

## CHAPTER 5: OFFICE COMMUNICATIONS

Offices provide a concrete example of the principles needed to understand the performance of computer communication systems. In offices, there is a great interest in measuring and improving productivity, coupled with trends of rising personnel costs and falling solid state electronic circuitry costs, just as there is in computer communication systems.

### 5.1 Why Offices?

An office is an example of a distributed information processing system where a variety of tasks are executed asynchronously and concurrently. These activities are typical of any data communication systems, and comprise data gathering, data manipulation, data communication, data analysis and display, and decision or policy making. Office systems are fundamentally *complex*, making it quite important to be systematic in order not to overlook anything. This requires controlled experimentation and measurement, coupled with the formation of hypotheses or models to explain behavior, as well as analysis.

Perhaps the fundamental idea in office automation is to move *ideas* or *information* to *people* and **not** vice versa. This means the office workers, secretaries and managers, do not physically move (walk, drive, fly, take a train) as much with automation, but rather communicate their ideas to one another with a variety of telecommunications systems (involving data, voice, facsimile, graphics and video output, delivered when desired).

#### 5.1.1 Additional Reading

- [1] Montgomery Phister, Jr. **Data Processing: Technology and Economics**, Second Edition, Digital Press, Bedford, Massachusetts, 1979.

### 5.2 Telephone Tag

You telephone a colleague, the colleague is not at the telephone, and a secretary takes your message asking your colleague to return your call. Later, your colleague gets your message and telephones, but now you are not in, and a secretary takes the message that your call has been returned. You call back, and the process repeats itself, until eventually you both talk to one another via telephone. This is called *telephone tag* because you and your colleague are tagging one another with telephone messages. Figure 5.1 summarizes the work flow.

5.2.1 *Workload* What are the resources here? We have two managers, you and your colleague, labeled one and two from this point on. Each of the managers has a secretary, labeled one and two for the respective manager. The resources required at each step are

- [1] Manager two and secretary one talk for a mean time of  $T_{sec,1}$  in order to leave a message for manager one
- [2] Manager one at some point receives the message and picks up the telephone to return the call, with all this taking a mean time of  $T_{mess,1}$
- [3] Manager one makes the telephone call to manager two: this requires looking up the telephone number, getting to a telephone and so forth, with a total mean time of  $T_{tel,1}$
- [4] Manager one and manager two talk with one another via the telephone for a mean time of  $T_{ans,1}$
- [5] Manager one and secretary two talk for a mean time of  $T_{sec,2}$  in order to leave a message for manager two
- [6] Manager two at some point receives the message and picks up the telephone to return the call, with a total mean time of  $T_{mess,2}$  passing

**Figure 5.1. Telephone Tag Work Flow**

[7] Manager two makes the telephone call to manager one, with a mean time of  $T_{tel,2}$  elapsing

[8] Manager two and manager one talk with one another via the telephone for a mean time of  $T_{ans,2}$

The table below summarizes the resources required for each step, and the mean time interval the resources are held:

**Table 5.1. Telephone Tag Step/Resource Summary**

<i>Step</i>	<i>Manager 1</i>	<i>Secretary 1</i>	<i>Manager 2</i>	<i>Secretary 2</i>	<i>Time</i>
1	0	1	1	0	$T_{sec,1}$
2	1	0	0	0	$T_{mess,1}$
3	1	0	0	0	$T_{tel,1}$
4	1	0	1	0	$T_{ans,1}$
5	1	0	0	1	$T_{sec,2}$
6	0	0	1	0	$T_{mess,2}$
7	0	0	1	0	$T_{tel,2}$
8	1	0	1	0	$T_{ans,2}$

Where did the tag go? We can have multiple visits to the branches for leaving messages, but only one visit to the branch to return the call. To account for this, we denote the mean number of visits to the secretary answering branch for the second manager by  $V_{tag,1}$  while the mean number of visits to the secretary branch for the first manager is denoted by  $V_{tag,2}$

**5.2.2 State Space** What might be one appropriate state space to describe the operation of this system? At any instant of time, we could choose a five tuple  $\underline{J}$  where

$$\underline{J} = \{J_{sec,1}, J_{man,1}, J_{sec,2}, J_{man,2}, I\}$$

where  $J_{sec,1}$  is either zero or one to show that secretary one is not or is busy with telephone call activity, and so forth, and  $I$  denotes the step. Not all combinations are feasible: we denote by  $F$  the set of feasible states, where

$$F = \{(1,0,0,1,1), (0,1,0,0,2), (0,1,0,0,3), (0,1,0,1,4), \\ (0,1,1,0,5), (0,0,0,1,6), (0,0,0,1,7), (0,1,1,0,8)\}$$

**5.2.3 Analysis** We monitor the system for a time interval of duration  $T$  minutes. Over that time interval, the system is in state  $I$  for a total time of  $T_I$  minutes. For each feasible  $\underline{J}$  we denote by  $\pi(\underline{J})$  the *fraction* of observation time that the system was in state  $\underline{J}$ . We see

$$\frac{T_I}{T} = \pi(\underline{J}) \geq 0 \quad \underline{J} \in F \quad \sum_{\underline{J} \in F} \pi(\underline{J}) = 1$$

from these definitions. If the observation interval becomes sufficiently large (days, weeks, months) so that the number of calls in progress at the start and end of the observation interval is negligible compared to the total number of calls that start and finish during the observation interval, we will use Little's Law to show that the mean number of calls in each step (eight here) equals the mean throughput rate for each step multiplied by the average duration of each step:

$$\begin{aligned} \text{average number of calls in process in state } I &= | \underline{J} |_I \\ &= (\text{average throughput rate in step } I) \times (\text{average duration of step } I) \quad I=1,2,\dots,8 \end{aligned}$$

Formally, we can write this as

$$\sum_{\underline{J} \in F} J_I \pi(\underline{J}) = \lambda T_I \quad I=1,2,\dots,8$$

Our measure of productivity is the mean rate of completing useful telephone calls. Substituting into the relationships, we see

$$\begin{aligned} \pi(1,0,0,1,1) &= \lambda V_{tag,1} T_{sec,1} & \pi(0,1,1,0,5) &= \lambda V_{tag,2} T_{sec,2} \\ \pi(0,1,0,0,2) &= \lambda V_{tag,1} T_{mess,1} & \pi(0,0,0,1,6) &= \lambda V_{tag,2} T_{mess,2} \\ \pi(0,1,0,0,3) &= \lambda V_{tag,1} T_{tel,1} & \pi(0,0,0,1,7) &= \lambda V_{tag,2} T_{tel,2} \\ \pi(0,1,0,1,4) &= \lambda T_{ans,1} & \pi(0,1,0,1,8) &= \lambda T_{ans,2} \end{aligned}$$

If we add up all of these, we see

$$\begin{aligned} \sum_{\underline{J} \in F} \pi(\underline{J}) &= \lambda T_{loop} \leq 1 \quad \rightarrow \quad \lambda \leq \frac{1}{T_{loop}} \\ T_{loop} &= V_{tag,1} [T_{sec,1} + T_{mess,1} + T_{tel,1}] + T_{ans,1} + V_{tag,2} [T_{sec,2} + T_{mess,2} + T_{tel,2}] + T_{ans,2} \end{aligned}$$

Let's substitute some illustrative numbers to see what the impact of tag might be. We assume that the time spent leaving the message with the secretary has a mean of two minutes, the time until the message is picked up and read has a mean of thirty minutes, the time to telephone is fifteen seconds, and the time to actually talk is ten minutes:

**Table 5.2. Illustrative Telephone Tag Step/Time Numerical Example**

Time	Amount
$T_{sec,1} = T_{sec,2}$	2 Minutes
$T_{mess,1} = T_{mess,2}$	30 Minutes
$T_{tel,1} = T_{tel,2}$	1/4 Minutes
$T_{ans,1} = T_{ans,2}$	10 Minutes

If we assume the mean number of tags is two, so that it takes two calls on the average for you and your colleague to talk, then

$$V_{tag,1} = V_{tag,2} = 2$$

then we see that the maximum mean throughput rate is

$$\lambda \leq \frac{1}{139 \text{ minutes}}$$

or roughly one telephone conversation lasting ten minutes every two and a half hours! If the mean number of tags increases to three, then the maximum mean throughput rate drops to one call lasting ten minutes every 203.5 minutes!

This is very frustrating for anyone. What can we do to shorten this time to complete one telephone call?

5.2.4 *An Alternative: Voice Storage* What if we replaced this mode of operation with a voice storage system, where the caller leaves a voice message in a storage system to be retrieved by the callee at convenience, as shown in the figure below

**Figure 5.2.Voice Storage Work Flow**

The resources required at each step are summarized below

**Table 5.3.Voice Storage System Resources/Step**

<i>Step</i>	<i>Manager 1</i>	<i>Manager 2</i>	<i>Voice Storage</i>	<i>Time</i>
1	0	1	1	$T_{mess,1}$
2	1	0	0	$T_{delay,1}$
3	1	0	0	$T_{tel,1}$
4	1	1	0	$T_{ans,1}$
5	1	0	1	$T_{mess,1}$
6	0	1	0	$T_{delay,1}$
7	0	1	0	$T_{tel,2}$
8	1	1	0	$T_{ans,2}$

Proceeding as before, and using the same illustrative numbers, but with  $V_{tag,1}=V_{tag,2}=1$ , we see that the maximum mean throughput rate is given by

$$\lambda \leq \frac{1}{74\frac{1}{2} \text{ minutes}}$$

or roughly one telephone conversation of ten minutes every hour and a quarter, halving the total handling time per call. The gain here is obvious: halving the number of messages for the harried secretary helps enormously! By being systematic, we have quantified the gain for both the secretary and manager. To see if you understand this, ask yourself what happens when the number of tags is greater than two, or if multiple calls are circulating (not just one like here).

### 5.2.5 Additional Reading

- [1] L.H.Mertes, *Doing your Office Over--Electronically*, Harvard Business Review, **59** (2), 127-135 (1981).

## 5.3 Copying and Reproduction

How many copiers or reproduction machines does an office need for making copies of letters and correspondence, articles of all sorts, bills, contracts, and on and on? More to the point, what are the minimum set of numbers needed to say anything whatsoever that is pertinent to this question?

The figure below is a block diagram of an office with only two entities: secretaries and copiers. The secretaries spend a certain amount of time preparing a paper for reproduction, and then they go to the copying machine and make the copies, collate and staple them, leave, and the process starts all over.

**Figure 5.3. Office Copying System Block Diagram**

The next figure below is a queueing network block diagram of this system, assuming we have  $S$  secretaries and  $C$  copiers:

**Figure 5.4. Queueing Network of Office Copying System**

To complete our description, we need to measure or estimate or guess the mean time a secretary requires for preparation of a document for reproduction, denoted by  $T_{secretary}$ , and the mean time a secretary spends copying a document with all the related steps of collating and stapling, denoted by  $T_{copy}$ .

We now have a wealth of information: what do we do next? Let's assume there is only one copier for all  $S$  secretaries, before looking at the more general case of  $C > 1$  copiers.

With only one copier and one secretary, we see a cycle takes place: the secretary generates the document and then reproduces it, again and again and again. The mean throughput rate of copying documents with one secretary is simply

$$\text{mean document copying rate} = \frac{1}{T_{\text{secretary}} + T_{\text{copy}}} \quad \text{one secretary, } S=1$$

As we add more and more secretaries, the best we can do is to have the mean copying rate grow linearly with the number of secretaries: going from one to two secretaries doubles the document copying rate, and so on:

$$\text{mean document copying rate} \leq \frac{S}{T_{\text{secretary}} + T_{\text{copy}}}$$

At some point, the copier will be completely busy reproducing documents, which also upper bounds the mean throughput rate:

$$\text{mean document copying rate} \leq \frac{1}{T_{\text{copy}}}$$

Combining these upper bounds, we see

$$\text{mean document copying rate} \leq \min \left[ \frac{S}{T_{\text{secretary}} + T_{\text{copy}}}, \frac{1}{T_{\text{copy}}} \right]$$

On the other hand, we might find that every time a secretary goes to make a copy, *all* the other secretaries are lined up in front of the copying machine (maybe it is a social gathering, maybe every so often there is a very very big job that all the little jobs have to wait for, and on and on). Now we see that the cycle is for a secretary to generate a document, and then to wait for  $S$  documents to be reproduced ( $S-1$  for the other secretaries plus your document):

$$\text{mean document copying rate} \geq \frac{S}{T_{\text{secretary}} + ST_{\text{copy}}}$$

Two regimes are evident:

- if the secretaries are the bottleneck (not enough documents are ready to be reproduced) then

$$\text{mean document copying rate} \approx \frac{S}{T_{\text{secretary}} + T_{\text{copy}}}$$

- If the copying machine is the bottleneck, running all the time, then

$$\text{mean document copying rate} \approx \frac{1}{T_{\text{copy}}}$$

The breakpoint number of secretaries between these two regimes is given by

$$S_{\text{breakpoint}} = \frac{T_{\text{secretary}} + T_{\text{copy}}}{T_{\text{copy}}}$$

For example, if each secretary spends one hour in document preparation ( $T_{\text{secretary}}=1 \text{ hour}$ ) and five minutes in walking to the copier, making the copies, addressing envelopes, and so forth ( $T_{\text{copy}} = 5 \text{ minutes}$ ) then the breakpoint number of secretaries is simply

$$S_{\text{breakpoint}} = \frac{60 + 5}{5} = 13 \text{ secretaries}$$

If we assign ten or fewer secretaries to a copier, the copying machine will rarely be congested; if we assign twenty or more secretaries to a copier, the copying machine will be rarely idle.

What if we add a second copying machine? With two machines completely busy, the upper bound on mean throughput rate is twice that for one machine. However, this will not affect the mean time to make a copy of a document, only the mean delay to get to a copying machine. The upper bound on mean throughput rate is now given by

$$\text{mean document copying rate} \leq \min \left[ \frac{S}{T_{\text{secretary}} + T_{\text{copy}}}, \frac{2}{T_{\text{copy}}} \right]$$

while the lower bound on mean throughput rate becomes

$$\text{mean document copying rate} \geq \frac{S}{T_{\text{secretary}} + \frac{S}{2} T_{\text{copy}}}$$

We summarize all these bounds graphically in the figure below:

### Figure 5.5. Mean Document Copying Rate

Finally, what is the gain in going from one to two copiers? Using the earlier numbers, we see

$$S_{\text{breakpoint}} = \frac{T_{\text{secretary}} + T_{\text{copy}}}{\frac{1}{2} T_{\text{copy}}} = \frac{60+5}{5/2} = 26 \text{ secretaries}$$

We have doubled the breakpoint, so that twenty or fewer secretaries could be accommodated by two copiers, with the copiers rarely being a point of congestion, while with thirty or more secretaries the copiers will be congested most of the time.

#### 5.4 Document Preparation

The process of document preparation is undergoing a great change at the present time, again due to computer technology. More and more text is being handled by a digital computer system consisting of terminals that replace typewriters, a storage system (today with moving header magnetic disks, tomorrow with optical laser disks), a printer for generating the physical documents, and a processor for controlling all of these steps. There might be access to a network of other such systems elsewhere. All of this is shown in the figure below:

Three steps are involved in document preparation

- [1] Entering the document into the system
- [2] Editing the document one or more times
- [3] Reproducing or printing requisite number of copies of the document

**Figure 5.6.Document Preparation System Hardware Block Diagram**

The figure below shows a queueing network block diagram of this system:

**Figure 5.7.Document Preparation Queueing Network Block Diagram**

How many secretaries can be active before the congestion inside the document preparation system becomes unacceptable? What numbers do we need to measure or estimate in order to answer this question?

The mean time required for each of the three steps of document preparation is a natural starting point for quantifying performance, along with the resources required at each step of the way; we do so in a hierarchical manner, starting first simply with secretaries using the system, and then breaking down the actions inside the system:



**Table 5.4.Document Preparation Step/Resource Table**

<i>Step</i>	<i>Secretary</i>	<i>Time</i>	<i>System</i>	<i>Time</i>
Entry	1	$T_{sec,entry}$	1	$T_{sys,entry}$
Edit	1	$T_{sec,edit}$	1	$T_{sys,edit}$
Print	1	$T_{sec,print}$	1	$T_{sys,print}$

**Table 5.5.Document Step/Resource Processor Summary**

<i>Step Type</i>	<i>Resource and Time</i>	
	<i>Processor</i>	<i>Time</i>
Entry	1	$T_{proc,entry}$
Edit	1	$T_{proc,edit}$
Print	1	$T_{proc,print}$

**Table 5.6.Document Resource/Step Disk Summary**

<i>Step Type</i>	<i>Resource and Time</i>	
	<i>Disk</i>	<i>Time</i>
Entry	1	$T_{disk,entry}$
Edit	1	$T_{disk,edit}$
Print	1	$T_{disk,print}$

**Table 5.7.Document Resource/Step Printer Summary**

<i>Step Type</i>	<i>Resource and Time</i>	
	<i>Printer</i>	<i>Time</i>
Entry	0	--
Edit	0	--
Print	1	$T_{printer,print}$

We have done this in two steps to carry out two different levels of analysis, one a coarse aggregate rough sizing, the other a more refined analysis (which needs more information).

In the first level of analysis, simply with secretaries and a system, the rough sizing would be to put one secretary on the system and see how long on the average one document can be generated:

$$T_{doc} = T_{sec,entry} + T_{sys,entry} + T_{sec,edit} + T_{sys,edit} + T_{sec,print} + T_{sys,print}$$

When we examine a system, we see that it is reasonable to assume that the processor or disk time consumed to do document entry and editing is negligible compared with the time required for the processor, disk, and printer to reproduce the requisite hard copy manuscript. On the other hand, the time required for the secretary to do the entry and editing is typically much much greater than the time required to handle work associated with document printing. This is summarized by the following approximations:

$$T_{sec,entry} \gg T_{sys,entry} \quad T_{sec,edit} \gg T_{sys,edit} \quad T_{sys,print} \gg T_{sec,print}$$

The mean throughput rate is upper bounded by

$$mean \text{ throughput rate} \leq \min \left[ \frac{S}{T_{doc}}, \frac{1}{T_{sys,print}} \right]$$

where we have  $S$  secretaries total and using arguments in the earlier sections, and is lower bounded by observing that every time one secretary goes to print a document the other  $(S-1)$  secretaries are waiting in line to do exactly the same thing:

$$mean \text{ throughput rate} \geq \frac{S}{T_{doc} + (S-1)T_{sys,print}}$$

A more detailed look is in order concerning the system performance limits, using the additional information we have so laboriously gathered. The resources here are the secretaries, a processor, a disk, and a printer. The state of the system is given by a tuple whose components denote whether each

resource is idle or active. The total document preparation system is monitored for a time interval of duration  $T$  minutes which is assumed to be sufficiently long that the number of documents that are in preparation at the start and finish of the observation interval is assumed negligible compared to the total number of documents that start and finish during the observation interval. We denote by  $T_I$  the total time the system spent in step  $I$  during the observation interval  $T$ . For each feasible state  $\underline{J}$  in the set of feasible states  $F$  we denote by  $\pi(\underline{J})$  the fraction of observed time that the system spent in that state. We can now apply Little's Law:

$$\text{average number of documents in state } I = E[|\underline{J}|_I] = \lambda_I T_I \quad I=1,2,3$$

$$\lambda_I = \text{mean throughput for step } I \quad I=1,2,3$$

$$T_I = \text{mean duration of step } I \quad I=1,2,3$$

$$\sum_{\underline{J} \in F} |\underline{J}|_I \pi(\underline{J}) = \lambda T_I \quad I=1,2,3$$

We wish to maximize  $\lambda$  subject to this constraint, plus meet the following constraints:

$$\frac{T_I}{T} = \pi(\underline{J})_I \quad I=1,2,3$$

$$\sum_{\underline{J} \in F} \pi(\underline{J}) = 1 \quad \pi(\underline{J}) \geq 0$$

>From our earlier studies, we see that the following regimes can limit the maximum mean throughput rate:

- [1] Secretaries cannot generate enough documents and bottleneck the system

$$\lambda_{\max} = \frac{S}{T_{\text{sec,entry}} + T_{\text{sec,edit}} + T_{\text{sec,print}}}$$

- [2] The processor is completely busy and is the bottleneck

$$\lambda_{\max} = \frac{1}{T_{\text{proc,entry}} + T_{\text{proc,edit}} + T_{\text{proc,print}}}$$

- [3] The disk is completely busy and is the bottleneck

$$\lambda_{\max} = \frac{1}{T_{\text{disk,entry}} + T_{\text{disk,edit}} + T_{\text{disk,print}}}$$

- [4] The printer is completely busy and is the bottleneck

$$\lambda_{\max} = \frac{1}{T_{\text{printer,print}}}$$

This is basically what we argued earlier, but hopefully makes clearer and less ambiguous the number of assumptions and approximations.

To finish, let's substitute in some typical numbers to get a feel for whether any of this is reasonable. First, a secretary can type fifty words per minute, with each word being five letters. A document consists of two pages typically, with two hundred and fifty words per page, so the initial document typing time is simply ten minutes. We will allow a five minute set up time to be included in this initial document typing time. Next, we get out our stop watch and clip board and measure how long on the average it takes to edit and correct a document: we find this takes five minutes on the average (without a document preparation system whole pages would have to be retyped or rewritten, taking fifteen minutes or more on the average just for the editing). Finally, we need to print the document; two printers are available, one handling twenty five characters per second and the other handling one hundred characters per second. We will need two copies of every document. The slow printer can handle one page every two hundred and fifty seconds, and hence will generate four pages (two pages per document, two copies) in one thousand seconds or sixteen and two thirds minutes. The fast printer can handle this in one fourth the time. The only data we can gather from the computer system suggests that the processor is

busy on the average for ten seconds total for each document, while the disk is busy for thirty seconds total for each document. The limits on maximum mean document generation are

- [1] Secretaries are the bottleneck

$$\lambda_{\max} = \frac{S}{15 \text{ minutes}} \text{ documents/minute}$$

- [2] The processor is the bottleneck

$$\lambda_{\max} = \frac{1}{1/6 \text{ minute}} = 6 \text{ documents/minute}$$

- [3] The disk is the bottleneck

$$\lambda_{\max} = \frac{1}{1/2 \text{ minute}} = 2 \text{ documents/minute}$$

- [4] Printers are the bottleneck

$$\lambda_{\max} = \frac{1}{16 \frac{2}{3} \text{ minutes}} \text{ documents/minute} \quad \text{slow printer}$$

$$\lambda_{\max} = \frac{4}{16 \frac{2}{3} \text{ minutes}} \text{ documents/minutes} \quad \text{fast printer}$$

Thus, we see that one secretary can keep the slow printer busy, but when we put two secretaries on the system, the printer becomes a bottleneck, and hence we should get a fast printer which can handle up to four secretaries.

#### 5.4.1 Additional Reading

- [1] A.F.Shackil, *Design Case History: Wang's Word Processor*, IEEE Spectrum, **18** (8), 29-33 (1981).

### 5.5 Local Area Networks

Several years ago a minicomputer was installed in a particular small business for doing billing, accounts receivable and payable, payroll, general ledger activities, quarterly tax reports, and similar types of activities and services. The system consists of several terminals connected to a terminal controller with one processor and one disk.

The trade press is currently full of articles about *local area networks* which suggest that the terminal controller can be replaced with a single local area network, hooking all the terminals and the computer directly together. The two configurations are shown in the figures below:

**Figure 5.8.Existing Old System Hardware Block Diagram**

**Figure 5.9. Proposed New System Hardware Block Diagram**

How much will the local area network affect performance: what numbers do we need to gather or measure or estimate in order to quantify the benefits of the two approaches, the current and proposed?

Let's assume that there is only one type of transaction or job handled by the system, that has the following steps

- [1] Data entry and data validation
- [2] Data base management
- [3] Data retrieval
- [4] Data modification and removal
- [5] Report generation

The resources common to the two systems are the terminals, processor, disk and printer; the old system uses a terminal controller, while the new system uses a local area network to switch messages. The table below summarizes the resources required at each step of job execution

**Table 5.8. Transaction Processing Step/Resource Summary**

<i>Step Type</i>	<i>Resource</i>				
	<i>Terminal</i>	<i>Processor</i>	<i>Disk</i>	<i>Switch</i>	<i>Printer</i>
Entry	1	1	1	1	0
Execution	0	1	1	1	0
Retrieval	1	1	1	1	1
Modification	1	1	1	1	1
Report	0	1	1	1	1

The mean time required for each resource for each step is denoted by  $T_{resource,step}$ , where a resource is a terminal, processor or disk or printer, and the step is either data entry or execution or modification or report generation.

The bottlenecks in the system are

- [1] Clerks cannot generate enough load to keep the system busy

$$\lambda_{\max} = \frac{C}{\sum_l T_{clerk,l}}$$

- [2] Terminals are completely busy

$$\lambda_{\max} = \frac{C}{\sum_I T_{term,I}}$$

[3] The processor is completely busy

$$\lambda_{\max} = \frac{1}{\sum_I T_{proc,I}}$$

[4] The disk is completely busy

$$\lambda_{\max} = \frac{1}{\sum_I T_{disk,I}}$$

[5] The terminal controller or local area network is completely busy

$$\lambda_{\max} = \frac{1}{\sum_I T_{switch,I}}$$

[6] The printer becomes completely busy

$$\lambda_{\max} = \frac{1}{T_{printer,report}}$$

The reason for replacing the terminal controller with a local area network is that the terminal controller is congested or completely busy, which leads to unacceptable delays, and that presumably the clerks at the terminals will become the bottleneck with a local area network in place.

Let's substitute some typical numbers to see if this is reasonable:

**Table 5.9. Time/Resource per Step**

<i>Resource</i>	<i>Entry</i>	<i>Execution</i>	<i>Retrieve</i>	<i>Modify</i>	<i>Report</i>
Terminal	1.0 sec	0.0 sec	0.5 sec	0.5 sec	0.5 sec
Processor	5.0 sec	7.5 sec	2.0 sec	10.0 sec	2.5 sec
Disk	0.5 sec	10.0 sec	8.0 sec	12.0 sec	5.0 sec
Printer	0.0 sec	0.0 sec	0.0 sec	0.0 sec	100.0 sec
Controller	3.0 sec	0.0 sec	2.0 sec	2.0 sec	0.0 sec
Local Network	0.01 sec	0.0 sec	0.02 sec	0.02 sec	0.02 sec

Finally, we gather statistics on how frequently every hour each transaction type is executed, and summarize them in the table below:

**Table 5.10. Frequency of Execution**

Entry	10 times/hour
Execute	10 time/hour
Retrieve	100 times/hour
Modify	20 times/hour
Report	2 times/hour

The bottleneck here is the *disk!* Adding a local area network will not significantly improve performance, because the terminal controller is not the point to reach complete utilization first. The best choice from a performance point of view is not the local area network addition, but rather adding more disks.

5.5.1 Additional Reading

[1] J.M.Kryskow, C.K.Miller, *Local Area Networks Overview--Part I: Definitions and Attributes*, Computer Design, 22-35 (February, 1981), *Local Area Networks Overview--Part II: Standards Activities*, Computer Design, 12-20 (March, 1981).

- [2] B.W.Stuck, *Calculating the Maximum Mean Throughput Rate in Local Area Networks: IEEE Computer Society Project 802 Local Area Network Standards*, Computer, **16**, (5),72-76(1983).
- [3] B.W.Stuck, *Which Local Net Bus Access is Most Sensitive to Traffic Congestion?*, Data Communications, **12** (1), 107-120 (1983).

### 5.6 Professional Work Station Productivity Gains

In one particular office, professionals do four things

- [1] Work individually on different assignments
- [2] Attend meetings to communicate their findings and learn of others' work
- [3] Telephone others on work related matters
- [4] Document their findings and activities

The office staff manager proposes to provide each professional with a so called *work station* which would have access to all of the documentation via an on line data management system, and which would allow everyone using the system to communicate via either electronic mail (making document distribution much less time consuming for the office staff) and via voice mail (storing telephone calls and filing them when a professional is not available). The work flow of the old system and new system is shown in the figures below:

#### Figure 5.10.Old System Professional Work Flow

What would be the impact on productivity for the professional staff? What numbers need to be gathered to quantify these issues? What do we need to measure or estimate or guess?

The resources common to either system are

- [1] The number of professionals  $P$
- [2] The total number of work assignments  $W$
- [3] The total number of simultaneous meetings  $M$
- [4] The total number of documents in preparation  $D$

The resources unique to the old system are

- [1] The total number of telephone calls (including messages) in progress  $T$

The resources unique to the new system are

- [1] The total number of voice storage messages  $V$

**Figure 5.11. New System Professional Work Flow**

[2] The total number of electronic mail messages  $E$

The mean time required for each action is summarized in the table below

**Table 5.11. Time/Job Summary**

<i>Job</i>	<i>Mean Time</i>
Work	$T_{work}$
Meeting	$T_{meeting}$
Telephone	$T_{telephone}$
Document	$T_{document}$
Voice Mail	$T_{voice\ mail}$
Electronic Mail	$T_{electronic\ mail}$

The bottlenecks or resources that can reach complete utilization are

[1] Professionals are completely busy

$$\lambda_{\max} = \frac{P}{T_{work} + T_{meeting} + T_{telephone} + T_{document}} \quad \text{old system}$$

$$\lambda_{\max} = \frac{P}{T_{work} + T_{meeting} + T_{voice\ mail} + T_{electronic\ mail} + T_{document}} \quad \text{new system}$$

[2] Work assignments are the bottleneck

$$\lambda_{\max} = \frac{W}{T_{work}}$$

[3] Meetings are the bottleneck

$$\lambda_{\max} = \frac{M}{T_{meeting}}$$

[4] Document preparation is the bottleneck

$$\lambda_{\max} = \frac{D}{T_{document}}$$

[5] Messages are the bottleneck

$$\lambda_{\max} = \frac{T}{T_{telephone}} \quad \text{old system}$$

$$\lambda_{\max} = \min \left[ \frac{T}{T_{\text{telephone}}}, \frac{V}{T_{\text{voice mail}}}, \frac{E}{T_{\text{electronic mail}}} \right] \quad \text{new system}$$

The work station would help improve office productivity if

- [1] The number of meetings was a bottleneck and could be reduced via voice and electronic mail
- [2] The number of telephone calls was a bottleneck and could be reduced via voice and electronic mail
- [3] Documentation was a bottleneck (filing and gaining access to reports and so on) and could be reduced via electronic and voice mail

Let's illustrate all this with some numbers. The office we'll focus upon has five professionals. In the current system, each professional is working on four different projects simultaneously, and each has ten documents in preparation at any time. There is one conference room. In the current system the total number of telephone calls (including messages) in progress is roughly six per professional. The proposed system can handle roughly one hundred voice storage messages per professional and fifty electronic mail messages per professional. The savings in time are dramatic: the time spent by each professional per assignment will be cut from twenty hours to ten hours, with meeting time cut from five hours per assignment to two hours, telephone time cut from five hours to two hours, and document preparation time cut from twenty hours to five hours. Time spent on voice mail will be roughly fifteen minutes per assignment, while electronic mail will demand forty five minutes per assignment:

**Table 5.12. Illustrative Time/Resource Summary**

<i>Job Type</i>	<i>Maximum Jobs</i>		<i>Symbol</i>	<i>Mean Time</i>	
	<i>Old</i>	<i>New</i>		<i>Old</i>	<i>New</i>
Work	20	40	$T_{\text{work}}$	20 hrs	10 hrs
Meeting	1	1	$T_{\text{meeting}}$	5 hrs	2 hr
Telephone	30	60	$T_{\text{telephone}}$	5 hrs	2 hr
Document	50	200	$T_{\text{document}}$	20 hrs	5 hrs
Voice Mail	--	500	$T_{\text{voice mail}}$	--	1/4 hr
Electronic Mail	--	250	$T_{\text{electronic mail}}$	--	3/4 hr

For the two systems, the possible bottlenecks are

- [1] Professionals are completely busy

$$\lambda_{\max} = \frac{5}{20 + 5 + 5 + 20} = 0.1 \text{ jobs/hr} \quad \text{old system}$$

$$\lambda_{\max} = \frac{5}{10 + 5 + 2 + 2 + 1 + 5} = 0.2 \text{ jobs/hr} \quad \text{new system}$$

- [2] Work assignments are the bottleneck

$$\lambda_{\max} = \frac{20}{40} = 0.5 \text{ jobs/hr} \quad \text{old system}$$

$$\lambda_{\max} = \frac{40}{20} = 2.0 \text{ job/hr} \quad \text{new system}$$

- [3] Meetings are the bottleneck

$$\lambda_{\max} = \frac{1}{5} = 0.2 \text{ jobs/hr} \quad \text{old system}$$

$$\lambda_{\max} = \frac{1}{2} = 0.5 \text{ jobs/hr} \quad \text{new system}$$

- [4] Document preparation is the bottleneck



$$\lambda_{\max} = \frac{50}{20} = 2.5 \text{ jobs/hr } \textit{old system}$$

$$\lambda_{\max} = \frac{200}{5} = 40 \text{ jobs/hr } \textit{new system}$$

[5] Messages are the bottleneck

$$\lambda_{\max} = \frac{30}{2} = 15 \text{ jobs/hr } \textit{old system}$$

$$\lambda_{\max} = \min \left[ \frac{500}{1/4}, \frac{250}{3/4}, \frac{60}{2} \right] = 30 \text{ jobs/hr } \textit{new system}$$

The bottleneck in either case is the professional staff working all the time; however, by investing in office automation equipment, the staff can handle over twice the workload that the old system could handle. This must be weighed against the capital cost, and a number of other factors before jumping to conclusions, but they are illustrative of the productivity gains possible with such innovations. Substitute in your own numbers to see what the impact is for your office!

#### 5.6.1 Additional Reading

- [1] Clarence A. Ellis, Gary J. Nutt, *Office Information Systems and Computer Science*, Computing Surveys **12** (1), 27-60 (1980).
- [2] R.P.Uhlig, D.J.Farber, J.H.Bair, **The Office of the Future: Communication and Computers**, North-Holland, Amsterdam, 1979.

#### 5.7 Interactions of Secretaries and Managers

The example office system model we will examine has three types of entities, N managers, N secretaries, and N word processing stations.

#### Figure 5.12. Office Block Diagram

The sole function of the office is document preparation. There are three steps involved in document preparation:

- [1] A manager dictates a draft to a secretary. This step has a mean duration of  $T_1$  minutes
- [2] The secretary enters the draft into a file using a word processor station. This step has a mean duration of  $T_2$  minutes

- [3] The manager originating the document edits and proofs the document at a word processor station until the final corrected version is satisfactory. This step has a mean duration of  $T_3$  minutes

These are shown in the figure below:

**Figure 5.13.Document Preparation Work Flow**

Our problem is to determine an upper bound for  $\lambda$ , the mean throughput rate (measured in documents per minute) of document preparation, from start to finish. The first step in the analysis is to construct a state model for the office system behavior. If we imagine observing the office in operation at a given instant of time, say  $t$ , we would note at most three kinds of activities, one for each of the three steps. Let the three tuple  $\underline{J}=(j_1,j_2,j_3)$  denote the state of the office system, whose components are nonnegative integers. The statement that the office is in state  $\underline{J}$  at time  $t$  then means that at the time of observation, there were *concurrently* in progress  $j_1$  step one,  $j_2$  step two, and  $j_3$  step three activities. We alert the reader that not all values for  $\underline{J}$  are possible. We denote by  $F$  the set of  $\underline{J}$  vectors which are feasible. As an aid to constructing this set  $F$ , we form a step resource requirement table.

**Table 5.13.Step Resource Requirements**

Step Number	Resource			Time Required
	Manager	Secretary	Word Processor	
1	1	1	0	$T_1$
2	0	1	1	$T_2$
3	1	0	1	$T_3$

Each column shows the type and quantity of resources required by each step. Since we have a maximum of  $N$  units of each resource type, managers and secretaries and word processors,  $F_1$  is the set of three tuples  $\underline{J}$  such that

$$\begin{aligned}
 j_k &\in \{\text{nonnegative integers}\} \quad k=1,2,3 \\
 j_1 + j_2 &\leq N \quad \text{manager constraint} \\
 j_2 + j_3 &\leq N \quad \text{secretary constraint} \\
 j_1 + j_3 &\leq N \quad \text{word processor constraint}
 \end{aligned}$$

Now imagine that we monitor the office system for a time interval of  $T$  minutes. For each feasible  $\underline{J}$  we denote by  $\pi(\underline{J})$  the *fraction* of the observation time that the office was in state  $\underline{J}$ . We then have

$$\pi(\underline{J}) \geq 0 \quad \underline{J} \in F \quad \sum_{\underline{J} \in F} \pi(\underline{J}) = 1$$

by definition. Let us denote by  $\lambda T$  the number of document preparation completions observed in the time interval  $(0, T)$ . If  $T$  is sufficiently large (so that truncation effects due to partially executed jobs at the ends of the observation interval are negligible), we may apply Little's Law: the mean number of jobs in a system equals the mean rate of jobs flowing through the system multiplied by the mean time per job in the system. Here we have three systems, one for each step of execution:

$$\begin{aligned} & \text{average number of jobs in execution in step } I \\ & = (\text{average throughput rate for step } I) \times (\text{average duration of step } I) \quad I=1,2,3 \end{aligned}$$

More formally, we can write this as

$$\sum_{\underline{J} \in F} j_I \pi(\underline{J}) = \lambda T_I \quad I=1,2,3$$

Before proceeding with the general analysis, let us consider a special case to gain insight, where  $N=1$ . For this case, it is clear that  $F$  consists of just four vectors:

$$F = \{(0,0,0), (1,0,0), (0,1,0), (0,0,1)\}$$

Our earlier expression now becomes

$$\pi(1,0,0) = \lambda T_1 \quad \pi(0,1,0) = \lambda T_2 \quad \pi(0,0,1) = \lambda T_3$$

If we add the left and right hand sides, respectively, of the earlier expression, we find

$$1 \geq \pi(1,0,0) + \pi(0,1,0) + \pi(0,0,1) = \lambda(T_1 + T_2 + T_3)$$

This yields the desired upper bound on  $\lambda$ :

$$\lambda \leq \frac{1}{T_1 + T_2 + T_3}$$

This is obvious on intuitive grounds: when  $N=1$  only one step may be in progress at any one time, there is no concurrency or parallel execution of tasks, and the total number of minutes required for document preparation is  $T_1 + T_2 + T_3$  minutes.

We now examine the general case of an arbitrary positive integer valued  $N$ . Our problem is to maximize the mean throughput rate  $\lambda$  over the feasible  $\pi(\underline{J}), \underline{J} \in F$ :

$$\lambda_{\max} = \underset{\pi(\underline{J}), \underline{J} \in F}{\text{maximum}} \lambda$$

This maximization is subject to the following constraints:

$$\begin{aligned} \sum_{\underline{J} \in F} j_I \pi(\underline{J}) &= \lambda T_I \quad I=1,2,3 \\ \sum_{\underline{J} \in F} \pi(\underline{J}) &= 1 \quad \pi(\underline{J}) \geq 0 \end{aligned}$$

A general approach to solving this optimization problem is to rewrite it as a linear programming problem (Omahen, 1977; Dantzig, 1963), and then use one of a variety of standard numerical packages for approximating the solution to such problems. Here, since our problem is simple, we shall proceed analytically rather than numerically, in order to gain insight into the nature and characteristics of the solution. We do so in an appendix to this section, and merely cite the final result before discussing how to interpret this result.

The final result is this upper bound on the maximum mean throughput rate of completed jobs:

$$\lambda \leq \min \left[ \frac{N}{T_1 + T_2}, \frac{N}{T_2 + T_3}, \frac{N}{T_1 + T_3}, \frac{\left\lfloor \frac{3N}{2} \right\rfloor}{T_1 + T_2 + T_3} \right]$$

As a check, we see that this agrees with the above with  $N=1$ .

As an example of how to apply this result, let us assume that  $N=2$  and  $T_1 = T_2 = T_3 = 15$  minutes. We wish to compare the following two configurations:

- [1] Each manager has his own private secretary and word processor work station, so there are two independent office systems with  $N=1$
- [2] The secretaries and word processor work stations are shared, forming a single pooled office system with  $N=2$

In the first case, the upper bound on  $\lambda$  will be twice that of a single office:

$$\lambda_{\max, \text{case one}} = \frac{2}{45} \text{ documents per minute} = \frac{8}{3} \text{ documents per hour}$$

For the second case, using the above relations with  $N=2$  we see

$$\lambda_{\max, \text{case two}} = \frac{3}{45} \text{ documents per minute} = 4 \text{ documents per hour}$$

Going to  $N=2$  *doubles* total system resources. The second case results in *three* times the maximum mean throughput rate of the  $N=1$  case, while the first case is *twice* the maximum mean throughput rate of the  $N=1$  case. The fifty per cent gain in maximum mean throughput rate of document preparation is entirely due to the policy of pooling (versus dedicating) resources. The intuitive idea for the gain is that more work can be done *concurrently*; put differently, in the first case the *interaction* between the available resources was limiting the maximum mean throughput rate, while in the second case these constraints were relatively less severe.

5.7.1 *Appendix* >From known results (Cairns, p.66, 1966) we observe that a value of  $\lambda$  is possible *if and only if* the point  $(\lambda T_1, \lambda T_2, \lambda T_3)$  belongs to the smallest convex set in Euclidean three space containing  $F$ , i.e., the *convex hull*, denoted by  $C(F)$ , of  $F$ . Since  $F$  is a finite set,  $C(F)$  will be a convex polyhedron or simplex. Next, we show that  $C(F)$  is defined by the set of points  $\underline{x} = (x_1, x_2, x_3)$  where  $x_K, K=1,2,3$  that are positive *real* numbers, with

$$\begin{aligned} x_K &\geq 0 \quad K=1,2,3 \\ x_1 + x_2 &\leq N \quad \text{manager constraint} \\ x_2 + x_3 &\leq N \quad \text{secretary constraint} \\ x_1 + x_3 &\leq N \quad \text{word processor constraint} \\ x_1 + x_2 + x_3 &\leq \left\lfloor \frac{3N}{2} \right\rfloor \end{aligned}$$

where  $\lfloor y \rfloor$  denotes the largest integer less than or equal to  $y$ , the so called *floor* function. If we substitute  $(\lambda T_1, \lambda T_2, \lambda T_3)$  for  $(x_1, x_2, x_3)$  in the above we immediately get the desired result.

### 5.7.2 Additional Reading

- [1] S.S.Cairns, **Introductory Topology**, Ronald Press, New York, New York (Revised Printing), 1968.
- [2] G.B.Dantzig, **Linear Programming and Extensions**, Princeton University Press, Princeton, New Jersey, 1963.
- [3] K.Omahen, *Capacity Bounds for Multiresource Queues*, J.A.C.M., **24**, 646-663 (1977).

### 5.8 An Office System Model

We close with a more sophisticated model of an office than what we considered earlier. Although it is more complex, the same techniques discussed in the earlier example still apply. Consider an office with  $M$  managers,  $S$  secretaries, with each manager having a telephone, each secretary having a typewriter and telephone, and  $C$  copiers for the entire staff. There are two types of jobs performed, document preparation (type 1) and telephone call answering (type 2). Document preparation consists of seven steps shown below:

- [1] Step(1,1)--A manager generates a hand written draft of a document. The mean time duration for generating a draft is  $T_{1,1}$  minutes.
- [2] Step(1,2)--A secretary produces a typewritten version of the draft and returns it to the originator. The mean duration of this step is  $T_{1,2}$  minutes.
- [3] Step (1,3)--The manager corrects the typewritten document. This step has a mean duration of  $T_{1,3}$  minutes and is executed an average of  $V_{1,3}$  times per document
- [4] Step (1,4)--If after step (1,3) changes are required, a secretary makes the changes and returns the document to the originator. This step has a mean duration of  $T_{1,4}$  minutes
- [5] Step (1,5)--If no changes are required after step (1,3), a secretary walks to a copier. The mean time required is  $T_{1,5}$  minutes
- [6] Step (1,6)--A secretary reproduces the requisite number of copies. The mean duration of time is  $T_{1,6}$ .
- [7] A secretary returns the document with copies to the originator. This requires a mean time interval of  $T_{1,7}$  minutes

At any given instant of time there are a maximum of  $D$  documents in the sum total of all these stages.

The telephone call answering job consists of four steps:

- [1] Step (2,1)--A secretary answers a telephone for a manager, talks, and passes the message along to the appropriate manager; this has a mean time of  $T_{2,1}$
- [2] Step (2,2)--A secretary answers a telephone for a manager and then passes the caller on to the manager; this has a mean time of  $T_{2,2}$
- [3] Step (2,3)--A manager answers a telephone with a mean time of  $T_{2,3}$
- [4] Step (2,4)--A manager receives a call that is first handled by a secretary and talks for a mean time  $T_{2,4}$

The fraction of calls handled by a secretary alone is  $V_{2,1}$ , while the fraction handled by a manager alone is  $V_{2,3}$  and the fraction handled by a secretary first and then a manager is  $V_{2,2}$ :

$$V_{2,1} + V_{2,2} + V_{2,3} = \sum_{K=1}^3 V_{2,K} = 1 \quad V_{2,4} = 1$$

We next construct the step requirements table for this office:

**Figure 5.14.Document Preparation Steps****Table 5.14.Document Step Resource Requirements**

<i>Step Number</i>	<i>Resource</i>						<i>Time Interval</i>
	<i>Manager</i>	<i>Secretary</i>	<i>Typewriter</i>	<i>Telephone</i>	<i>Copier</i>	<i>Document</i>	
1	1	0	0	0	0	1	$T_{1,1}$
2	0	1	1	0	0	1	$T_{1,2}$
3	1	0	0	0	0	1	$T_{1,3}$
4	0	1	1	0	0	1	$T_{1,4}$
5	0	1	0	0	0	1	$T_{1,5}$
6	0	1	0	0	1	1	$T_{1,6}$
7	0	1	0	0	0	1	$T_{1,7}$

**Figure 5.15. Telephone Message Handling Block Diagram**

**Table 5.15. Telephone Answering Step Resource Table**

<i>Step Number</i>	<i>Resource</i>		<i>Time Interval</i>
	<i>Manager</i>	<i>Secretary</i>	
1	0	1	$T_{2,1}$
2	0	1	$T_{2,2}$
3	1	0	$T_{2,3}$
4	1	0	$T_{2,4}$

The documents circulate through the office system, with each document either waiting for one or more resources to become available, or being executed in steps (1,1) through (1,7). It is therefore convenient to append an additional step, (1,8), to our model: step (1,8) is the waiting state of a document, and  $T_{wait} \equiv T_{1,8}$  denotes the mean time a document spends waiting for resources. If we denote the mean throughput rate for document preparation, job type 1, by  $\lambda_1$  jobs per minute, and the mean telephone call answering rate for type 2 jobs by  $\lambda_2$  jobs per minute, then our goal is to determine upper bounds on  $\lambda_1, \lambda_2$  and lower bounds on  $T_{wait}$ . The state of the system at any instant of time is represented by a twelve tuple or vector denoted by  $\underline{J}$ , whose components are nonnegative integers:

$$\underline{J} = (j_{1,1}, j_{1,2}, \dots, j_{1,8}, j_{2,1}, j_{2,2}, j_{2,3}, j_{2,4}) \quad j_{1,K} \in \{non\ negative\ integers\}, I=1,2; K=1, \dots, 8$$

>From the step requirements table and the discussion we can write that the feasible set of  $\underline{J}$  is denoted by  $F$ , while the above implies the components of  $\underline{J} \in F$  are nonnegative integers such that

$$j_{1,6} \leq C$$

$$j_{1,2} + j_{1,4} + j_{1,5} + j_{1,6} + j_{1,7} + j_{2,1} + j_{2,2} \leq S$$

$$j_{1,1} + j_{1,2} + j_{1,3} + j_{1,4} + j_{1,5} + j_{1,6} + j_{1,7} + j_{2,3} + j_{2,4} = M$$

$$j_{1,1} + j_{1,2} + j_{1,3} + j_{1,4} + j_{1,5} + j_{1,6} + j_{1,7} + j_{1,8} = D$$

The convex hull of  $F$ , denoted  $C(F)$ , is given by the set of twelve tuples with *real* valued nonnegative entries  $\underline{X} = (x_{1,1}, \dots, x_{1,8}, x_{2,1}, \dots, x_{2,4})$  that satisfy the following constraints:

$$x_{1,1}, x_{1,2}, \dots, x_{1,8}, x_{2,1}, \dots, x_{2,4} \geq 0$$

$$x_{1,6} \leq C$$

$$x_{1,2} + x_{1,4} + x_{1,5} + x_{1,6} + x_{1,7} + x_{2,1} + x_{2,2} \leq S$$

$$x_{1,1} + x_{1,2} + x_{1,3} + x_{1,4} + x_{1,5} + x_{1,6} + x_{1,7} + x_{1,8} + x_{2,3} + x_{2,4} \leq M$$

$$x_{1,1} + x_{1,2} + x_{1,3} + x_{1,4} + x_{1,5} + x_{1,6} + x_{1,7} + x_{1,8} = D$$

Using Little's Law, we can write that the mean number of managers active in each step of document preparation equals the document arrival rate multiplied by mean document time per step:

$$\sum_{J \in F} j_{1,K} \pi(J) = \lambda_1 T_{1,K} \quad K=1,2,5,6,7,8$$

The mean number of secretaries busy at each step of document preparation must equal the mean document arrival rate times the mean document time per step:

$$\sum_{J \in F} j_{1,3} \pi(J) = \lambda_1 V T_{1,3}$$

$$\sum_{J \in F} j_{1,4} \pi(J) = \lambda_1 (V-1) T_{1,4}$$

Finally, the mean number of telephone calls in each of four steps must equal the telephone call arrival rate multiplied by the mean time per call step:

$$\sum_{J \in F} j_{2,K} \pi(J) = \lambda_2 V_{2,K} T_{2,K} \quad K=1,2,3,4$$

The relations for steps (1,3) and (1,4) reflect the fact that there are a mean number of  $V_{1,3} \geq 1$  steps of type (1,3) per job 1 and  $(V_{1,3}-1)$  steps of type (1,4) per job 1. The relations for steps (2,1) through (2,4) reflect the fact that there are a mean number of visits  $0 \leq V_{2,K} \leq 1, K=1, \dots, 4$  to each step.

The values  $\lambda_1, \lambda_2, T_{wait}$  are possible if and only if the point

$$(\lambda_1 T_{1,1}, \lambda_1 T_{1,2}, \lambda_1 V T_{1,3}, \lambda_1 (V-1) T_{1,4}, \lambda_1 T_{1,5}, \lambda_1 T_{1,6}, \\ \lambda_1 T_{1,7}, \lambda_1 T_{1,8}, \lambda_2 V_{2,1} T_{2,1}, \lambda_2 V_{2,2} T_{2,2}, \lambda_2 V_{2,3} T_{2,3}, \lambda_2 V_{2,4} T_{2,4})$$

is a member of the convex hull of the feasible set  $F$ . Substituting into the above we have

$$\lambda_1 T_{copy} \leq C \quad \lambda_1 T_{doc,sec} + \lambda_2 T_{tel,sec} \leq S$$

$$\lambda_1 T_{doc,man} + \lambda_2 T_{tel,man} \leq M \quad \lambda_1 (T_{doc,man} + T_{doc,sec} + T_{wait}) = D$$

where

$$T_{doc,sec} = T_{1,2} + (V-1) T_{1,4} + T_{1,5} + T_{1,6} + T_{1,7} \quad T_{tel,sec} = V_{2,1} T_{2,1} + V_{2,2} T_{2,2}$$

$$T_{doc,man} = T_{1,1} + V T_{1,3} \quad T_{tel,man} = V_{2,3} T_{2,3} + V_{2,4} T_{2,4}$$

$$T_{copy} = T_{1,6}$$

The physical meaning of each of these terms is

- $T_{doc,sec}$  --The mean time a secretary spends on a document
- $T_{tel,sec}$  --The mean time a secretary spends answering a telephone call
- $T_{doc,man}$  --The mean time a manager spends preparing and revising documents
- $T_{tel,man}$  --The mean time a manager spends answering a telephone call



- $T_{copy}$ --The mean time to make copies of a document

Note that there are really only *five* time intervals that we really need: the mean time to make a telephone call for a manager and a secretary, the mean time to handle a document for a manager and a secretary, and the mean time to make sufficient copies of a document. We also need *four* numbers: the total number of managers, secretaries, documents, and copiers. This is the minimum information needed to say *anything* concerning productivity in any quantitative sense. This can be summarized as follows:

$$\lambda_1 \leq \min \left[ \frac{M - \lambda_2 T_{tel,man}}{T_{doc,man}}, \frac{D}{T_{doc,man}}, \frac{S - \lambda_2 T_{tel,sec}}{T_{doc,man}}, \frac{C}{T_{copy}} \right]$$

$$\lambda_2 \leq \min \left[ \frac{M - \lambda_1 T_{doc,man}}{T_{tel,man}}, \frac{S - \lambda_1 T_{doc,sec}}{T_{doc,sec}} \right]$$

$$T_{wait} = \frac{D}{\lambda_1} - T_{doc,man} - T_{doc,sec}$$

We remark that the set of feasible points  $(\lambda_1, \lambda_2)$  form a convex polygon.

### Figure 5.16. Feasible Set of Mean Throughput Rates

For a fixed value of  $\lambda_2$  ( $\lambda_2 < S/T_{tel,sec}$ ), we can use the above to determine the potential bottlenecks:

- [1] Managers handling documents are the bottleneck

$$\lambda_{1,max} = \frac{M - \lambda_2 T_{doc,man}}{T_{doc,man}}$$

- [2] Secretaries handling documents are the bottleneck

$$\lambda_{1,max} = \frac{S - \lambda_2 T_{tel,sec}}{T_{doc,sec}}$$

- [3] Copiers are the bottleneck

$$\lambda_{1,max} = \frac{C}{T_{copy}}$$

- [4] Documents are the bottleneck

$$\lambda_{1,max} = \frac{D}{T_{document}}$$

- [5] Managers handling telephone calls are the bottleneck

$$\lambda_{2,max} = \frac{M - \lambda_1 T_{doc,man}}{T_{tel,man}}$$

- [6] Secretaries handling telephone calls are the bottleneck

$$\lambda_{2,max} = \frac{S - \lambda_1 T_{doc,sec}}{T_{tel,sec}}$$

Where do we want the bottleneck: perhaps managers handling documents? What do you think?

First we illustrate the upper bound on mean throughput rate as a function of the number of secretaries  $S$ ,

$$S > \max(\lambda_2 T_{tel,sec}, C)$$

in the figure below. The feasible operating regions are also shown.

### Figure 5.17. Mean Document Completion Rate vs Number of Secretaries

The breakpoint is clearly evident: fewer secretaries than the breakpoint, and the secretaries are the bottleneck, while greater than the breakpoint number and the copies, the number of documents, or the managers are the bottleneck.

This can be completed with the mean document waiting time feasible operating region, shown in Figure 5.18.

**Figure 5.18. Mean Document Waiting Time vs Number of Secretaries**

The reader hopefully will see the importance of being systematic in approaching such an operation, enumerating all possible states, because nothing will be overlooked.

The table below summarizes some illustrative mean times required to do the different aggregate steps:

**Table 5.16. Illustrative Mean Times**

<i>Job Step</i>	<i>Time(Hr)</i>
$T_{doc,sec}$	1/2
$T_{tel,sec}$	1/30
$T_{doc,man}$	2
$T_{tel,man}$	1/6
$T_{copy}$	1/3

Suppose we have one copier and one secretary for five managers, with one document per manager in preparation. Where is the bottleneck resource? Let's check one resource at a time:

- [1] Managers handling documents can do a maximum of

$$\lambda_{1,max} = \frac{5}{2} = 2.5 \text{ documents/hr}$$

- [2] Secretaries handling documents can do a maximum of

$$\lambda_{1,max} = \frac{1}{\frac{1}{2}} = 2 \text{ documents/hr}$$

- [3] The copier can handle

$$\lambda_{1,max} = \frac{1}{\frac{1}{3}} = 3 \text{ documents/hr}$$

- [4] The documents in circulation limit us to

$$\lambda_{1,max} = \frac{5}{2 + \frac{1}{3} + \frac{1}{2}} = 1 \frac{13}{17} \text{ documents/hr}$$

- [5] Managers handling telephone calls

$$\lambda_{2,max} = \frac{5}{1/6} = 30 \text{ calls/hr}$$

[6] Secretaries handling telephone calls

$$\lambda_{2,max} = \frac{1}{1/30} = 30 \text{ calls/hr}$$

The limiting bottleneck here is the *number* of documents in circulation: managers have to have more than one document going at a time. Suppose we double this, so each manager has two documents in the mill at once? What is the new bottleneck? Now it is the secretaries working flat out to keep up with the document load. If we add another secretary to cure this, then the new bottleneck is the managers working full time at document generation.

### 5.8.1 Additional Reading

- [1] G.H.Engel, J.Groppuso, R.A.Lowenstein, W.G.Traub, *An Office Communications System*, IBM Systems Journal, **18** (4), 402-431, 1979.
- [2] P.C.Gardner, *A System for the Automated Office Environment*, IBM Systems Journal, **20** (3), 321-345 (1981).

## Problems

1) Measurements are gathered on clerical work activity during a normal business day both before and after the installation of an online transaction processing computer communications system:

**Table 5.17. Clerk Normal Business Day**

<i>Work Activity</i>	<i>Fraction of Time</i>	
	<i>Before</i>	<i>After</i>
Telephone	10%	20%
Enter Data	20%	10%
File Data	30%	10%
Retrieve Data	30%	20%
Misc	10%	40%

Answer the following questions:

- A. What is the state space for the activities for each clerk?
- B. What is the potential gain in productivity, measured in amount of work done per unit time?
- C. What is the net percentage change in the number of clerks required to carry out the required work?

2) A secretary does different activities during a normal business day. The table below summarizes the fraction of time spent per activity before and after installation of an office communication system:

**Table 5.18. Secretary's Normal Business Day**

<i>Work Activity</i>	<i>Fraction of Time</i>	
	<i>Before</i>	<i>After</i>
Face to Face Meetings	10%	20%
Telephone Calls	10%	20%
Typing	35%	40%
Reading/Writing	15%	20%
Mail Handling	10%	5%
Copy Documents	10%	5%
Filing	10%	5%

Answer the following questions:

- A. What is the state space for activities for each secretary?
- B. What is the gain in productivity, defined as the amount of work done per unit time?
- C. What is the percentage change in number of secretaries?

3) A series of measurements are carried out on the activities of professionals in an office environment, both before and after the installation of an office communications system. During a normal business day, the table below summarizes the fraction of time spent in each work activity:

**Table 5.19. Professional Normal Business Day**

<i>Work Activity</i>	<i>Fraction of Time</i>	
	<i>Before</i>	<i>After</i>
Face to Face Meetings	50%	25%
Telephone	10%	20%
Read/Write	20%	25%
Misc	20%	30%

Answer the following questions:

- A. What is the state space for activities for each professional?
- B. What is the gain in productivity, defined as amount of work done per unit time?
- C. What is the percentage change in number of professionals?

4) Measurements are carried out on the activities of professionals in an office environment, both before and after the installation of an office communication system. The data are aggregated by the fraction of time spent in a given activity during a normal business day:

**Table 5.20. Professionals' Normal Business Day**

<i>Work Activity</i>	<i>Fraction of Time</i>	
	<i>Before</i>	<i>After</i>
Search for Data	15%	10%
Input Data	15%	5%
Validate Data	25%	5%
Process Data	15%	5%
Distribute Data	5%	5%
Think	20%	65%
Administration	5%	5%

Answer the following questions:

- A. What is the state space for activities for a professional?
- B. What is the gain in productivity, defined as amount of work done per unit time?
- C. What is the percentage change in number of professionals?

5) A office currently has one secretary for every five professionals. If the professionals are not available, the secretary will answer their telephones and write down any messages. Two different systems are currently being evaluated for reducing the message answering work load on the secretary: one involves electronic mail, where each professional has a special terminal that allows messages to be entered from a key board, displayed, edited, transmitted, filed, archived, retrieved, and deleted as need be. The second involves voice mail, where each professional uses a voice telephone to carry out the same functions. The resources required for each step are summarized in the table below:

**Table 5.21. Step/Resource Summary**

<i>Job Step</i>	<i>Resource</i>					<i>Time Interval</i>
	<i>Terminal</i>	<i>Port</i>	<i>Processor</i>	<i>Disk</i>	<i>Printer</i>	
Enter	1	1	1	1	0	$T_{enter}$
Edit	1	1	1	1	1	$T_{edit}$

Send	1	1	1	1	1	$T_{send}$
File	0	1	1	1	1	$T_{file}$
Retrieve	1	1	1	1	1	$T_{retrieve}$
Delete	1	1	1	1	1	$T_{delete}$

The mean time intervals for each system are summarized below:

**Table 5.22. Mean Time Interval/Step**

<i>Symbol</i>	<i>Current</i>	<i>Voice Mail</i>	<i>Electronic Mail</i>
Enter	1 Minute	2 Minute	5 Minute
Edit	0 Minute	0 Minute	1 Minute
Send	30 Minute	30 Minute	30 Minute
File	1 Minute	0 Minute	0 Minute
Retrieve	5 Minute	0 Minute	0 Minute
Delete	0 Minute	0 Minute	0 Minute

For the current system,  $V_{message}=3$  is the mean number of calls made to actually have one professional talk to another. For either proposed system,  $V_{message}=1$  is the mean number of calls required to handle any given matter.

Answer the following questions:

- A. What is the state space for each system?
- B. Which resource will reach complete utilization first for each system?
- C. Plot the mean throughput rate versus number of professionals per one secretary. How many professionals are needed per secretary for each system?

6) A copying machine can be purchased with or without an automatic feeder. When an operator makes one copy of one page, three steps are involved

- [1] Set up time denoted by  $T_{setup}$  which is the time to set the document properly aligned onto the copier
- [2] Copying time denoted by  $T_{copy}$  which is the time to make one copy of one page
- [3] Clean up time denoted by  $T_{cleanup}$  which is the time to remove the document from the copier

For the two configurations, the time intervals are summarized below

**Table 5.23. Mean Time/Step**

<i>Step</i>	<i>No Feeder</i>	<i>With Feeder</i>
Set Up	5 sec	1 sec
Copy	2 sec	2 sec
Clean Up	5 sec	1 sec

Answer the following questions:

- A. What is the state space for this model?
- B. What is an upper bound on mean throughput rate for each system?
- C. Suppose twenty per cent of the documents are five pages long, while eighty per cent of the documents are one page long: find an upper bound on the mean throughput rate for each system?

7) Two different systems for preparing documents are under consideration. In the first system, one secretary is assigned to ten professionals, and handles all document preparation needs. In the second

system, a central text processing center is set up that handles all document preparation needs of all professionals. The main differences in the two approaches are

- Each secretary is given one printer capable of printing thirty characters per second maximum while the central text processing center can afford one high speed printer capable of printing two pages of text (two hundred and fifty words per page, five characters per word) per second maximum
- The central text processing center requires every document be logged in and logged out, while the local system involves much less time consuming procedures for control of documents

We assume each professional generates a two page document every day, and each clerk can type at thirty words per minute. Two minutes are required to log in every document at the central text processing center; fifteen seconds is required for the local secretary to do this.

Answer the following questions:

- A. What is the state space for each system?
- B. Find an upper bound on the mean number of documents per unit time either system can handle?
- C. How many professionals and secretaries are required for either system assuming the upper bound on mean number of documents per unit time is being handled?

8) Two different office communication systems are under consideration. In the current system, people walk to and from offices, copying machines, and typewriters. In the proposed system, a high speed local area network is installed that reduces the need to walk to and from offices, copying machines and typewriters, and secondly reduces the time to transmit information from one place to another. The table below summarizes illustrative time intervals for each job

**Table 5.24. Illustrative Time/Step Summary**

<i>Job Step</i>	<i>Time Interval</i>		
	<i>Symbol</i>	<i>Current</i>	<i>Proposed</i>
Office to office	$T_{office}$	5 minutes	2 minutes
Office to copier	$T_{copier}$	5 minutes	1 minute
Office to printer	$T_{print}$	10 minutes	2 minutes

**Table 5.25. Illustrative Visits/Step Summary**

<i>Job Step</i>	<i>Mean Number of Visits</i>		
	<i>Symbol</i>	<i>Current</i>	<i>Proposed</i>
Office to office	$V_{office}$	5	2
Office to copier	$V_{copier}$	5	2
Office to printer	$V_{printer}$	2	1

Answer the following questions:

- A. What is the state space for each system?
- B. Find an upper bound on the mean rate of doing office communication jobs for each system.
- C. What is the potential gain, if a job typically requires one hour of other work in addition to communication? What changes if a job requires fifty hours of other work in addition to communication?

9) A charity has an executive office staffed by a director and  $S$  secretaries. The current mode of operation involves a great deal of manual work, filing activities with paper index cards, and typing. We wish to compare this mode of operation with a proposed mode of operation, involving conversion to an automated system consisting of work stations, one for each secretary, plus a local network between work stations. The difference in the two modes of operation is the *equipment* available to the secretaries.



Each secretary can do two types of jobs, donor registration (type 1) and telephone call answering (type 2). Donor registration consists of seven steps:

- [1] Step (1,1)--The donor file is searched to see if the member is already there or not. The mean duration for this step is  $T_{1,1}$  minutes.
- [2] Step (1,2)--The address of the donor is checked against that in the file and appropriate modifications are entered. The mean duration of this step is  $T_{1,2}$  minutes.
- [3] Step(1,3)--A donor number is assigned from a list of available numbers. This requires  $T_{1,3}$  minutes on the average.
- [4] Step(1,4)--A donor card is typed. This requires  $T_{1,4}$  minutes.
- [5] Step(1,5)--An envelope is addressed and stuffed with the requisite donor card and other written material. This requires  $T_{1,5}$  minutes.
- [6] Step(1,6)--The mailing list is updated using a card punch. This requires  $T_{1,6}$  minutes.
- [7] Step(1,7)--The new name is entered onto the newsletter mailing list. This requires  $T_{1,7}$  minutes.

The telephone call answering job consists of two steps:

- [1] Step(2,1)--A secretary answers a telephone, talks, and determines the purpose of the call. The mean duration of this job is  $T_{2,1}$  minutes.
- [2] Step(2,2)--If the secretary can handle the call, this requires  $T_{2,2}$  minutes. Otherwise the director handles the call.

The total time to handle each type of job is given by adding up the time to do each step:

$$T_{donor} = T_{1,1} + T_{1,2} + T_{1,3} + T_{1,4} + T_{1,5} + T_{1,6} + T_{1,7}$$

$$T_{telephone} = T_{2,1} + T_{2,2}$$

Answer the following questions:

- A. What is the state space for this model?
- B. The total arrival rate of transactions (both donor gifts and telephone calls) is  $\lambda$  transactions per minute. The fraction of arrivals due to each type is  $F_{donor}, F_{telephone}$ , and hence the arrival rate of each type of transaction is  $\lambda F_{donor}$  and  $\lambda F_{telephone}$ , respectively. Determine an analytic expression for an upper bound on the total mean number of transactions per minute as a function of the number of secretaries, and plot this versus S, the number of secretaries.
- C. Table 5.26 summarizes the average or mean time to handle each step of donor processing:

**Table 5.26.Donor Processing**

<i>Step</i>	<i>Current</i>	<i>Proposed</i>
Look Up in File	1 Minute	1/4 Minute
Check/Change Address	1 Minute	1/4 Minute
Assign Donor Number	1/4 Minute	0 Minutes
Prepare Donor Card	1 Minute	1/4 Minute
Address/Stuff Envelope	2 Minutes	1/2 Minute
Update Zipcode List	1 Minute	0 Minutes
Update Newsletter List	1/2 Minute	0 Minutes
<b>Total</b>	<b>6 3/4 Minutes</b>	<b>1 1/4 Minutes</b>

The table below summarizes the mean amount of time required to handle telephone call work:

**Table 5.27. Telephone Call Work**

<i>Step</i>	<i>Current</i>	<i>Proposed</i>
Answer Telephone	1/4 Minute	1/4 Minute
Answer Query	2 Minutes	1/2 Minute
Total	2 1/4 Minutes	3/4 Minutes

Each secretary works 270 days per year, spending roughly four hours per day handling donor records and telephone calls. For each mode of operation, how many secretaries are needed to handle 100,000 transactions per year, assuming  $F_{donor}=0.80$ ? assuming  $F_{donor}=0.20$ ?

**10)** Consider an office with  $M$  managers,  $S$  secretaries, with each manager having a telephone, each secretary having a typewriter and telephone, and  $C$  copiers for the entire staff. There are two types of jobs performed, document preparation (type 1) and telephone call answering (type 2). Document preparation consists of seven step:

- [1] Step(1,1)--A manager generates a hand written draft of a document. The mean time duration for generating a draft is  $T_{1,1}$  minutes.
- [2] Step(1,2)--A secretary produces a typewritten version of the draft and returns it to the originator. The mean duration of this step is  $T_{1,2}$  minutes.
- [3] Step (1,3)--The manager corrects the typewritten document. This step has a mean duration of  $T_{1,3}$  minutes and is executed an average of  $V_{1,3}$  times per document
- [4] Step (1,4)--If after step (1,3) changes are required, a secretary makes the changes and returns the document to the originator. This step has a mean duration of  $T_{1,4}$  minutes
- [5] Step (1,5)--If no changes are required after step (1,3), a secretary walks to a copier. The mean time required is  $T_{1,5}$  minutes
- [6] Step (1,6)--A secretary reproduces the requisite number of copies. The mean duration of time is  $T_{1,6}$ .
- [7] A secretary returns the document with copies to the originator. This requires a mean time interval of  $T_{1,7}$  minutes

At any given instant of time there are a maximum of  $D$  documents in the sum total of all these stages.

The telephone call answering job consists of at most four tasks:

- [1] Step (2,1)--A secretary answers a telephone for a manager, talks, and passes the message along to the appropriate manager; this has a mean time of  $T_{2,1}$
- [2] Step (2,2)--A secretary answers a telephone for a manager and then passes the caller on to the manager; this has a mean time of  $T_{2,2}$
- [3] Step (2,3)--A manager answers a telephone with a mean time of  $T_{2,3}$
- [4] Step (2,4)--A manager receives a call that is first handled--by a secretary and talks for a mean time  $T_{2,4}$

The fraction of calls handled by a secretary alone is  $V_{2,1}$ , while the fraction handled by a manager alone is  $V_{2,3}$  and the fraction handled by a secretary first and then a manager is  $V_{2,2}$ :

$$V_{2,1} + V_{2,2} + V_{2,3} = \sum_{K=1}^3 V_{2,K} = 1 \quad V_{2,4} = 1$$

We next construct the step requirements table for this office:

**Table 5.28.Document Step Resource Requirements**

Step Number	Resource						Time Interval
	Manager	Secretary	Typewriter	Telephone	Copier	Document	
1	1	0	0	0	0	1	$T_{1,1}$
2	0	1	1	0	0	1	$T_{1,2}$
3	1	0	0	0	0	1	$T_{1,3}$
4	0	1	1	0	0	1	$T_{1,4}$
5	0	1	0	0	0	1	$T_{1,5}$
6	0	1	0	0	1	1	$T_{1,6}$
7	0	1	0	0	0	1	$T_{1,7}$

**Table 5.29.Telephone Answering Step Resource Table**

Step Number	Resource		Time Interval
	Manager	Secretary	
1	0	1	$T_{2,1}$
2	0	1	$T_{2,2}$
3	1	0	$T_{2,3}$
4	1	0	$T_{2,4}$

The documents circulate through the office system, with each document either waiting for one or more resources to become available, or being executed in steps (1,1) through (1,7). It is therefore convenient to append an additional step, (1,8), to our model: step (1,8) is the waiting state of a document, and  $T_{wait} \equiv T_{1,8}$  denotes the mean time a document spends waiting for resources. We denote for the mean throughput rate for document preparation, job type 1, by  $\lambda_1$  jobs per minute, and for the mean telephone call answering rate for type 2 jobs by  $\lambda_2$  jobs per minute.

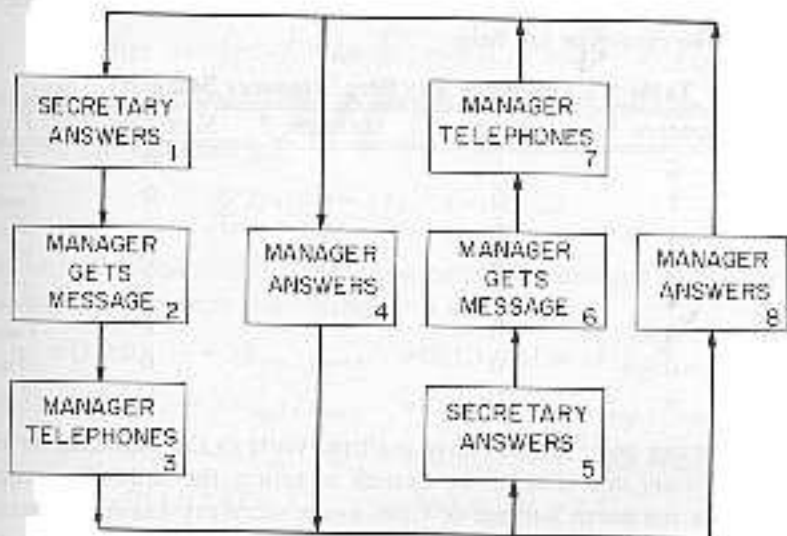
Answer the following questions:

- A. What is the state space for this system?
- B. What are the bottlenecks in this system?
- C. What is the maximum mean throughput rate for document generation?
- D. What is the maximum mean throughput rate for telephone call answering?
- E. Plot the mean waiting time for document generation versus number of secretaries.
- F. The table below summarizes some mean time intervals to handle different steps:

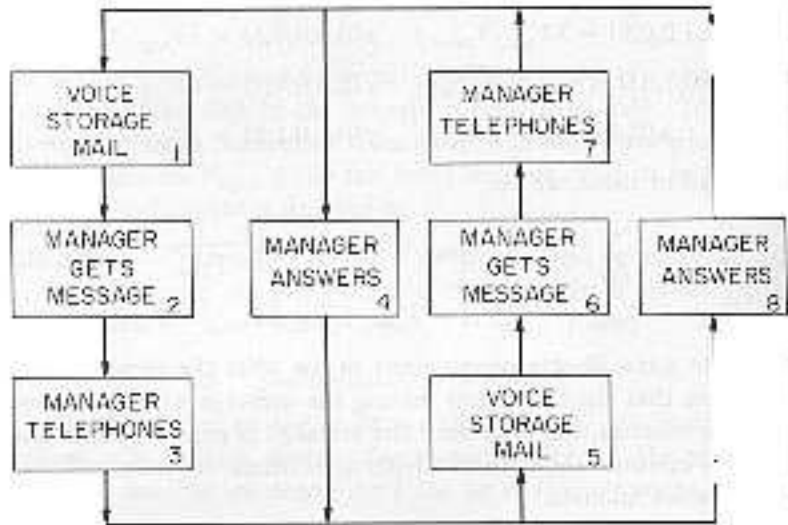
**Table 5.30.Illustrative Mean Times/Step**

Job Step	Time(Hr)
$T_{doc,sec}$	1/2
$T_{tel,sec}$	1/30
$T_{doc,man}$	2
$T_{tel,man}$	1/6
$T_{copy}$	1/3

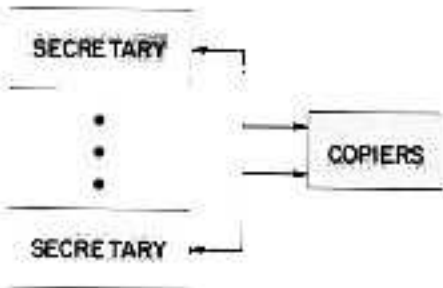
Suppose we have one copier and one secretary for ten managers, with three documents per manager in preparation. Where is the bottleneck resource?



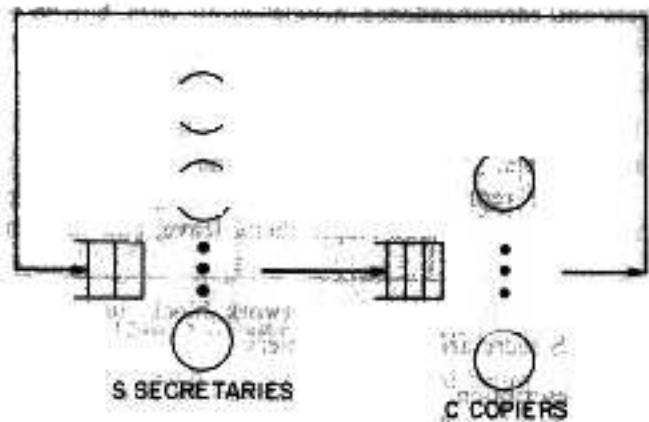
**Figure 5.1. Telephone Tag Work Flow**



**Figure 5.2.Voice Storage Work Flow**



**Figure 5.3. Office Copying System Block Diagram**



**Figure 5.4. Queueing Network of Office Copying System**

MEAN  
DOCUMENT  
COPYING  
RATE

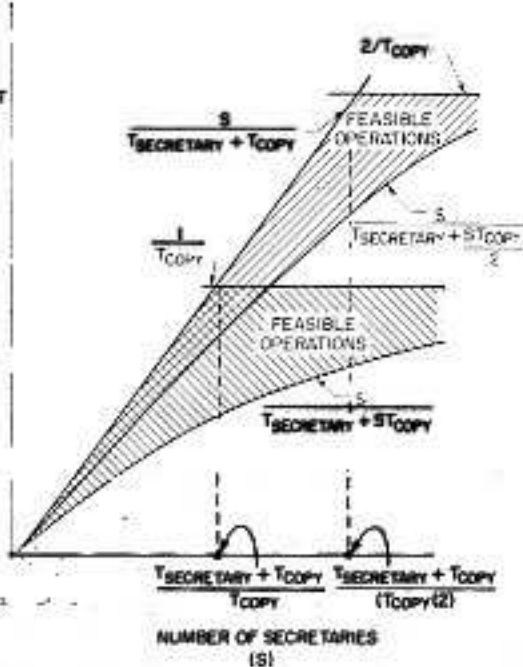


Figure 5.5. Mean Document Copying Rate



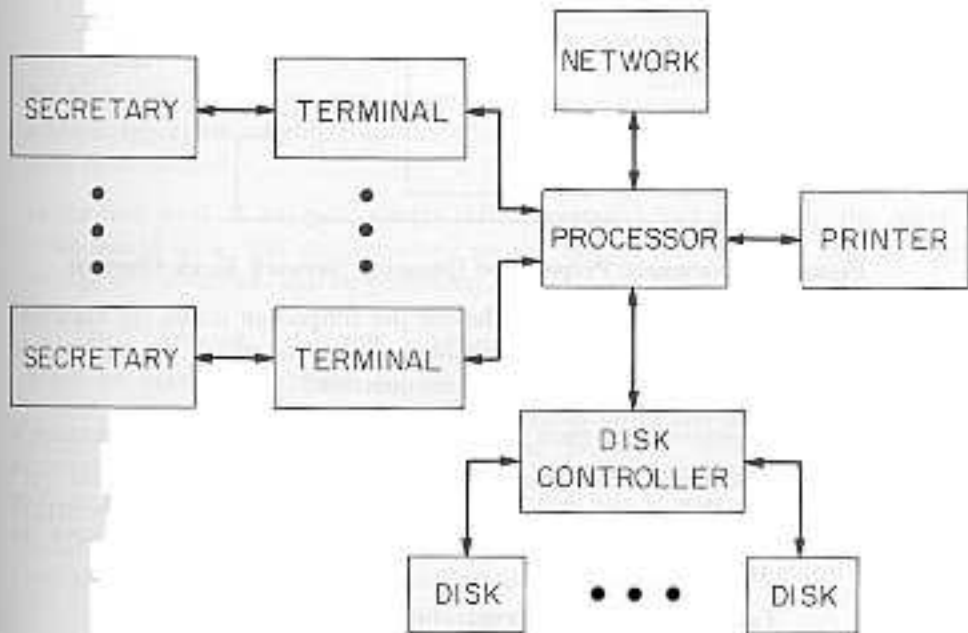
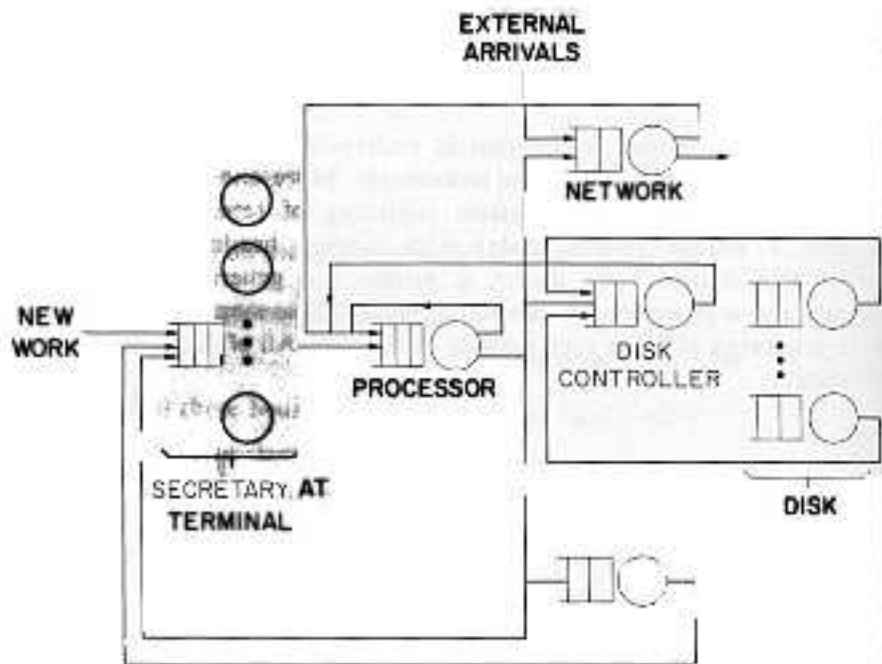
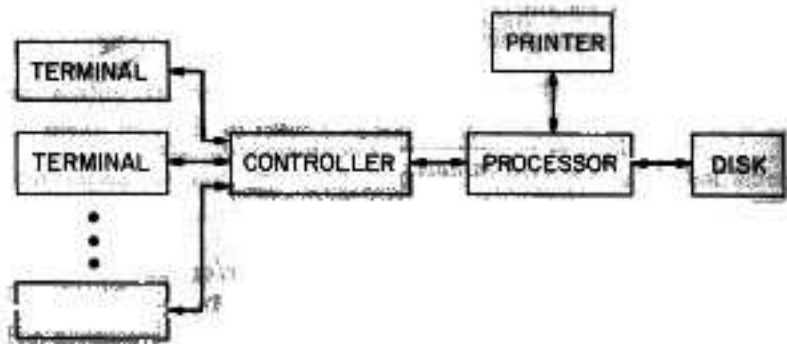


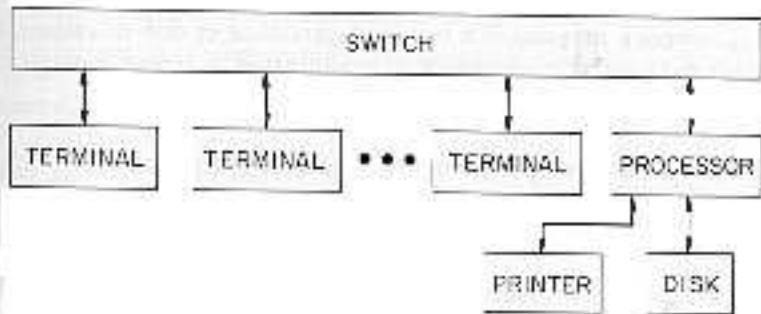
Figure 5.6. Document Preparation System Hardware Block Diagram



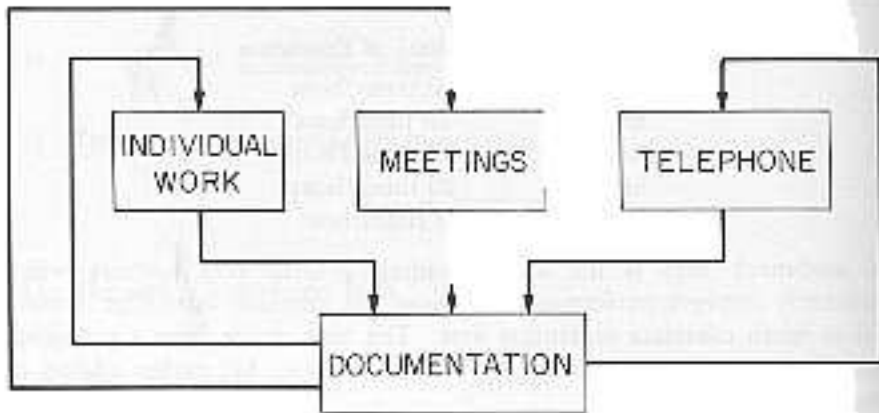
**Figure 5.7. Document Preparation Queuing Network Block Diagram**



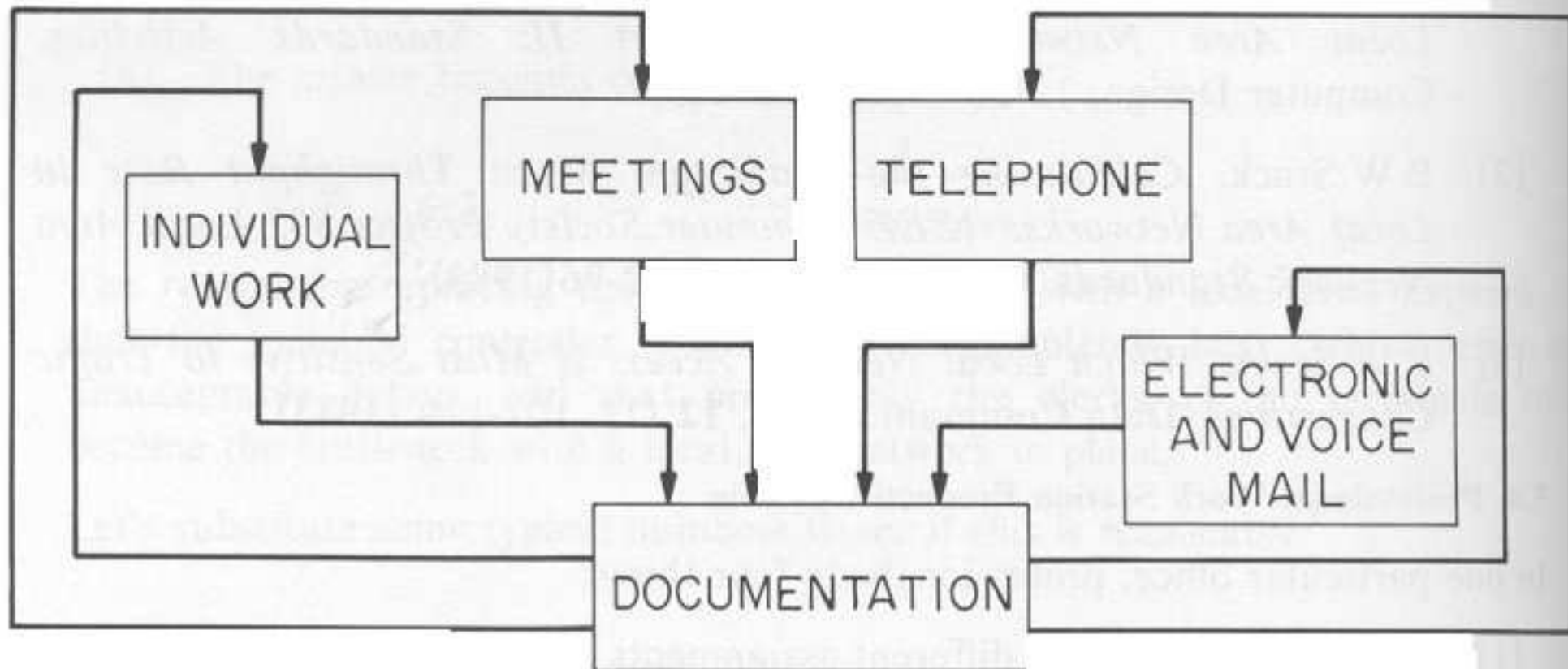
**Figure 5.8.Existing Old System Hardware Block Diagram**



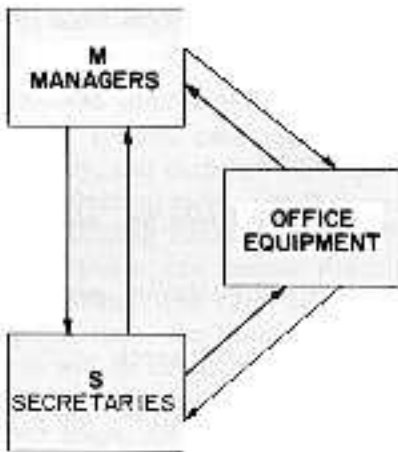
**Figure 5.9. Proposed New System Hardware Block Diagram**



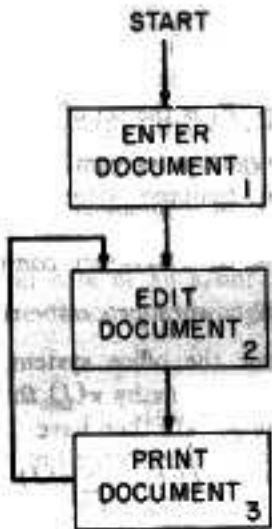
**Figure 5.10.Old System Professional Work Flow**



**Figure 5.11. New System Professional Work Flow**



**Figure 5.12. Office Block Diagram**



**Figure 5.13. Document Preparation Work Flow**



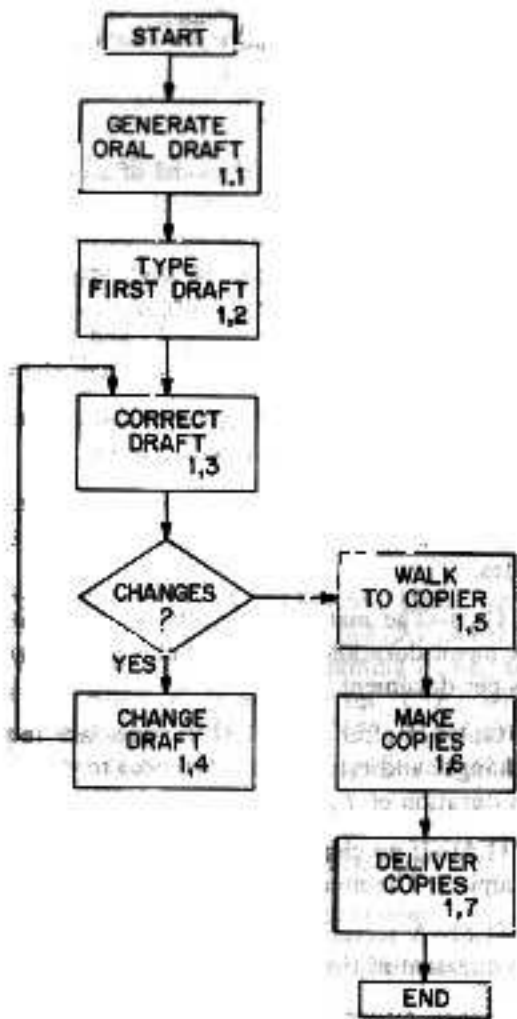


Figure 5.14. Document Preparation Steps

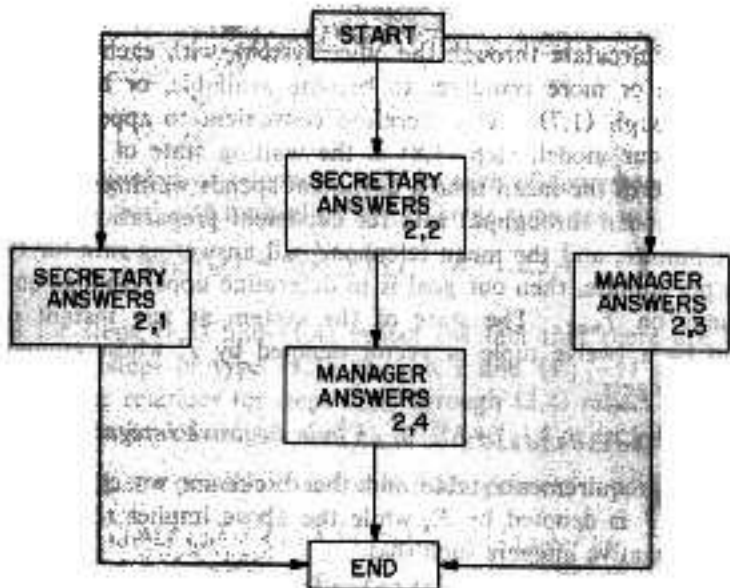


Figure 5.15. Telephone Message Handling Block Diagram

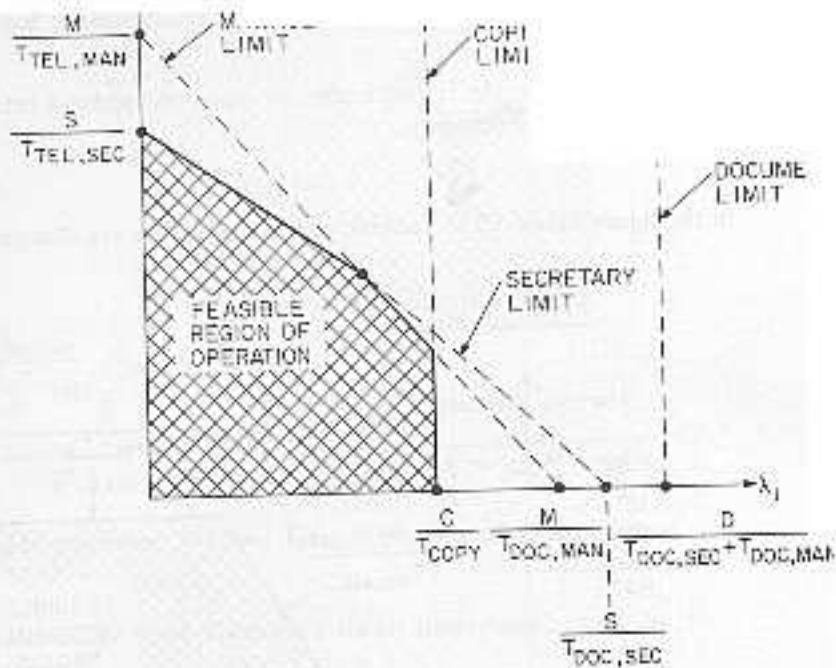


Figure 5.16. Feasible Set of Mean Throughput Rates

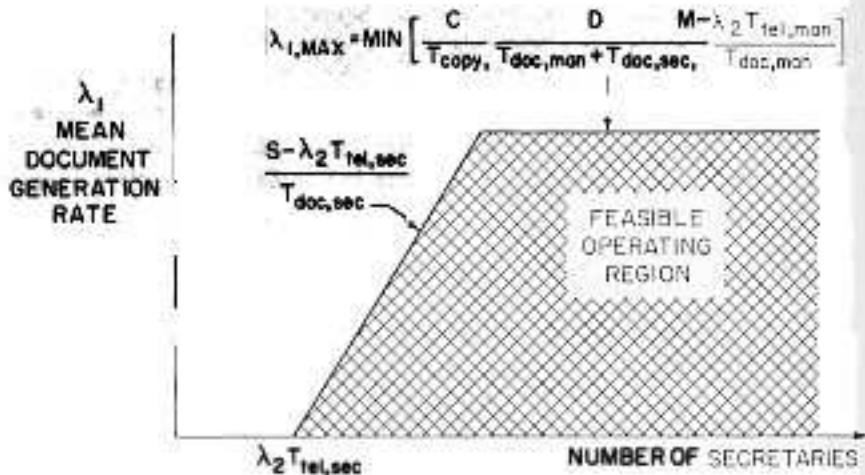


Figure 5.17. Mean Document Completion Rate vs Number of Secretaries

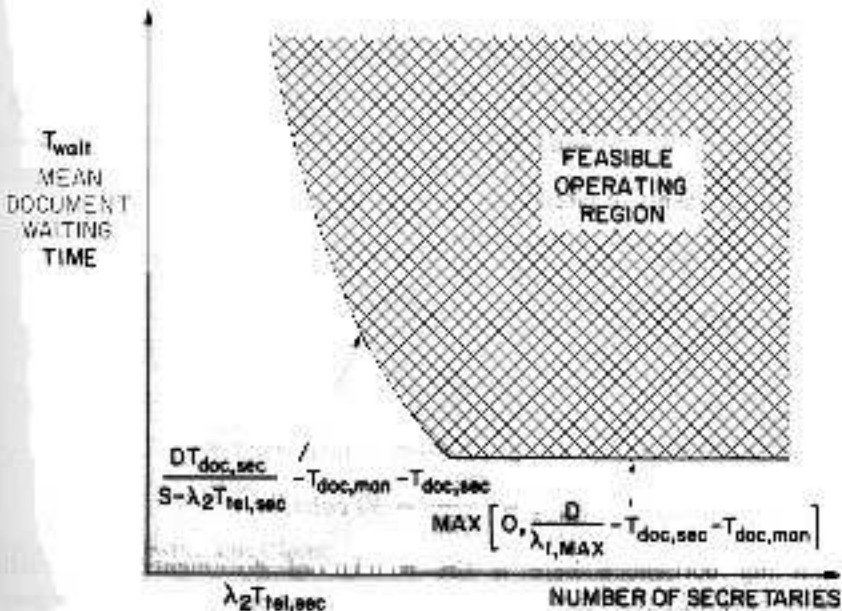


Figure 5.18. Mean Document Waiting Time vs Number of Secretaries