves near digester (white liquor and black liquor valves) | log | 3=1.58 |
| Check level in digester | log | 2=1.0 |
| Opens water valve | log | 2=1.0 |
| Pushes button on panel board to close digester cap | log | 2=1.0 |
| Introduces pin in cap lock | log | 2=1.0 |
| Changes position of chip feeder on fifth floor with button on panel board | log | 2=1.0 |
| Read amount of chips fed into digester | log | 300=8.25 |
| Record amount on Digester Cooking Report | log | 300=8.25 |
| | bits/cycle | 124.4 |

[1] Chart numbers only appear for identification purposes.

# APPENDIX G

## Entropy of Tasks Performed by Cook, Batch Digester, Kraft Pulp Mill 2

### Part I. Scanning of Input Stimuli

Only entropy related to tasks where operator scans Foxboro Controllers charts was included:

| | |
|---|---|
| Checks Foxboro Chart #898631 to determine temperature and pressure rise (5 times per cycle each) | 5(log 65 + log 45)=57.2 |
| Checks Foxboro Chart #89865 to determine height of digested pulp in two blow tanks (twice/cycle) | 4(log 20)=17.28 |
| Checks time digester has remained up to pressure the required time | log 70 = 6.13 |
| Reduce steam flow with gate valve Foxboro Chart #898095 | log 10 = 3.32 |
| Total bits/cycle | 83.9 |

### Part II. Entropy of Instrument Loop. Calculation of Charge, Batch Digester

Matrix of Alternatives

| Variables<br>Filling Procedure | Number of Alternatives |
|---|---|
| Digester No. (must keep track of order in which fired | 7 |
| Weight of chips. (only concerned whether digester full or not) | 2 |
| White Liquor | |
| a) Effective alkali lbs/cu. ft.. (range 5.0 - 5.5) | 6 |

Exhibit G. (continued)

| | |
|---|---|
| b) Active alkali lb./cu. ft.<br>(range 5.8 - 6.4) | 8 |
| c) Effective charge cu. ft.<br>(range 5200 - 5400) | 5 |
| d) Volume White Liquor cu. ft.<br>(range 800 - 1000)<br>(obtained as a product of alternatives in a) and c) | 30 |
| e) Black liquor u. ft.<br>(range 0 - 300) | 20 |
| f) Knots, volume cu. ft.<br>(range 0 - 300) | 20 |
| g) Total volume of liquor<br>const. at 1450 cu. ft. | -- |

Note: e + f + d = 1450 cu. ft.

Timing of Action

| | |
|---|---|
| Spacing of digestors (seven)<br>(stay alert one position of needle in 60) | 7x60 |
| "Steam On" time. No uncertainty once calculated | -- |
| "Up to Temp" time. Established when digester reaches appropriate temp. and pressure. No uncertainty | -- |
| Time for blowout. One position of clock in 60 | 60 |
| | $7.76 \times 10^9$ |

Entropy per cycle $= \log 7.76 \times 10^9 = 23.8$ bits

# APPENDIX H

Table H-1. Instrument Loop Entropy processed by control computer, Kamyr Digester, Pulp Mill 2

| Set Point No. | Name of Instrument Loop | Variables Entering Calculation | Number of Alternatives | Entropy in bits/cycle |
|---|---|---|---|---|
| #1 | Chip Meter A | Percent of production rate | 14 | log 14 = 3.8 |
| #2 | B | Ibid. | 14 | log 14 = 3.8 |
| #3 | White Liquor Flow | Production rate | 14 | |
| | | Changes in desired K No. | 200 | |
| | | Changes in White liquor flows (active alkali test) | 8x10 | log $2.24x10^{7}$=24.4 |
| | | Changes in Black liquor (Resid, Alkali test) | 10x10 | |
| #4 | Upper heater temp. to dig. (hot side) | Variable #2250 | 18x10 | |
| | | Vol. flow rate of chips | 18x10 | |
| | | Chip moisture | 36x10 | |
| | | Chip meter A | 18x10 | |
| | | Chip Meter B | 18x10 | |
| | | Black liquor flow | 40 | log $5.3x10^{25}$=84.5 |
| | | White liquor flow | 257 | |
| | | White liquor act. alkali | 8x10 | |
| | | White liquor sulfidity | 70 | |
| | | Top circulation temp (2) | 2x10x10 | |
| | | Flow rate of liquor | 2x10 | |
| | | Temp of liquor (2) | 2x16x10 | |
| | | K. number predicted | 200 | |

Table H-1. (continued)

| Set Point No. | Name of Instrument Loop | Variables Entering Calculation | Number of Alternatives | Entropy in bits/cycle |
|---|---|---|---|---|
| #5 | Lower temp to digester(hot side) | Temperature lower heater(2) | 2x4x10 | |
| | | Lower heater liquor flow | 4x10 | |
| | | Volume flow of liquor | | |
| | | Variable # 2281 | 36x10 | |
| | | Variable # 2250 | 18x10 | |
| | | Variable # 2260 | 18x10 | |
| | | Variable # 2204 | 40x10 | |
| | | Variable # 2222 | 1x10 | |
| | | Sulfidity of white liq. flow | 70 | log $2.21 \times 10^{41} = 137$ |
| | | Temp at top of dig.(2) | 2x16x10 | |
| | | AA of white liquor | 8x10 | |
| | | GPM of white liquor | 257 | |
| | | Production rate | 14 | |
| | | Temp hot of upper heater | 16x10 | |
| | | Temp cold of upper heater | 16x10 | |
| | | Upper heater liquor flow | 2x10 | |
| | | Test K No. | 200 | |
| | | 2nd stage cooler liquor temp. | Const. | |
| | | 2nd stage cooler liquor flow | Const. | |
| | | Extraction zone temp. | 40x10 | |
| | | Desired K No. | 200 | |

Table H-1. (continued)

| Set Point No. | Name of Instrument Loop | Variables Entering Calculation | Number of Alternatives | Entropy in bits/cycle |
|---|---|---|---|---|
| #6 | Extraction flow | Chip Feed rate A | 18x10 | |
| | | Chip Feed rate B | 18x10 | |
| | | Volume flow of chips and liquid | | |
| | | Variable # 2281 | 36x10 | $\log 2.27 \times 10^{15} = 51.0$ |
| | | Variable # 2250 | 18x10 | |
| | | Variable # 2250 | 18x10 | |
| | | Variable # 2222 | Const | |
| | | Variable # 2204 | 40x10 | |
| | | Rapid change in blow line consistency | 15x10 | |
| #7 | 2nd Stage cooler Temp (out) | Lower Cooking temp. to digester | 14x10 | log 140 = 7.2 |
| #8 | Wash flow | Chip Meter rate A | 14x10 | log 280 =14.2 |
| | | Chip Meter rate B | 14x10 | |
| #9 | Lower wash temp to digester (hot side) | Lower wash (cold) temp from digester | 16x10 | |
| | | Lower wash liquor flow | 6x10 | $\log 5.04 \times 10^{11} = 38.9$ |
| | | Digester dilution flow | 75x10 | |
| | | Counter wash flow | 10x10 | |
| | | Blow line temp. | 70x10 | |

Table H-1. (continued)

| Set Point No. | Name of Instrument Loop | Variables Entering Calculation | Number of Alternatives | Entropy in bits/cycle |
|---|---|---|---|---|
| #10 | Counter Wash flow | Chip feeder rate A | 18x10 | |
| | | Chip feeder rate B | 18x10 | log $2.42 \times 10^{7}$ =24.0 |
| | | Digester dilution flow | 75x10 | |
| #11 | Outlet device | Changes in blow line consistency | 15x10 | |
| | | Chip level indicated by top separator load motor A | 15x10 | log $4 \times 10^{6}$ =22.0 |
| | | Ibid., top separator load motor B | 15x10 | |
| #12 | Blow line flow | Variable # 2250 | 18x10 | |
| | | Variable # 2291 | 18x10 | |
| | | Digester chip level A | 15x10 | log $12.96 \times 10^{10}$ =36.9 |
| | | Digester chip level B | 15x10 | |
| | | Blow line consistency | 15x10 | |
| | | | Total | 448 bits/cycle |
| | | | say | 450 bits/cycle |

Table H-2. Instrument Loop Entropy processed by Kamyr Digester operator without control Computer, Pulp Mill 2

| Set Point No. | Name of Instrument Loop | Variables Entering Calculation | Number of Alternatives | Entropy in bits/cycle |
|---|---|---|---|---|
| No. 1 | Chip meter A | Percent of max. production rate | 14 | log 14= 3.8 |
| No. 2 | Chip meter B | Ibid. | 14 | log 14= 3.8 |
| No. 3 | White liquor flow | Production rate | 14 | |
| | | Chip meter revolutions | 9 | |
| | | $lbs/ft^3$ of Active alkali | 8 | log 1008=10.0 |
| No. 4 | Upper heater Temperature to digester (hot side) | Production rate | 14 | |
| | | Desired K. number (range 20 - 40) | 20 | log 280= 8.1 |
| No. 5 | Lower heater temperature (hot side) | Production rate | 14 | |
| | | Desired K. number | 20 | log 280= 8.1 |
| No. 6 | Extraction flow | Production rate | 14 | |
| | | Trend of blow line consistency (range 30-40; 1% steps) | 10 | |
| | | Blowing rate (range 800-1200; 15 gpm steps) | 30 | log 4200=12.0 |

Table H-2. (continued)

| Set Point No. | Name of Instrument Loop | Variables Entering Calculation | Number of Alternatives | Entropy in bits/cycle |
|---|---|---|---|---|
| No. 7 | Second stage Cooler temperature (out) | Constant | 0 | 0 |
| No. 8 | Wash flow | Constant | 0 | 0 |
| No. 9 | Lower wash temperature to digester (hot side) | Constant | 0 | 0 |
| No. 10 | Counter wash flow | Trend of blow line consistency | 30 | log 30=4.9 |
| No. 11 | Outlet device speed | Constant | 0 | 0 |
| No. 12 | Blow line flow | Production rate | 14 | |
| | | Blow line consistency | 30 | |
| | | Chip level (too high or too low) | 2 | log 840=9.7 |
| | | Total entropy bits/cycle | | =60.4 |

# APPENDIX I

Table I-1. Comparison of entropy processed in Kamyr digester system with and without computer control.

| WITHOUT COMPUTER CONTROL | | | WITH COMPUTER CONTROL | | | |
|---|---|---|---|---|---|---|
| | | | Operator | | Computer | |
| Variable | Op. or Comp. | Entropy in bits/Hr. n log N | Entropy in bits/Hr. Oper. | n log N | Entropy in bits/Hr. Comp. | n log N |
| Pulp production rate | Op. | 0.13 log 8 = 0.39 | Op. | 0.13 log 11 = 0.45 | | |
| Chip moisture | Not logged | | Op. | | | |
| Chip meter A side | Op. | 0.14 log 6 = 0.36 | | | Comp. | 0.13 log 10 = 0.43 |
| High pressure feeder A | Consider Const. | 0.03 log 2 = 0.03 | | Const. | | |
| Steam vessel pressure A | Const. | Const. | | Const. | | |
| Chip meter B side | Op. | 0.14 log 6 = 0.36 | | | Comp. | 0.13 log 10 = 0.43 |
| High press feed B | Const. | 0.03 log 2 = 0.03 | | | | |
| Steam vessel press B | Const. | Const. | | Const. | | |
| Alkali to wood % | Const. | Const. | | Const. | | |
| Effective alkal i test | Phoned in | 0.57 log 7 = 1.6 | Op. | 0.60 log 10 = 1.99 | | |
| Calculation on chart of white liquor flow | 9 x 8 Alt. | log 72 = 6.17 | | | Comp. | log 72 = 6.17 |
| White liquor flow | (chart) | 0.40 log 204 = 3.07 | | | Comp. | 0.65 log 257 = 5.2 |
| Cooler temp in | | Const. | | Const. | | |
| Cooler temp out | | Const. | | Const. | | |
| #1 filtrate | No action | | | | | |
| Extraction liquid to evaporator | | 0.36 log 40 = 1.92 | | | Comp. | 0.18 log 22 = 0.80 |

Table I-1. (Continued)

| WITHOUT COMPUTER CONTROL | | | WITH COMPUTER CONTROL | | | |
|---|---|---|---|---|---|---|
| | | | Operator | | Computer | |
| Variable | Op. or Comp. | Entropy in bits/Hr. n log N | Entropy in bits/Hr. Oper. | n log N | Entropy in bits/Hr. Comp. | n log N |
| #1 vat. temp. | No action | | | | | |
| Make up liquor flow 1250-1800 | Op. | 0.4 log 11 = 0.38 | | | Comp. | 0.45 log 12 = 1.61 |
| Top separators | | | | | | |
| A side | | 1.0 log 2 = 1.0 | Op. | 1.0 log 2 = 1.0 | | |
| B side | | 1.0 log 2 = 1.0 | Op. | 1.0 log 2 = 1.0 | | |
| Top circulation | | | | | | |
| A side | Op. | 1.0 log 2 = 1.0 | Op. | 1.0 log 2 = 1.0 | | |
| B side | Op. | 1.0 log 2 = 1.0 | Op. | 1.0 log 2 = 1.0 | | |
| Cooking zone | | | | | | |
| Upper flow | Op. | 0.04 log 2 = 0.04 | Op. | 0.06 log 2 = 0.06 | | |
| Upper temp. to dig. | Op. | 0.11 log 3 = 0.17 | | | Comp. | 0.26 log 18 = 1.09 |
| Upper temp. from dig. | No action | | | | | |
| Lower flow | Op. | 0.06 log 4 = 0.12 | Op. | 0.06 log 3 = 0.1 | | |
| Lower temp. to dig. | Op. | 0.16 log 5 = 0.37 | | | Comp. | 0.32 log 14 = 1.22 |
| Lower temp. from dig. | No action | | No action | | | |
| 2nd stage Cooking | | | | | | |
| Flow | Op. | Const. | Op. | Const. | | |
| Temp to dig. | Op. | Const. | | | Comp. | Const. |
| Temp from dig. | No action | | No action | | | |

Table I-1. (Continued)

| WITHOUT COMPUTER CONTROL | | | WITH COMPUTER CONTROL | | | |
|---|---|---|---|---|---|---|
| | | | Operator | | Computer | |
| Variable | Op. or Comp. | Entropy in bits/Hr. n log N | Oper. | Entropy in bits/Hr. n log N | Comp. | Entropy in bits/Hr. n log N |
| <u>Extraction zone</u> | | | | | | |
| Quench circulator flow | Op. | 0.05 log 3 = 0.05 | Op. | 0.08 log 4 = 0.16 | | |
| Temp. °F | Op. | | Op. | No action | | |
| To flash tank flow | Op. | 0.68 log 24 = 3.12 | | | Comp. | 0.58 log 28 = 2.8 |
| To flash tank temp. | No action | | No action | | | |
| <u>Washing zone</u> | | | | | | |
| Cool blow total flow | Op. | 0.79 log 13 = 2.92 | | | Comp. | 0.50 log 80 = 3.16 |
| Wash circulation flow | Op. | Const. | | | Comp. | 0.19 log 14 = 0.72 |
| Wash cir. temp. in | No action | - | - | | | |
| Wash cir. temp. out | No action | - | - | | | |
| Washing zone counter wash flow | Op. | 0.10 log 10 = 0.33 | | | Comp. | 0.28 log 10 = 0.93 |
| Digester pressure | Const. | Const. | | | Comp. | Const. |
| <u>Blowing zone</u> | | | | | | |
| Outlet device RPM speed | Op. | 0.28 log 4 = 0.56 | | | Comp. | Const. |
| Drive amps | Op. | 1.0 log 2 = 1.0 | Op. | 1.0 log 2 = 1.0 | | |

Table I-1. (Continued)

| WITHOUT COMPUTER CONTROL | | | WITH COMPUTER CONTROL | | | |
|---|---|---|---|---|---|---|
| | | | Operator | | Computer | |
| | | Entropy in bits/Hr. | Entropy in bits/Hr. | | Entropy in bits/Hr. | |
| Variable | Op. or Comp. | n log N | Oper. | n log N | Comp. | n log N |
| Temp. °F | No action | | | | | |
| Consistency | Op. | 0.55 log 15 = 2.15 | | | Comp. | 0.64 log 10 = 2.13 |
| Blow line flow | Op. | 0.36 log 24 = 1.69 | | | Comp. | 0.61 log 160 = 4.46 |
| Permanganate K. No. | Op. | 0.55 log 101 = 3.66 | Op. | 0.55 log 144 = 3.9 | Comp. | 0.55 log 144 = 3.94 1/ |
| | | bits/Hr. 34.5 | | bits/Hr. 11.7 | | bits/Hr. 35.1 |

1/ Handled by both operator and by computer.

Table I-2. Summary of Tables I-3 and I-4. Entropy displayed by Controllers and Recorders in Kamyr Digester Operation with and without process control computer.

| Source | All Manual Operation No Computer bits/Hour | Operation With Computer Assistance bits/Hour |
|---|---|---|
| Entropy from Controllers[1] | | |
| Processed by Operator | 19.3 | 10.5 |
| Processed by Computer | -- | 14.6 |
| Total entropy | 19.3 | 25.1 |
| Entropy from Recorders[2] | | |
| Processed by Operator | 9.7 | 8.90 |
| Processed by Computer | -- | 12.00 |
| Total entropy | 9.7 | 20.9 |

[1]From data in Table I-3

[2]From data in Table I-4

Table I-3. Entropy displayed by controllers, Kamyr Digester operation with and without process control computer.

| Controllers | All Manual<br>n log N | Manual and Computer *<br>n log N | |
|---|---|---|---|
| Steam Vessel Press. A (2.21)[1] | Const | -- | |
| Relief Valve (2.22) | Const | -- | |
| White Liquor Flow (2.19) | 0. 4 log 204=3.07 | 0.65 log 257=5.20 | * |
| Make-up Liquor Flow (2.20) | 0. 4 log 11=0.38 | 0.45 log 12=1.61 | |
| Cooking Zone | | | |
| Upper Temp to Dig (2.23) | 0. 1 log 3=0.17 | 0.26 log 18=1.1 | * |
| Lower Temp to Dig (2.25) | 0.16 log 5=0.37 | 0.32 log 14=1.2 | * |
| 2nd Stage Cooking | | | |
| Temp to Dig (2.29) | Const | Const | |
| Extraction Zone | | | |
| Quench Circ. Flow (3.19) | 0.05 log 3=0.05 | 0.05 log 3=0.05 | * |
| Flash Tank level #1 (2.30) | 0.68 log 24=3.12 | 0.58 log 28=2.8 | |
| Flash Tank level #2 (2.31) | 0.68 log 24=3.12 | 0.58 log 28=2.8 | |
| Extraction Valve Control (3.18) | 0.36 log 40=1.92 | 0.18 log 22=0.8 | * |
| Washing Zone | | | |
| Digester Dilution Flow (3.20) | Const | Const | * |
| Counter Wash Flow (2.33) | 0. 1 log 10=0.33 | 0.28 log 10=0.93 | * |
| Wash Circ. Temp in (3.21) | Const | Const | * |
| Digester Pressure (3.14) | Const | Const | |
| Blow Line Flow (3.16) | 0.36 log 24=1.69 | 0.61 log 160=4.46 | * |

Table I-3. (continued)

| | All Manual | Manual and Computer (*) |
|---|---|---|
| Controllers | n log N | n log N |
| Controller Blow Line Valve A | -- | |
| Controller Blow Line Valve B (3.9a&b) | -- | |
| Chip Meter Level A (2.26) | 0.14 log 6=0.36 | 0.13 log 10=0.43 |
| Chip Meter Level B (2.27) | | |
| Level Tank Level (2.28) | 0.68 log 24=3.12 | 0.58 log 28=2.8 |
| Filtrate Temp (2.32) | -- | |
| Pressure Relief (3.15) | -- | |
| Chip Meter Side A | 0.13 log 14=0.5 | 0.13 log 14=0.5 * |
| Chip Meter Side B | 0.13 log 14=0.5 | 0.13 log 14=0.5 * |
| Outlet Device Speed | 0.28 log 4=0.56 | Const |
| Entropy processed by operator bits/HR | 19.3 | 10.5 |
| Entropy processed by computer bits/HR* | | 14.61* |
| Total entropy processed bits/HR | 19.3 | 25.1 |

[1] These numbers serve only as identification.

*Sum of items marked with asterisk.

Table I-4. Entropy displayed by recorders, Kamyr Digester operation, with and without process control computer.

| | Manual Operation | Manual and Computer Operation |
|---|---|---|
| Recorders | n log N | n log N |
| H. P. Steam Flow (2.11) | | |
| L. P. Steam Flow (2.12) | | |
| White Liquor Flow (2.13) | 0. 4 log 204=3.07 | 0.65 log 257=5.20 * |
| Steam Vessel Press. (2.14) | Const | Const |
| Upper Cooking Temp (2.15) (cold side) | 0.11 log 3=0.17 | 0.26 log 18=1.09 * |
| Upper Cooking Temp (2.16) (hot side) | 0.11 log 3=0.17 | 0.26 log 18=1.09 |
| Lower Cooking Temp (2.17) (cold side) | 0.16 log 5=0.37 | 0.32 log 14=1.22 * |
| Lower Cooking Temp (2.18) (hot side) | 0.16 log 5=0.37 | 0.32 log 14=1.22 |
| Wash Zone Dig Press (3.6) | Const | Const |
| 2nd Stage Temp. (3.8) | Const | Const |
| Blow Line Consistency | 0.55 log 15=2.15 | 0.64 log 10=2.13 |
| Blow Line Valve A 3.9a | 0.36 log 24=1.69 | 0.61 log 160=4.46 * |
| Blow Line Valve B 3.9b | 0.36 log 24=1.69 | 0.61 log 160=4.46 |
| Entropy processed by operator bits/HR | 9.68 | 8.90 |
| Entropy processed by computer bits/HR* | | 12.00* |
| Total entropy processed bits/HR | 9.68 | 20.9 |

*Sum of items marked with asterisk