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TECHNICAL REPORT NO. S 1006

PLANNING AND SCHEDULING

JOBS ON A COMPUTER

USING CPM



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May 1969

by Irwin F. Goodman

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U.S. ARMY TANK AUTOMOTIVE COMMAND Warren, Michigan

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## ABSTRACT

This report presents by example the application of the critical path method (CPM) for the planning and scheduling of jobs on a computer. It provides a step by step preparation and analysis of a network representation of a computer system application. Also, included is a glossary of relevant terms and a fairly comprehensive bibliography on the subject of CPM/PERT and scheduling and sequencing.

## FOREWORD

The author wishes to acknowledge Mr. Angelo Constance, ADP Computer Operations, for providing preliminary network representations of a few select computer system applications.

PLANNING AND SCHEDULING  
JOBS ON A COMPUTER  
USING CPM

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## I. Introduction

This study, the planning and scheduling of jobs on computers using the critical path method was prompted by the need of routine file maintenance during the cyclic computer processing of an inventory management system. Concurrently, with the conduct of this study, preliminary network representations are being developed by the computer activity for select systems applications. The purpose of this report is to present by example the application of CPM for the planning and scheduling of jobs on a computer; thereby, providing the computer activity and higher management with an in-advance working example of CPM planning and scheduling. Based upon a preliminary network representation of one of the system applications, the MILSTRIP/MILSTRAP process, a further refined and modified network has been prepared for demonstrating the CPM techniques. It should be emphasized that the network used in this report has been prepared primarily to demonstrate CPM rather than describe a particular system application. Consequently, it has been distorted and somewhat simplified for the sake of demonstration.

## II. Steps in the Critical Path Method Procedure

1. Define various computer jobs (activities).
2. Establish precedence relationship for various computer jobs (activities).
3. Prepare network diagram representation.
4. Estimate expected time to perform each activity in network.
5. Analyze network with CPM analysis techniques.
  - a. Establish critical path(s).
  - b. Determine earliest and latest start time, earliest and latest finish time, and float (slack) time for all activities, especially file maintenance jobs.
6. Interpret results.
7. Prepare a table showing for each activity the subsequent sequence time and activities that must immediately precede it.
8. Establish several feasible alternative sequences for assigning and scheduling activities.
9. Evaluate alternative sequences.



### III. Example of the Critical Path Method Procedure

#### a. Basic Data for CPM Network Representation (steps 1-2)

##### (1) Events by Number and Description

| <u>Event No.</u> | <u>Event Description</u>            | <u>Immediately Preceding<br/>Event No's</u>                  |
|------------------|-------------------------------------|--|
| 1                | Start Process                       |  |
| 6                | Start Initialization of Process     | 1  |
| 9; 109; 209      | Start Validation Process            | 6; 100; 200  |
| 12; 112; 212     | Complete Validation Process         | 9; 109; 209  |
| 15; 115; 215     | Start MRHSF Daily Process           | 12; 142; 112; 242, 212                                       |
| 18; 118; 218     | Start TWOS XREF Edit Process        | 12; 112, 145; 212, 245                                       |
| 21; 121; 221     | Start CHEF Process                  | 12; 112, 148; 212, 248                                       |
| 33; 133; 224     | Complete MRHSF Daily Process        | 15; 115; 215   |
| 36; 136; 236     | Complete TWOS XREF Edit Process     | 18; 118; 218   |
| 39; 139; 239     | Complete CHEF Process               | 21; 121; 221   |
| 54; 154; 254     | Start MSP Process                   | 33; 175, 133; 275, 233                                       |
| 57; 157; 257     | Complete MSP Process                | 54; 154; 254   |
| 60; 160; 260     | Start IMDR Process                  | 57, 33; 157, 133;<br>257, 233                                |
| 63; 163; 263     | Start IMDR Process on Machine I     | 60; 160; 260   |
| 66; 166; 266     | Start IMDR Process on Machine II    | 60; 160; 260   |
| 69; 169; 269     | Complete IMDR Process on Machine I  | 63; 163; 263   |
| 72; 172; 272     | Complete IMDR Process on Machine II | 66; 166; 266   |
| 78; 178; 278     | Complete IMDR Process               | 69, 72, 36, 39; 169,<br>172, 136, 139; 266,<br>272, 236, 239 |

III. Example of the Critical Path Method Procedure (cont...)

| <u>Event No.</u> | <u>Event Description</u>                  | <u>Immediately Preceding<br/>Event No's</u> |
|------------------|---|---|
| 99               | Complete Initialization of Process        | 184   |
| 100; 200         | Start 1st; 2nd Cycle                      | 9; 284, 100                                 |
| 124; 224         | Start MRHSF Daily Update Next Cycle       | 12; 112                                     |
| 127; 227         | Start TWOS KREF Edit Update Next Cycle    | 12; 112                                     |
| 130; 230         | Start CHEF Update Next Cycle              | 12; 112                                     |
| 142; 242         | Complete MRHSF Daily Update Next Cycle    | 124; 224                                    |
| 145; 245         | Complete TWOS KREF Edit Update Next Cycle | 127; 227                                    |
| 148; 248         | Complete CHEF Update Next Cycle           | 130; 230                                    |
| 151; 251         | Start MSP Update Next Cycle               | 33; 133                                     |
| 175; 275         | Complete MSP Update Next Cycle            | 151; 251                                    |
| 181; 281         | Start TEF Update Next Cycle               | 78; 199                                     |
| 184; 284         | Complete TEF Update Next Cycle            | 181; 281                                    |
| 199; 299         | Complete 1st; 2nd Cycle                   | 178; 278                                    |
| 999              | End Process                               | 299   |

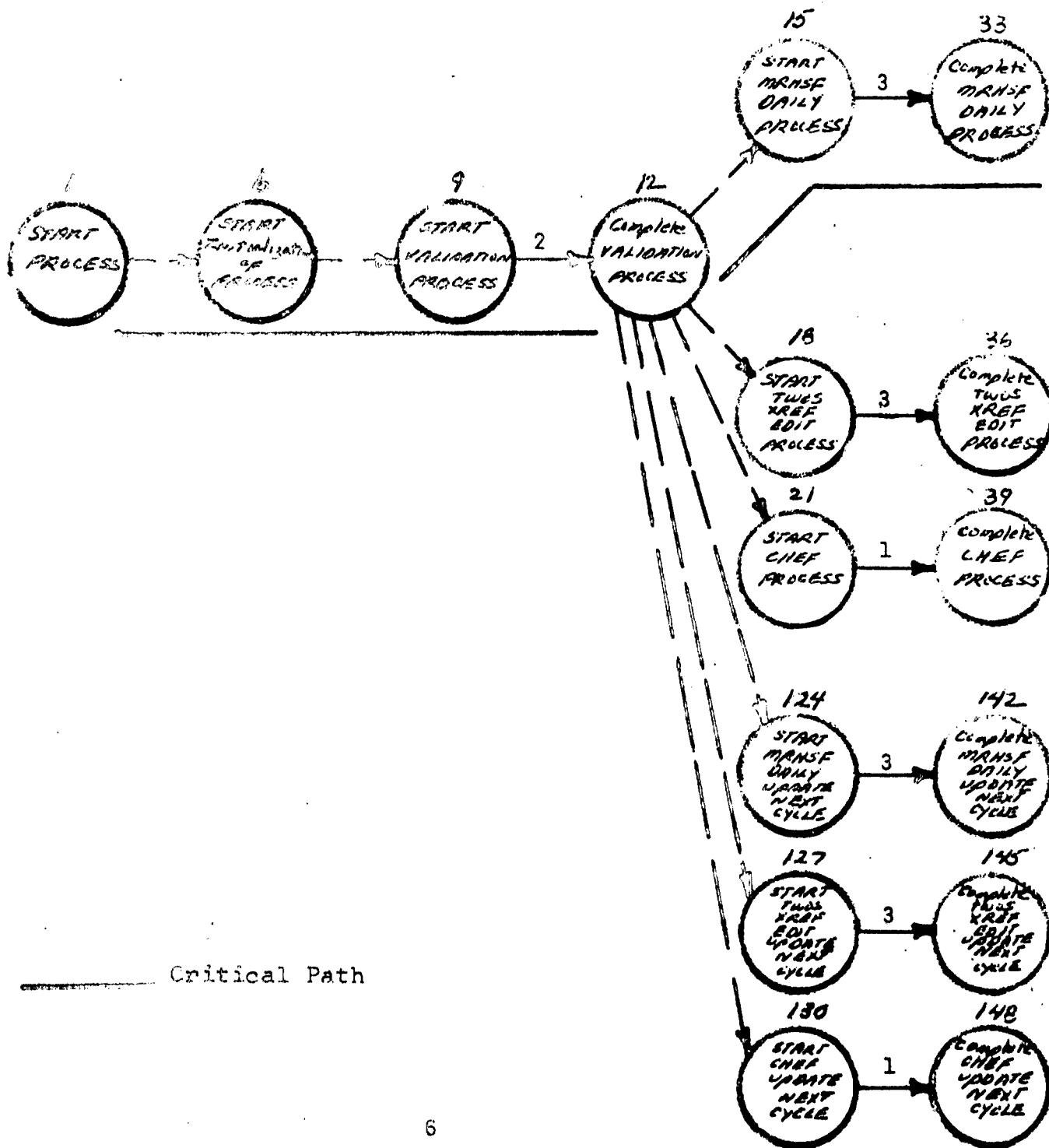
III. Example of the Critical Path Method Procedure (cont...)

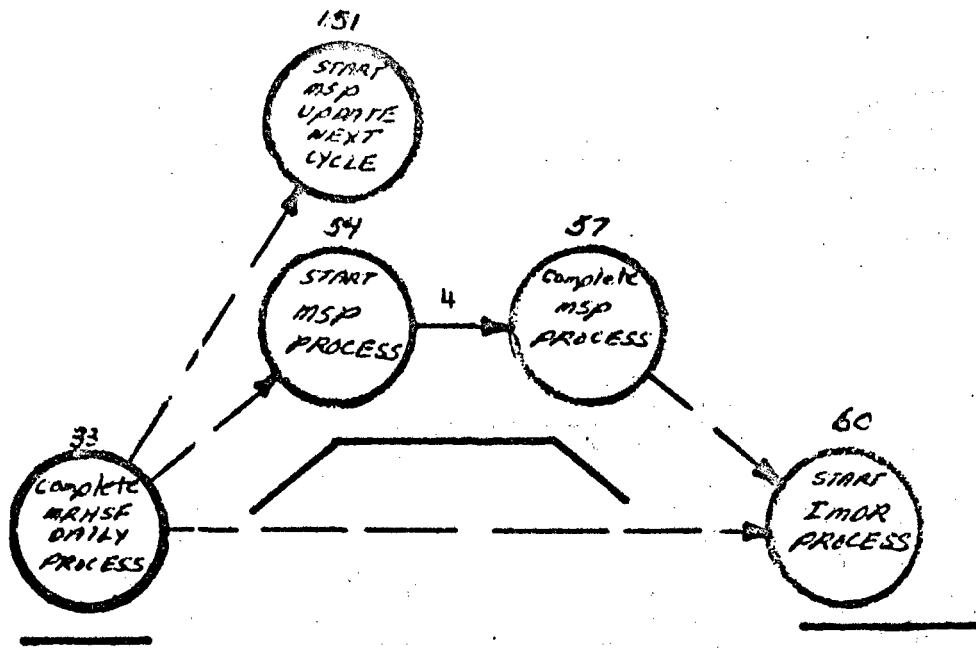
(2) Activity by Number, Description Duration, and Immediately Preceding Activities (Steps 1, 2 and 7)

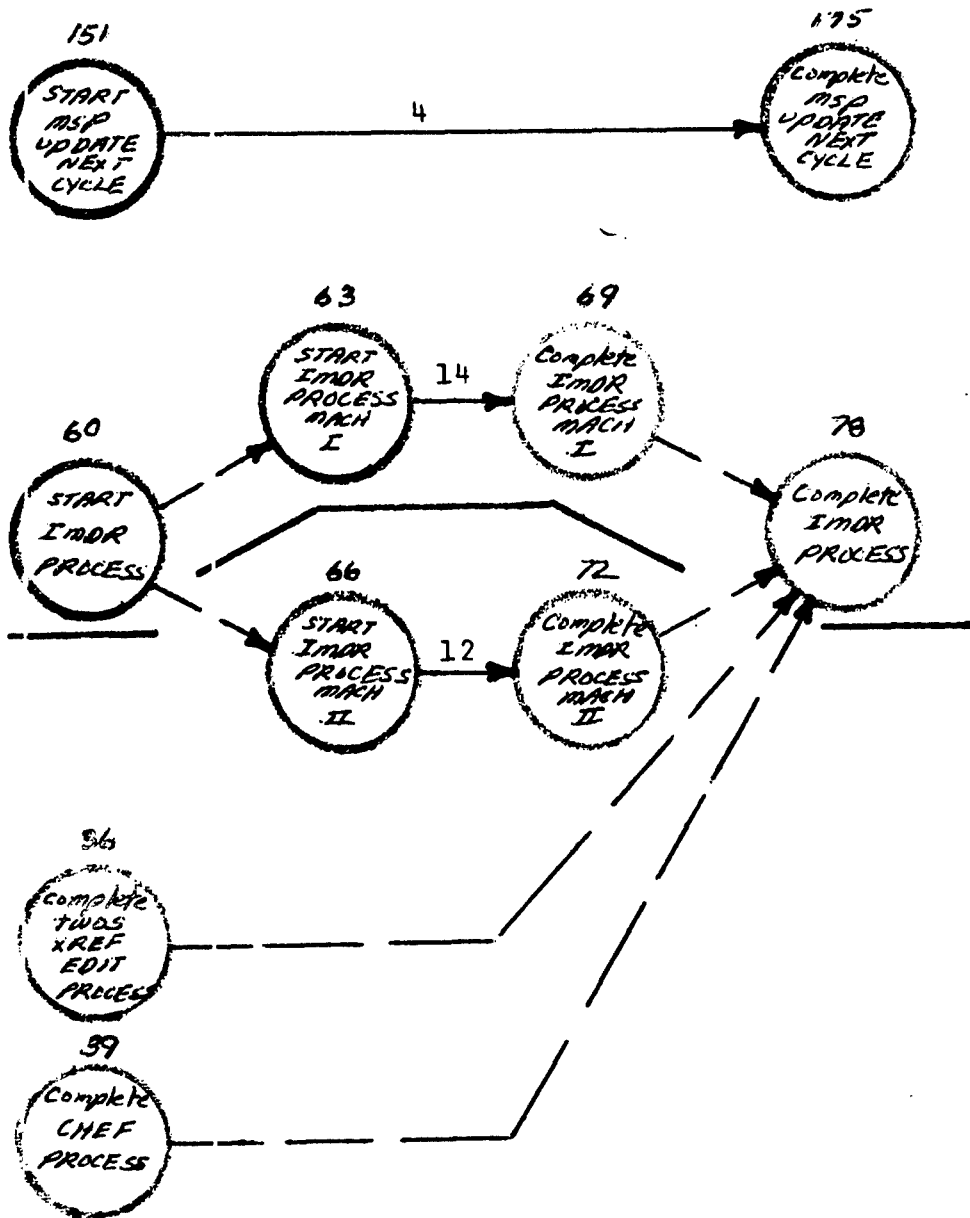
| <u>Activity No.</u>        | <u>Activity Description</u>            | <u>Activity Duration (Hours)</u> | <u>Immediately Preceding Activities</u>                                 |
|----------------------------|--|----------------------------------|---|
| 9-12; 109-112;<br>209-212  | Validation Process                     | 2                                | -; 181-184;<br>281-284, 100-200   |
| 15-33; 115-133;<br>215-233 | MRHSF Daily Process                    | 3                                | 9-12; 124-142,<br>109-112; 224-242,<br>209-212                          |
| 18-36; 118-136;<br>218-236 | TWOS XREF Edit Process                 | 3                                | 9-12; 109-112,<br>127-145; 209-212,<br>227-245                          |
| 21-39; 121-139;<br>221-239 | CHEF Process                           | 1                                | 9-12; 109-112;<br>130-148; 209-212,<br>230-248                          |
| 54-57; 154-157;<br>254-257 | MSP Process                            | 4                                | 15-33; 115-133,<br>151-175; 215-233,<br>251-275                         |
| 63-69; 163-169;<br>263-269 | IMDR Process Machine I                 | 14                               | 54-57; 154-157;<br>254-257  |
| 66-72; 166-172;<br>266-272 | IMDR Process Machine II                | 12                               | 54-57; 154-157;<br>254-257  |
| 100-200                    | Time Restraint Between<br>Cycle Starts | 24                               | 181-184   |
| 124-142; 224-242           | MRHSF Daily Update Next<br>Cycle       | 3                                | 9-12; 109-112   |
| 127-145; 227-245           | TWOS XREF Edit Update<br>Next Cycle    | 3                                | 9-12; 109-112   |
| 130-148; 230-248           | CHEF Update Next Cycle                 | 1                                | 9-12; 109-112   |
| 151-175; 251-275           | MSP Update Next Cycle                  | 4                                | 15-33; 115-133  |
| 181-184; 281-284           | TEF Update Next Cycle                  | 2                                | 63-69, 66-72, 18-36,<br>21-39; 163-169,<br>166-172, 118-136,<br>121-139 |

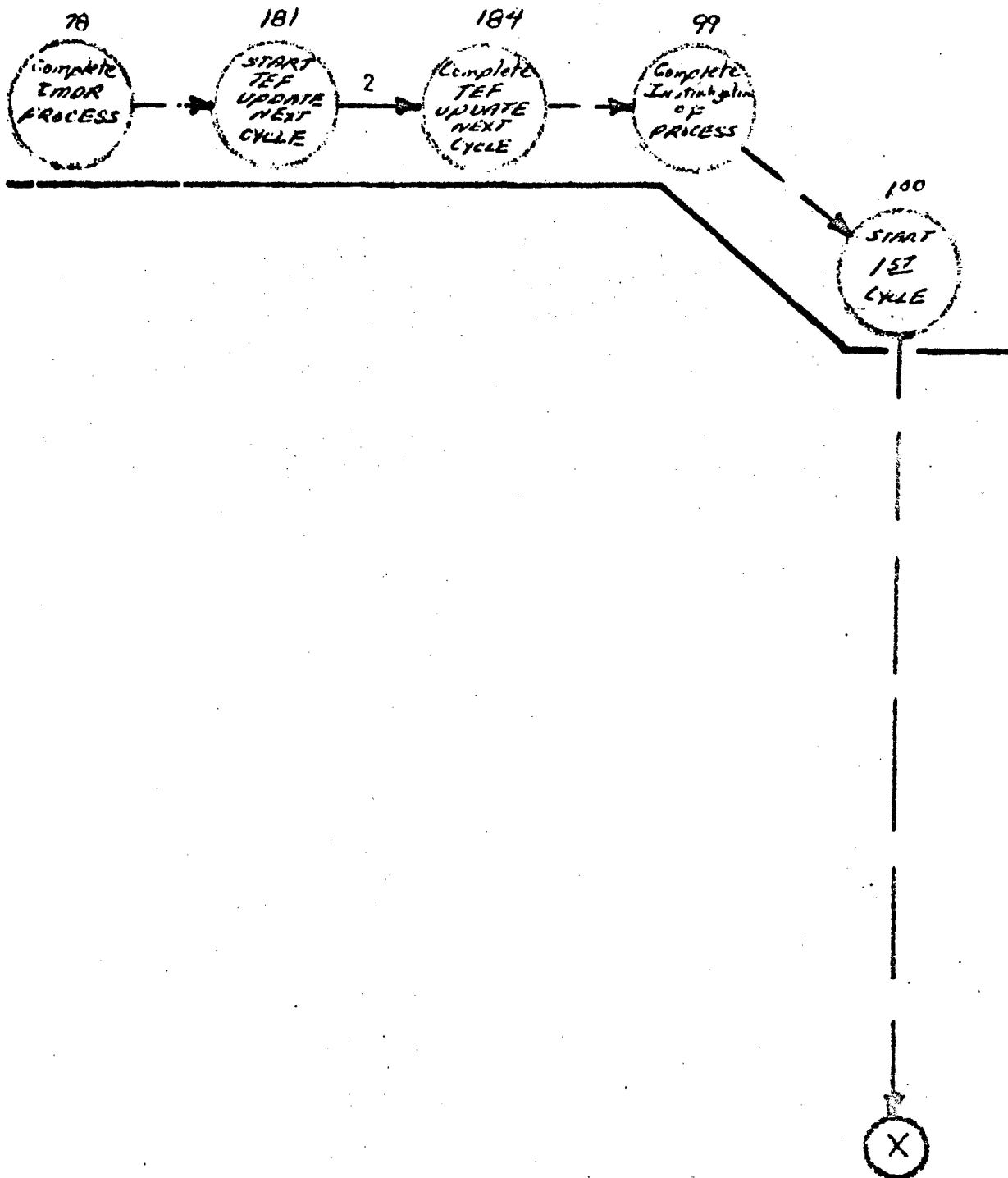
III. Example of the Critical Path Method Procedure (cont...)

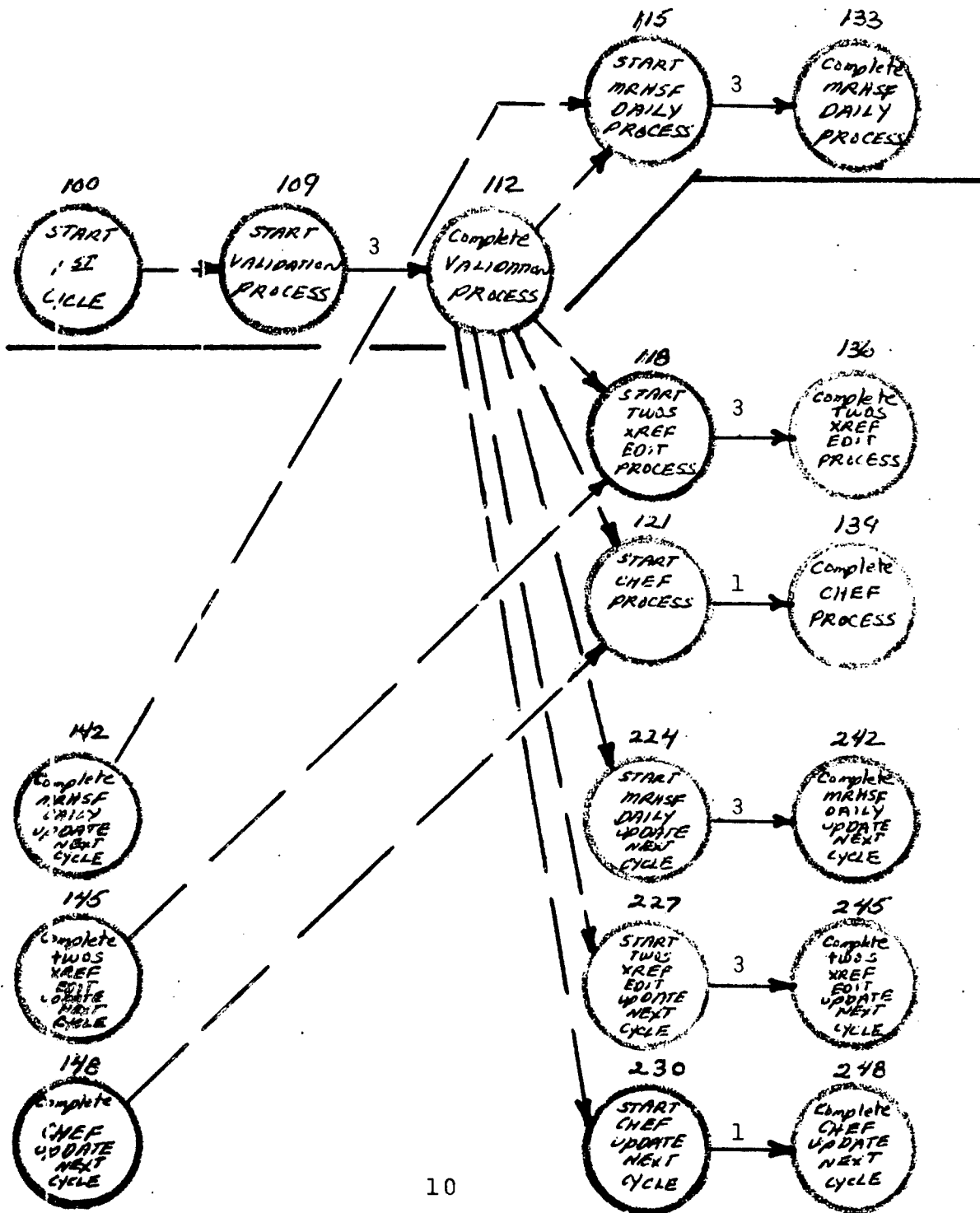
b. Network Diagram Representation (Steps 3-5)



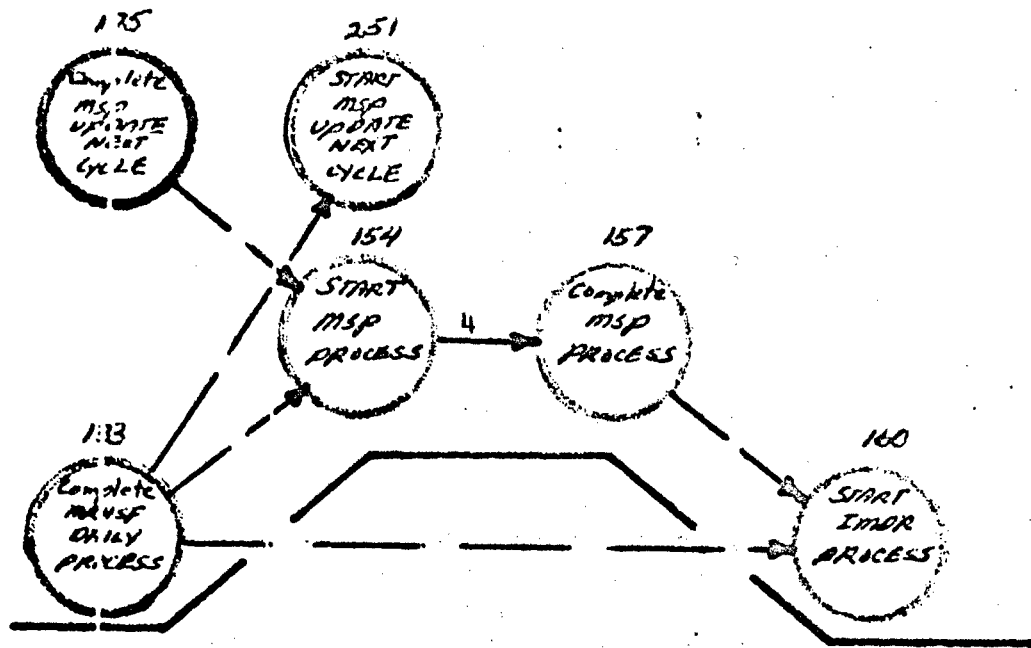


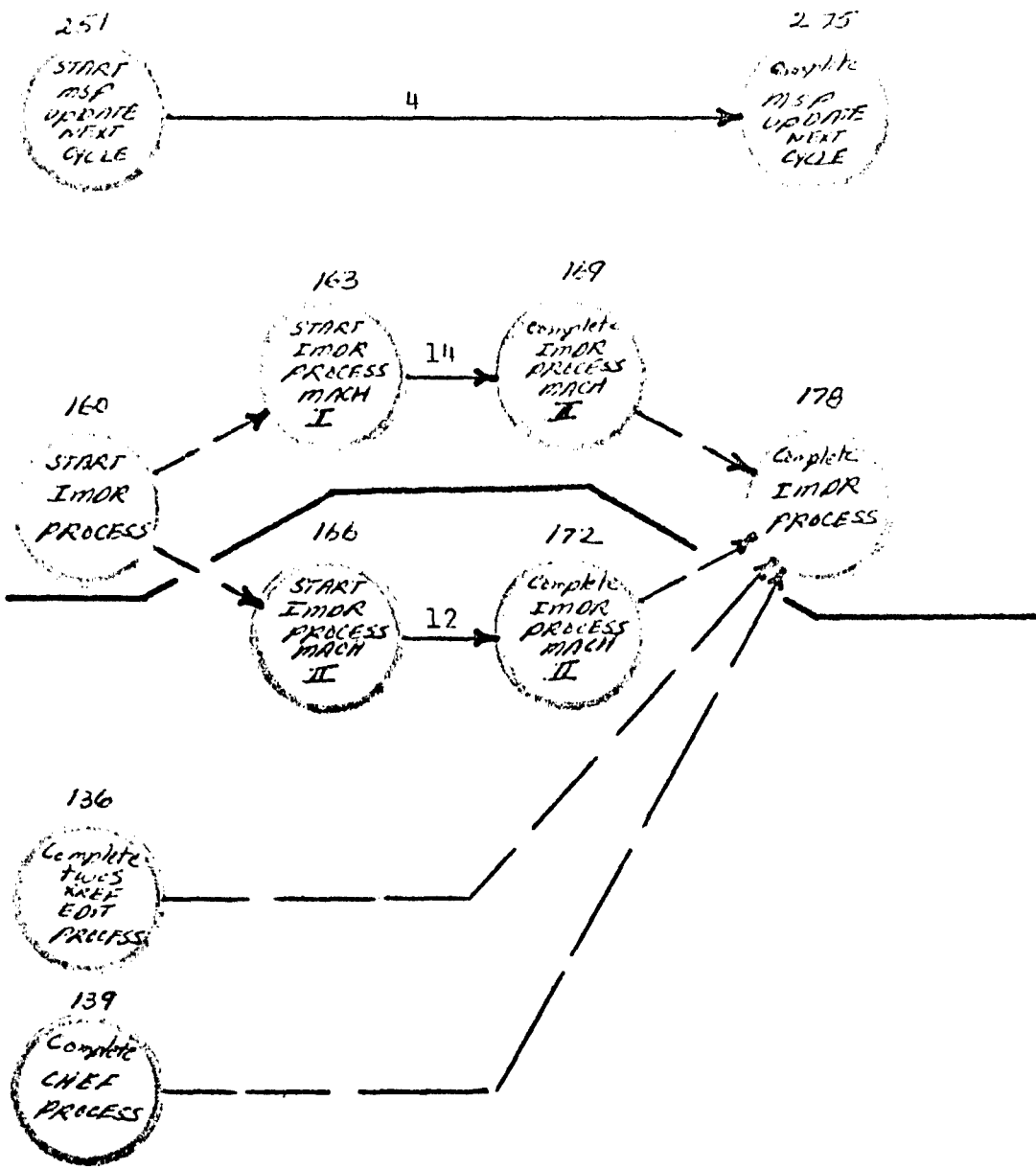


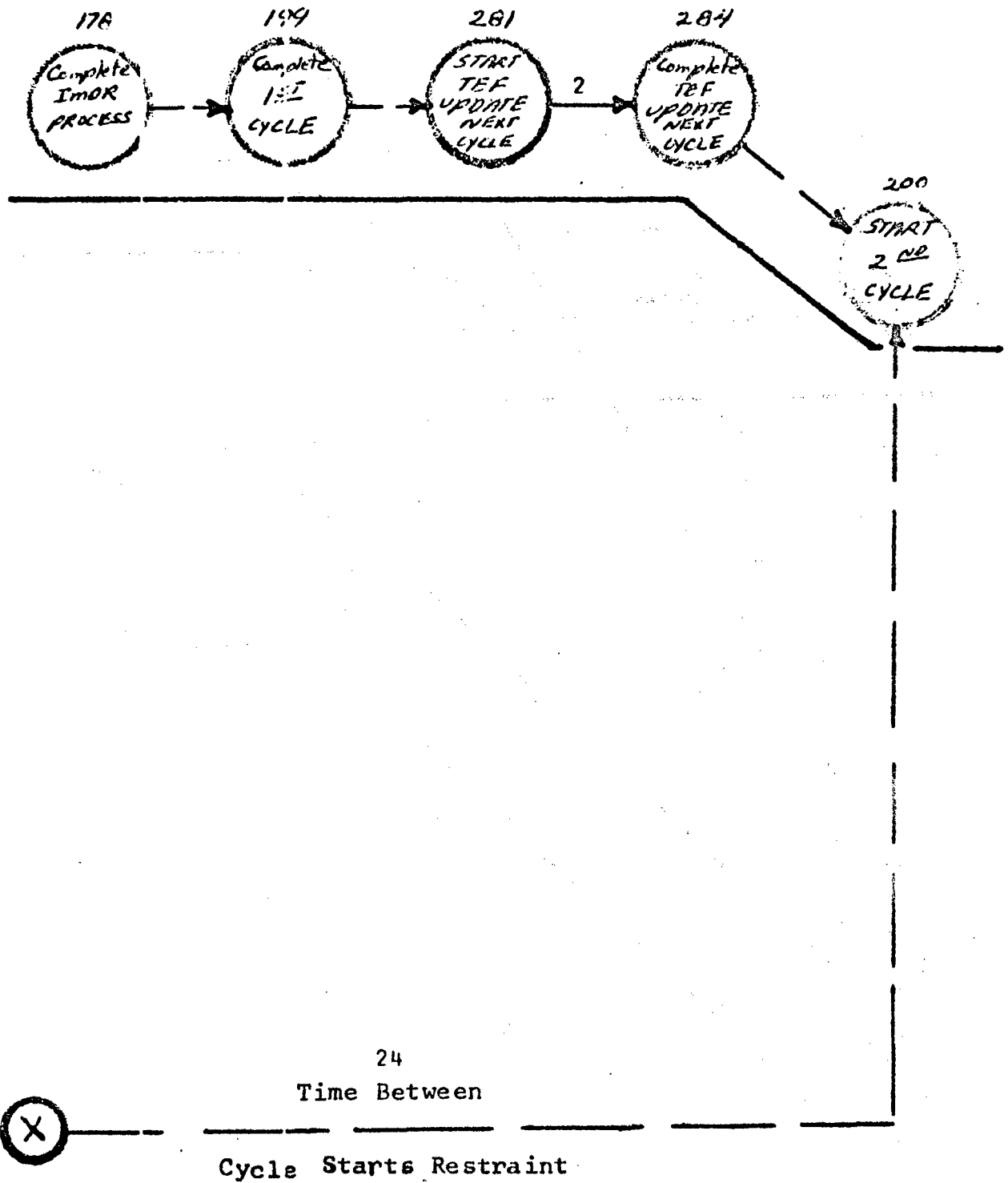


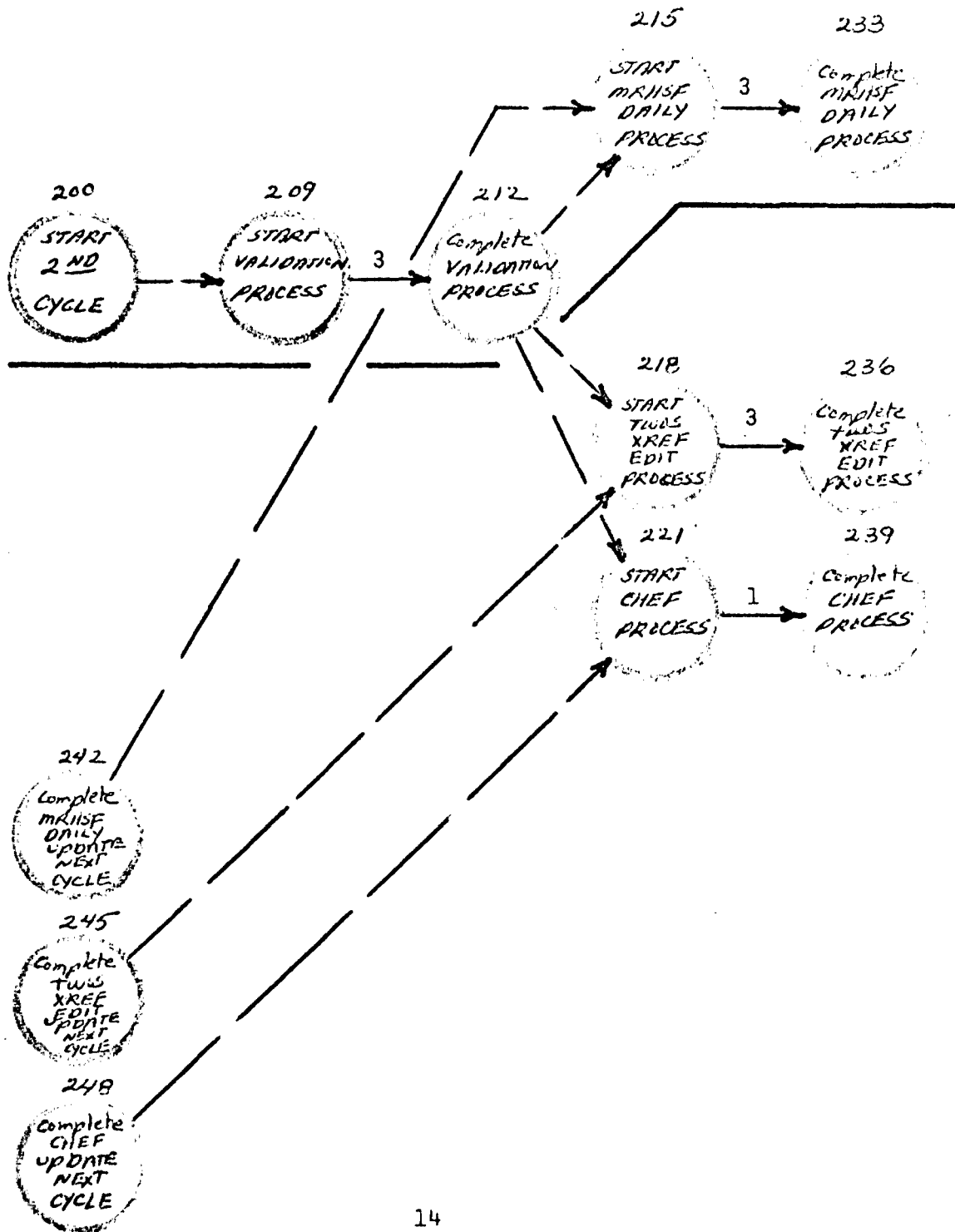


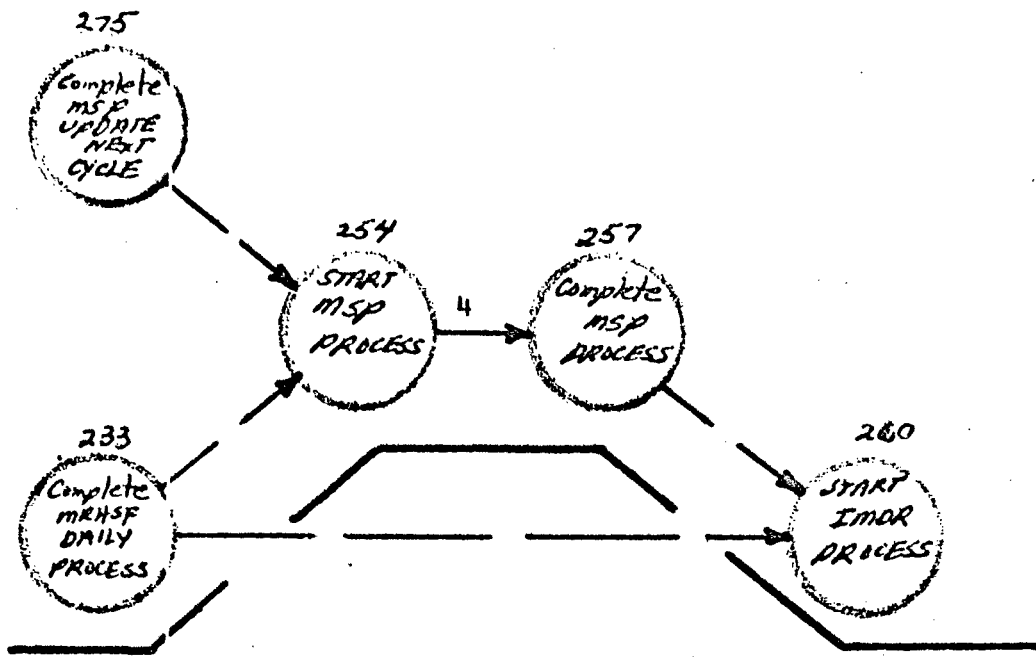


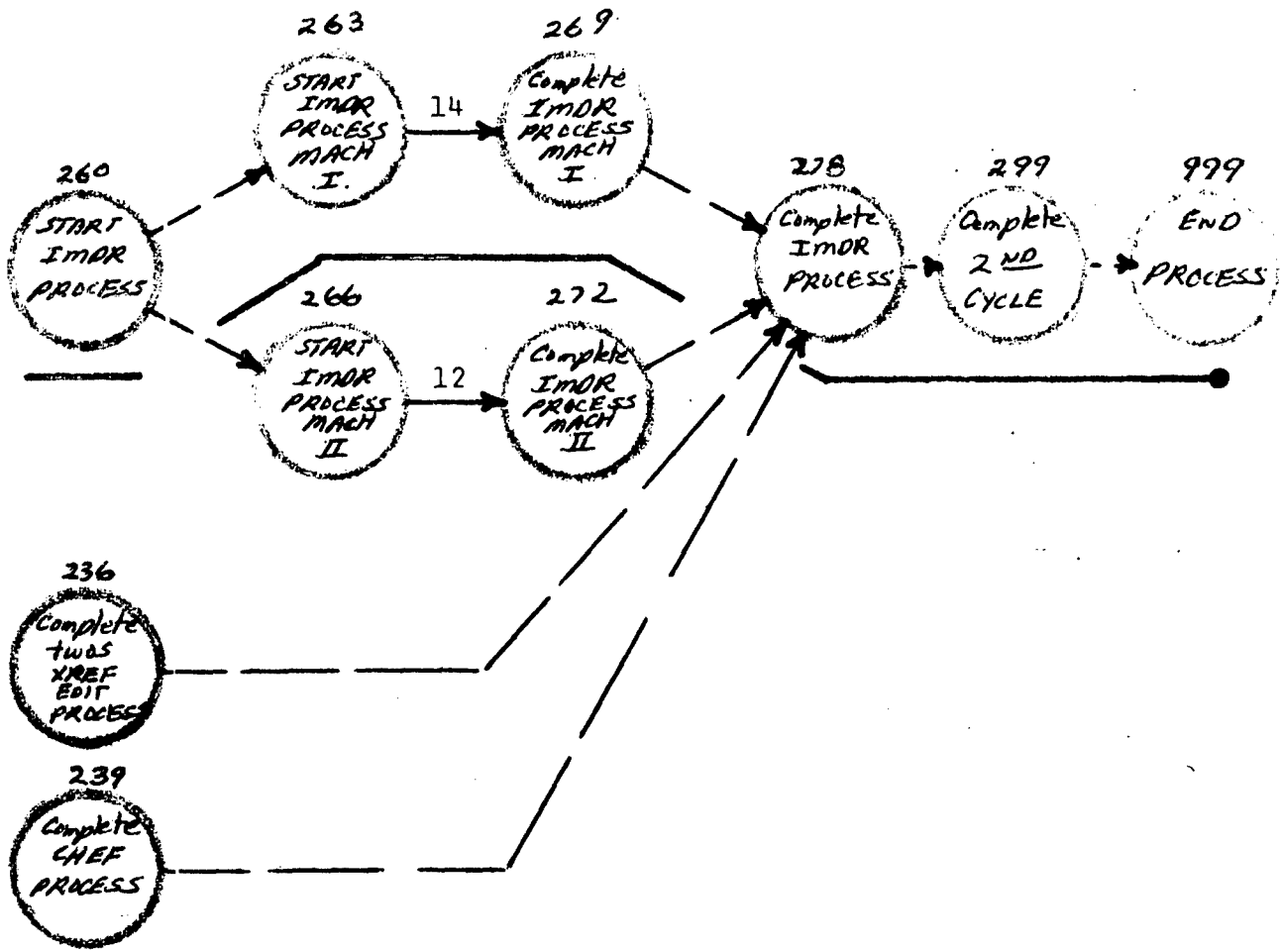












III. Example of the Critical Path Method Procedure (cont...)

c. Tabulation of Analysis Results (Step 5b)

The following input data was subjected to a CPM Analysis by use of a computer time-sharing terminal. The output data from the analysis consisted of the critical path(s), activity (i,j), activity duration (DUR), earliest start time (ES), earliest finish time (EF), latest start time (LS), latest finish time (LF), total float-slack time (TF), Level (LEV), cost when applicable (\$).

(1) Input Data

|    |   |
|----|---|
| 1  | 1, 6, 0, 00, 3, 9, 9, 00, 9, 12, 2, 00, 12, 15, 0, 00,                |
| 2  | 12, 15, 0, 00, 12, 21, 3, 00, 12, 124, 0, 00, 12, 127, 0, 00,         |
| 3  | 12, 152, 0, 00, 15, 33, 3, 00, 14, 32, 3, 00, 21, 33, 1, 00,          |
| 4  | 124, 142, 3, 00, 127, 145, 3, 00, 130, 142, 1, 00, 35, 151, 0, 00,    |
| 5  | 33, 34, 3, 00, 35, 39, 0, 00, 38, 72, 0, 00, 38, 73, 0, 00,           |
| 6  | 142, 113, 0, 00, 145, 115, 0, 00, 148, 121, 0, 00, 151, 175, 4, 00,   |
| 7  | 34, 37, 4, 00, 37, 62, 0, 00, 39, 63, 0, 00, 39, 64, 0, 00,           |
| 8  | 35, 39, 14, 00, 38, 72, 12, 00, 39, 73, 0, 00, 72, 73, 0, 00,         |
| 9  | 175, 154, 7, 00, 73, 131, 0, 00, 131, 134, 0, 00, 134, 30, 0, 00,     |
| 10 | 30, 100, 0, 00, 100, 103, 0, 00, 100, 206, 14, 00, 103, 112, 2, 00,   |
| 11 | 112, 115, 0, 00, 112, 113, 0, 00, 112, 121, 0, 00, 112, 224, 0, 00,   |
| 12 | 112, 227, 0, 00, 112, 230, 0, 00, 115, 133, 3, 00, 112, 136, 2, 00,   |
| 13 | 121, 139, 1, 00, 224, 242, 3, 00, 227, 245, 3, 00, 230, 240, 1, 00,   |
| 14 | 133, 251, 1, 00, 133, 154, 0, 00, 133, 160, 0, 00, 133, 173, 0, 00,   |
| 15 | 139, 173, 0, 00, 242, 215, 0, 00, 245, 213, 0, 00, 243, 221, 0, 00,   |
| 16 | 251, 275, 4, 00, 154, 157, 4, 00, 157, 160, 0, 00, 160, 163, 0, 00,   |
| 17 | 160, 166, 0, 00, 163, 169, 14, 00, 166, 173, 12, 00, 169, 173, 0, 00, |
| 18 | 172, 173, 0, 00, 275, 254, 0, 00, 173, 199, 0, 00, 199, 231, 0, 00,   |
| 19 | 231, 234, 2, 00, 234, 200, 0, 00, 200, 209, 0, 00, 209, 212, 2, 00,   |
| 20 | 212, 215, 0, 00, 215, 233, 3, 00, 213, 236, 3, 00, 221, 239, 1, 00,   |
| 21 | 233, 254, 0, 00, 233, 260, 0, 00, 236, 273, 0, 00, 239, 273, 0, 00,   |
| 22 | 254, 257, 4, 00, 257, 260, 0, 00, 260, 263, 0, 00, 260, 260, 0, 00,   |
| 23 | 263, 269, 14, 00, 266, 272, 12, 00, 269, 273, 0, 00, 272, 273, 0, 00, |
| 24 | 273, 299, 0, 00, 299, 999, 0, 00,                                     |
| 25 | 1, 999, -1, 0,  |

III. Example of the Critical Path Method Procedure (cont...)

(2) Output Results

CPM2 13:08 TUE. 03/04/69.

DARTMOUTH ALGOL.

WHAT CPM. FOR SORT AND HOW MANY ACT. 79,0

WHAT CPM. FOR SORT AND HOW MANY ACT. 73,94

| PROJECT DURATION: 73 |     |     | TOTAL COST: \$ 0 |    |    |    |    |     |   |
|----------------------|-----|-----|------------------|----|----|----|----|-----|---|
| CRIT I               | J   | DUR | EC               | EF | LS | LF | TF | LEV | C |
| * 1                  | 0   | 0   | 0                | 0  | 0  | 0  | 0  | 1   | 0 |
| * 3                  | 9   | 0   | 0                | 0  | 0  | 0  | 0  | 2   | 0 |
| * 9                  | 12  | 2   | 0                | 2  | 0  | 2  | 0  | 3   | 0 |
| * 12                 | 15  | 0   | 2                | 2  | 2  | 2  | 0  | 4   | 0 |
| * 15                 | 33  | 3   | 2                | 5  | 2  | 5  | 0  | 5   | 0 |
| * 33                 | 54  | 0   | 5                | 5  | 5  | 5  | 0  | 6   | 0 |
| * 54                 | 57  | 4   | 5                | 9  | 5  | 9  | 0  | 7   | 0 |
| * 57                 | 60  | 0   | 9                | 9  | 9  | 9  | 0  | 8   | 0 |
| * 60                 | 63  | 0   | 9                | 9  | 9  | 9  | 0  | 9   | 0 |
| * 63                 | 69  | 14  | 9                | 23 | 9  | 23 | 0  | 10  | 0 |
| * 69                 | 73  | 0   | 23               | 23 | 23 | 23 | 0  | 11  | 0 |
| * 73                 | 131 | 0   | 23               | 23 | 23 | 23 | 0  | 12  | 0 |
| * 131                | 134 | 2   | 23               | 25 | 23 | 25 | 0  | 13  | 0 |
| * 134                | 99  | 0   | 25               | 25 | 25 | 25 | 0  | 14  | 0 |
| * 99                 | 100 | 0   | 25               | 25 | 25 | 25 | 0  | 15  | 0 |
| * 100                | 109 | 0   | 25               | 25 | 25 | 25 | 0  | 16  | 0 |
| * 109                | 112 | 2   | 25               | 27 | 25 | 27 | 0  | 17  | 0 |
| * 112                | 115 | 0   | 27               | 27 | 27 | 27 | 0  | 18  | 0 |
| * 115                | 133 | 3   | 27               | 30 | 27 | 30 | 0  | 19  | 0 |
| * 133                | 154 | 0   | 30               | 30 | 30 | 30 | 0  | 20  | 0 |
| * 154                | 157 | 4   | 30               | 34 | 30 | 34 | 0  | 21  | 0 |
| * 157                | 160 | 0   | 34               | 34 | 34 | 34 | 0  | 22  | 0 |
| * 160                | 163 | 0   | 34               | 34 | 34 | 34 | 0  | 23  | 0 |
| * 163                | 169 | 14  | 34               | 43 | 34 | 43 | 0  | 24  | 0 |
| * 169                | 175 | 0   | 43               | 43 | 43 | 43 | 0  | 25  | 0 |
| * 175                | 199 | 0   | 43               | 43 | 43 | 43 | 0  | 26  | 0 |
| * 199                | 231 | 0   | 43               | 43 | 43 | 43 | 0  | 27  | 0 |
| * 231                | 234 | 2   | 43               | 50 | 43 | 50 | 0  | 28  | 0 |
| * 234                | 200 | 0   | 50               | 50 | 50 | 50 | 0  | 29  | 0 |
| * 200                | 209 | 0   | 50               | 50 | 50 | 50 | 0  | 30  | 0 |
| * 209                | 212 | 2   | 50               | 52 | 50 | 52 | 0  | 31  | 0 |
| * 212                | 215 | 0   | 52               | 52 | 52 | 52 | 0  | 32  | 0 |
| * 215                | 233 | 3   | 52               | 55 | 52 | 55 | 0  | 33  | 0 |
| * 233                | 254 | 0   | 55               | 55 | 55 | 55 | 0  | 34  | 0 |
| * 254                | 257 | 4   | 55               | 59 | 55 | 59 | 0  | 35  | 0 |
| * 257                | 260 | 0   | 59               | 59 | 59 | 59 | 0  | 36  | 0 |
| * 260                | 263 | 0   | 59               | 59 | 59 | 59 | 0  | 37  | 0 |
| * 263                | 269 | 14  | 59               | 73 | 59 | 73 | 0  | 38  | 0 |
| * 269                | 273 | 0   | 73               | 73 | 73 | 73 | 0  | 39  | 0 |
| * 273                | 299 | 0   | 73               | 73 | 73 | 73 | 0  | 40  | 0 |
| * 299                | 999 | 0   | 73               | 73 | 73 | 73 | 0  | 41  | 0 |



III. Example of the Critical Path Method Procedure (cont...)

(2) Output Results (cont...)

|     |     |    |    |    |    |    |    |    |   |
|-----|-----|----|----|----|----|----|----|----|---|
| 100 | 200 | 24 | 25 | 49 | 26 | 50 | 1  | 16 | 0 |
| 60  | 30  | 0  | 9  | 9  | 11 | 11 | 2  | 9  | 0 |
| 66  | 72  | 12 | 9  | 21 | 11 | 23 | 2  | 10 | 0 |
| 72  | 75  | 0  | 21 | 21 | 23 | 23 | 2  | 11 | 0 |
| 160 | 166 | 0  | 34 | 34 | 36 | 36 | 2  | 23 | 0 |
| 166 | 172 | 12 | 34 | 46 | 36 | 43 | 2  | 24 | 0 |
| 172 | 173 | 0  | 46 | 46 | 43 | 43 | 2  | 25 | 0 |
| 260 | 266 | 0  | 59 | 59 | 61 | 61 | 2  | 37 | 0 |
| 266 | 272 | 12 | 59 | 71 | 61 | 73 | 2  | 38 | 0 |
| 272 | 278 | 0  | 71 | 71 | 73 | 73 | 2  | 39 | 0 |
| 53  | 60  | 0  | 5  | 5  | 9  | 9  | 4  | 6  | 0 |
| 153 | 160 | 0  | 30 | 30 | 34 | 34 | 4  | 20 | 0 |
| 253 | 260 | 0  | 55 | 55 | 59 | 59 | 4  | 34 | 0 |
| 12  | 13  | 0  | 2  | 2  | 20 | 20 | 13 | 4  | 0 |
| 13  | 36  | 3  | 2  | 5  | 20 | 23 | 18 | 5  | 0 |
| 36  | 78  | 0  | 5  | 5  | 23 | 23 | 18 | 6  | 0 |
| 112 | 118 | 0  | 27 | 27 | 45 | 45 | 18 | 18 | 0 |
| 118 | 136 | 3  | 27 | 30 | 45 | 48 | 18 | 19 | 0 |
| 136 | 178 | 0  | 30 | 30 | 43 | 43 | 18 | 20 | 0 |
| 12  | 21  | 0  | 2  | 2  | 22 | 22 | 20 | 4  | 0 |
| 21  | 39  | 1  | 2  | 3  | 22 | 23 | 20 | 5  | 0 |
| 39  | 78  | 0  | 3  | 3  | 23 | 23 | 20 | 6  | 0 |
| 112 | 121 | 0  | 27 | 27 | 47 | 47 | 20 | 18 | 0 |
| 121 | 139 | 1  | 27 | 28 | 47 | 43 | 20 | 19 | 0 |
| 133 | 251 | 1  | 30 | 31 | 50 | 51 | 20 | 20 | 0 |
| 139 | 173 | 0  | 28 | 28 | 48 | 43 | 20 | 20 | 0 |
| 251 | 275 | 4  | 31 | 35 | 51 | 55 | 20 | 21 | 0 |
| 275 | 254 | 0  | 35 | 35 | 55 | 55 | 20 | 22 | 0 |
| 53  | 151 | 0  | 5  | 5  | 26 | 26 | 21 | 6  | 0 |
| 151 | 175 | 4  | 5  | 9  | 26 | 30 | 21 | 7  | 0 |
| 175 | 154 | 0  | 9  | 9  | 30 | 30 | 21 | 8  | 0 |
| 12  | 124 | 0  | 2  | 2  | 24 | 24 | 22 | 4  | 0 |
| 124 | 142 | 3  | 2  | 5  | 24 | 27 | 22 | 5  | 0 |
| 142 | 115 | 0  | 5  | 5  | 27 | 27 | 22 | 6  | 0 |
| 112 | 224 | 0  | 27 | 27 | 49 | 49 | 22 | 18 | 0 |
| 224 | 242 | 3  | 27 | 30 | 49 | 52 | 22 | 19 | 0 |
| 242 | 215 | 0  | 30 | 30 | 52 | 52 | 22 | 20 | 0 |
| 12  | 127 | 0  | 2  | 2  | 42 | 42 | 40 | 4  | 0 |
| 127 | 145 | 3  | 2  | 5  | 42 | 45 | 40 | 5  | 0 |
| 145 | 113 | 0  | 5  | 5  | 45 | 45 | 40 | 6  | 0 |
| 112 | 227 | 0  | 27 | 27 | 67 | 67 | 40 | 18 | 0 |
| 227 | 245 | 3  | 27 | 30 | 67 | 70 | 40 | 19 | 0 |
| 245 | 213 | 0  | 30 | 30 | 70 | 70 | 40 | 20 | 0 |
| 213 | 236 | 3  | 30 | 33 | 70 | 73 | 40 | 21 | 0 |
| 236 | 273 | 0  | 33 | 33 | 73 | 73 | 40 | 22 | 0 |
| 12  | 130 | 0  | 2  | 2  | 46 | 46 | 44 | 4  | 0 |
| 130 | 143 | 1  | 2  | 3  | 46 | 47 | 44 | 5  | 0 |
| 143 | 121 | 0  | 3  | 3  | 47 | 47 | 44 | 6  | 0 |
| 112 | 230 | 0  | 27 | 27 | 71 | 71 | 44 | 18 | 0 |
| 230 | 243 | 1  | 27 | 28 | 71 | 72 | 44 | 19 | 0 |
| 243 | 221 | 0  | 28 | 28 | 72 | 72 | 44 | 20 | 0 |
| 221 | 239 | 1  | 28 | 29 | 72 | 73 | 44 | 21 | 0 |
| 239 | 273 | 0  | 29 | 29 | 73 | 73 | 44 | 22 | 0 |

III. Example of the Critical Path Method Procedure (cont...)

(3) Summary of Pertinent Analysis Results Relevant to Routine File Maintenance

| <u>Activity</u>    | <u>Description</u>               | <u>Process Time</u> | <u>Earliest Start Time-Hr (ES)</u> | <u>Latest Start Time-Hr (LS)</u> |
|--------------------|----------------------------------|---------------------|------------------------------------|----------------------------------|
| 124-142<br>224-242 | MRHSF Daily Update Next Cycle    | 3                   | 2<br>27                            | 24<br>49                         |
| 127-145<br>227-245 | TWOS XREF Edit Update Next Cycle | 3                   | 2<br>27                            | 42<br>67                         |
| 130-148<br>230-248 | CHEF Update Next Cycle           | 1                   | 2<br>27                            | 46<br>71                         |
| 151-175<br>251-275 | MSP Update Next Cycle            | 4                   | 5<br>31                            | 26<br>51                         |
| 181-184<br>281-284 | TEF Update Next Cycle            | 2                   | 23<br>48                           | 23<br>48                         |

### III. Example of the Critical Path Method Procedure (cont...)

#### d. Establish a Feasible Scheduling Sequence (Steps 7-8)

There are many techniques and procedures available for sequencing jobs on machines in the literature. The state-of-the-art is such today that none of them are sufficient for obtaining the optimum sequence for scheduling jobs on a computer nor are they practical for implementation. Therefore, the following technique is presented for the sake of demonstration rather than recommendation. It is a fairly simple technique but will require evaluation before it should be implemented. The technique was developed by Hedgeson and Bernie\*.

The technique concerns itself with the balancing of assembly operations in order to keep the unassigned or idle time required to complete an assembly operation to a minimum. Two formulations of the problem are presented in the referenced technical paper:

- (1) Minimize the number of work stations for a given cycle time.
- (2) Minimize the cycle time for a given number of work stations.

The technique for the first formulation is the one that is demonstrated in the following. The Algorithm (set of rules) for this technique are included in Appendix A.

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\*Reference: Hedgeson, W.B. and Bernie, D.P., "Assembly Line Balancing Using the Ranked Positional Weight Technique", The Journal of Industrial Engineering, Volume XII, No. 6, pp 394-398, 1961

### III. Example of the Critical Path Method Procedure (cont...)

(1) Establish a table depicting by activity, the latest finish time (LF), subsequent sequence time (MAX Subsequent Sequence Time - LF), Process Time (DUR), and activities that must immediately precede it (see table 1).

(2) Reorder preceding data table in order of decreasing "subsequent-sequence time" (see table 2).

(3) Determine a desirable cycle time. Since in the current example, there are 143 computer hours required to complete two cycles and assuming four computers available, an optimum cycle time would be  $143/(4)(2)=143/8=18$  Hours. A review of table 1 reveals that the activity with the longest duration has a duration of 14 hours, so a cycle time of 14 hours is the minimum that can currently be achieved with this data set. Since the optimum cycle time of 18 hours is greater than 14 hours, the maximum activity duration time, the 18 hours can be used when assigning the activities to the computer.

If the maximum activity duration time had been larger than the optimal cycle time, then the maximum activity duration time of 14 hours would have to be used as the lower limit for cycle time values when assigning activities to the computer.

In the following, a possible assignment and sequence of operations was determined assuming a 22 hour and 18 hour cycle time. The solutions have been presented both in a tabular form and also a Gantt Chart.

TABLE 1

Latest Finish Time, Subsequent Sequence Time, Process Time,  
and Preceding Activities.

| Activity | Activity Number | Latest Finish Time (HR) | Subsequent Sequence Time | Process Time (HR) | Activities that must Immediately Precede |
|----------|-----------------|-------------------------|--------------------------|-------------------|--|
| 9-12     | 9               | 2                       | 71                       | 2                 | -  |
| 15-33    | 15              | 5                       | 68                       | 3                 | 9  |
| 18-36    | 18              | 23                      | 50                       | 3                 | 9  |
| 21-39    | 21              | 23                      | 50                       | 1                 | 9  |
| 54-57    | 54              | 9                       | 64                       | 4                 | 15                                       |
| 63-69    | 63              | 23                      | 50                       | 14                | 54                                       |
| 66-72    | 66              | 23                      | 50                       | 12                | 54                                       |
| 109-112  | 109             | 27                      | 46                       | 2                 | 131                                      |
| 115-133  | 115             | 30                      | 43                       | 3                 | 124, 109                                 |
| 118-136  | 118             | 48                      | 25                       | 3                 | 109, 127                                 |
| 121-139  | 121             | 48                      | 25                       | 1                 | 109, 130                                 |
| 124-142  | 124             | 27                      | 46                       | 3                 | 9  |
| 127-145  | 127             | 45                      | 28                       | 3                 | 9  |
| 130-148  | 130             | 47                      | 26                       | 1                 | 9  |
| 151-175  | 151             | 30                      | 43                       | 4                 | 15                                       |
| 154-157  | 154             | 34                      | 39                       | 4                 | 115, 151                                 |
| 163-169  | 163             | 48                      | 25                       | 14                | 154                                      |
| 166-172  | 166             | 48                      | 25                       | 12                | 154                                      |
| 181-184  | 181             | 25                      | 48                       | 2                 | 63, 66, 18, 21                           |
| 209-212  | 209             | 52                      | 21                       | 2                 | 231                                      |
| 215-233  | 215             | 55                      | 18                       | 3                 | 224, 209                                 |
| 218-236  | 218             | 73                      | 0                        | 3                 | 209, 227                                 |
| 221-239  | 221             | 73                      | 0                        | 1                 | 209, 230                                 |
| 224-242  | 224             | 52                      | 21                       | 3                 | 109                                      |
| 227-245  | 227             | 70                      | 3                        | 3                 | 109                                      |
| 230-248  | 230             | 72                      | 1                        | 1                 | 109                                      |
| 251-275  | 251             | 55                      | 18                       | 4                 | 115                                      |
| 254-257  | 254             | 59                      | 14                       | 4                 | 215, 251                                 |
| 263-269  | 263             | 73                      | 0                        | 14                | 254                                      |
| 266-272  | 266             | 73                      | 0                        | 12                | 254                                      |
| 281-284  | 281             | 50                      | 23                       | 2                 | 163, 166, 118, 121                       |

TOTAL: 143 HR

### III. Example of the Critical Path Method Procedure (cont...)

(4) Following the rules outlined in the Algorithm, reference Appendix A, and referring to Table 2, the activities are assigned to the computers. Essentially, attention is given to the operations that must precede and activities having the greatest subsequent processing time are assigned first. The solutions, possible assignment and sequence of operations, are presented on Tables 3 and 4 for the 18 hour cycle time and on Tables 5 and 6 for the 22 hour cycle time.

TABLE 2

Subsequent Sequence Times and Preceding Activities in Order  
of Decreasing Subsequent Sequence Time.

| Activity<br>Number | Subsequent<br>Sequence<br>Time<br>(HR) | Process<br>Time<br>(HR) | Activities That<br>Must Immediately<br>Precede |
|--------------------|--|-------------------------|--|
| 9                  | 71                                     | 2                       | -  |
| 15                 | 68                                     | 3                       | 9  |
| 54                 | 64                                     | 4                       | 15   |
| 18                 | 50                                     | 3                       | 9  |
| 21                 | 50                                     | 1                       | 9  |
| 63                 | 50                                     | 14                      | 54   |
| 66                 | 50                                     | 12                      | 54   |
| 181                | 48                                     | 2                       | 63, 66, 18, 21                                 |
| 109                | 46                                     | 2                       | 181  |
| 124                | 46                                     | 3                       | 9  |
| 115                | 43                                     | 3                       | 124, 109                                       |
| 151                | 43                                     | 4                       | 15   |
| 154                | 39                                     | 4                       | 115, 151                                       |
| 127                | 28                                     | 3                       | 9  |
| 130                | 26                                     | 1                       | 9  |
| 118                | 25                                     | 3                       | 109, 127                                       |
| 121                | 25                                     | 1                       | 109, 130                                       |
| 163                | 25                                     | 14                      | 154  |
| 166                | 25                                     | 12                      | 154  |
| 281                | 23                                     | 2                       | 163, 166, 118, 121                             |
| 209                | 21                                     | 2                       | 281  |
| 224                | 21                                     | 3                       | 109  |
| 215                | 18                                     | 3                       | 224, 209                                       |
| 251                | 18                                     | 4                       | 115  |
| 254                | 14                                     | 4                       | 215, 251                                       |
| 227                | 3                                      | 3                       | 109  |
| 230                | 1                                      | 1                       | 109  |
| 218                | 0                                      | 3                       | 209, 227                                       |
| 221                | 0                                      | 1                       | 209, 230                                       |
| 263                | 0                                      | 14                      | 254  |
| 266                | 0                                      | 12                      | 254  |

TABLE 3

Possible Assignment and Sequence of Activities  
(18 Hours Cycle Time)

| Station<br>Number/<br>Computer<br>(Number) | Activities<br>Assigned         | Time (Hours)<br>Assigned -<br>Remaining (-)                    |
|--|--------------------------------|--|
| I<br>(I)                                   | 9, 15, 54, 18, 21, 124,<br>130 | 2, 3, 4, 3, 1, 3<br>(16), (13), (9), (6), (5), (2)<br>1<br>(1) |
| II<br>(II)                                 | 63, 151                        | 14, 4<br>(4), (0)  |
| III<br>(III)                               | 66, 181, 109, 121, 230         | 12, 2, 2, 1, 1<br>(6), (4), (2), (1), (0)                      |
| IV<br>(I)                                  | 115, 154, 127, 118, 224        | 3, 4, 3, 3, 3<br>(15), (11), (8), (5), (2)                     |
| V<br>(II)                                  | 163, 251                       | 14, 4<br>(4), (0)  |
| VI<br>(III)                                | 166, 281, 209, 221             | 12, 2, 2, 1<br>(6), (4), (2), (1)                              |
| VII<br>(I)                                 | 215, 254, 227, 218             | 3, 4, 3, 3<br>(15), (11), (8), (5)                             |
| VIII<br>(II)                               | 263                            | 14<br>(4)  |
| IX<br>(III)                                | 266                            | 12<br>(6)  |



TABLE 4

Possible Assignment and Sequence of Activities  
 (18 Hours Cycle Time)

GANTT CHART

CLOCK HOURS

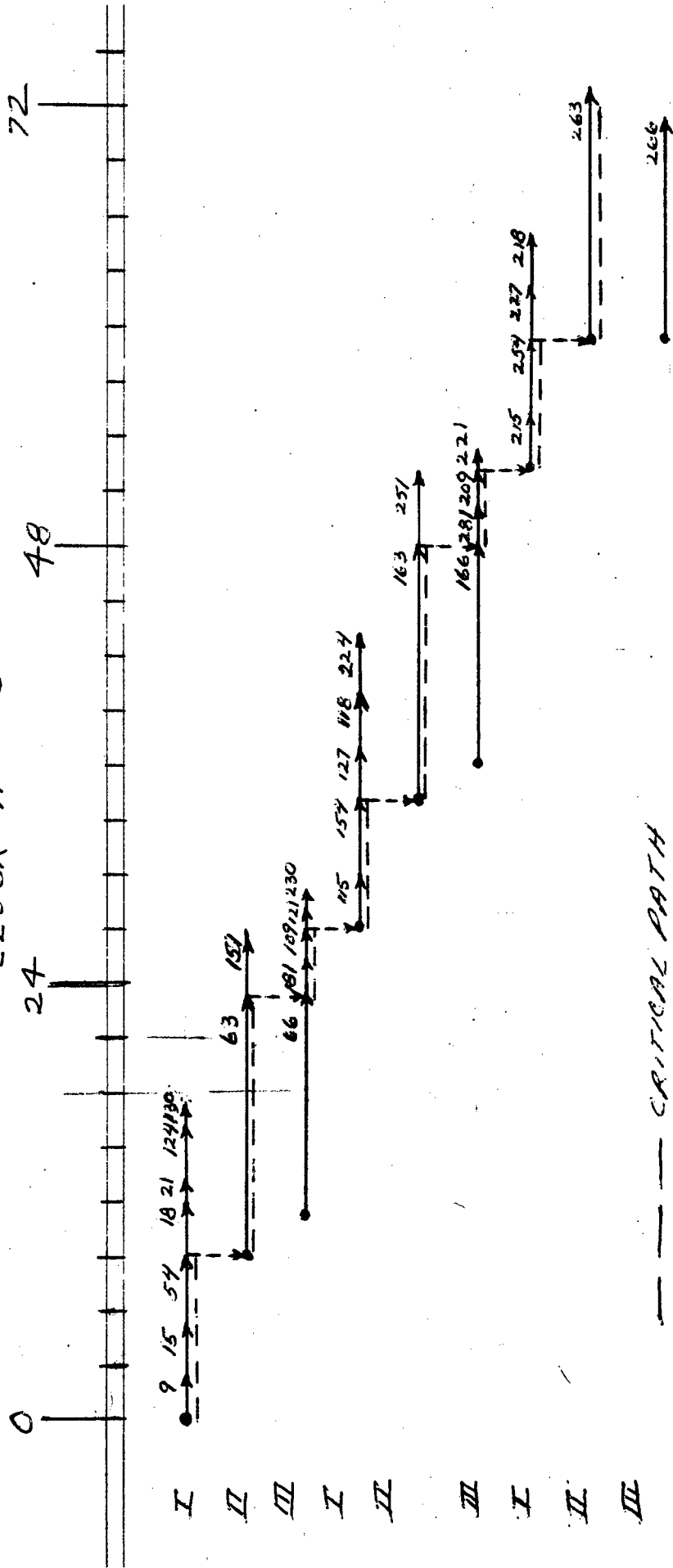


TABLE 5

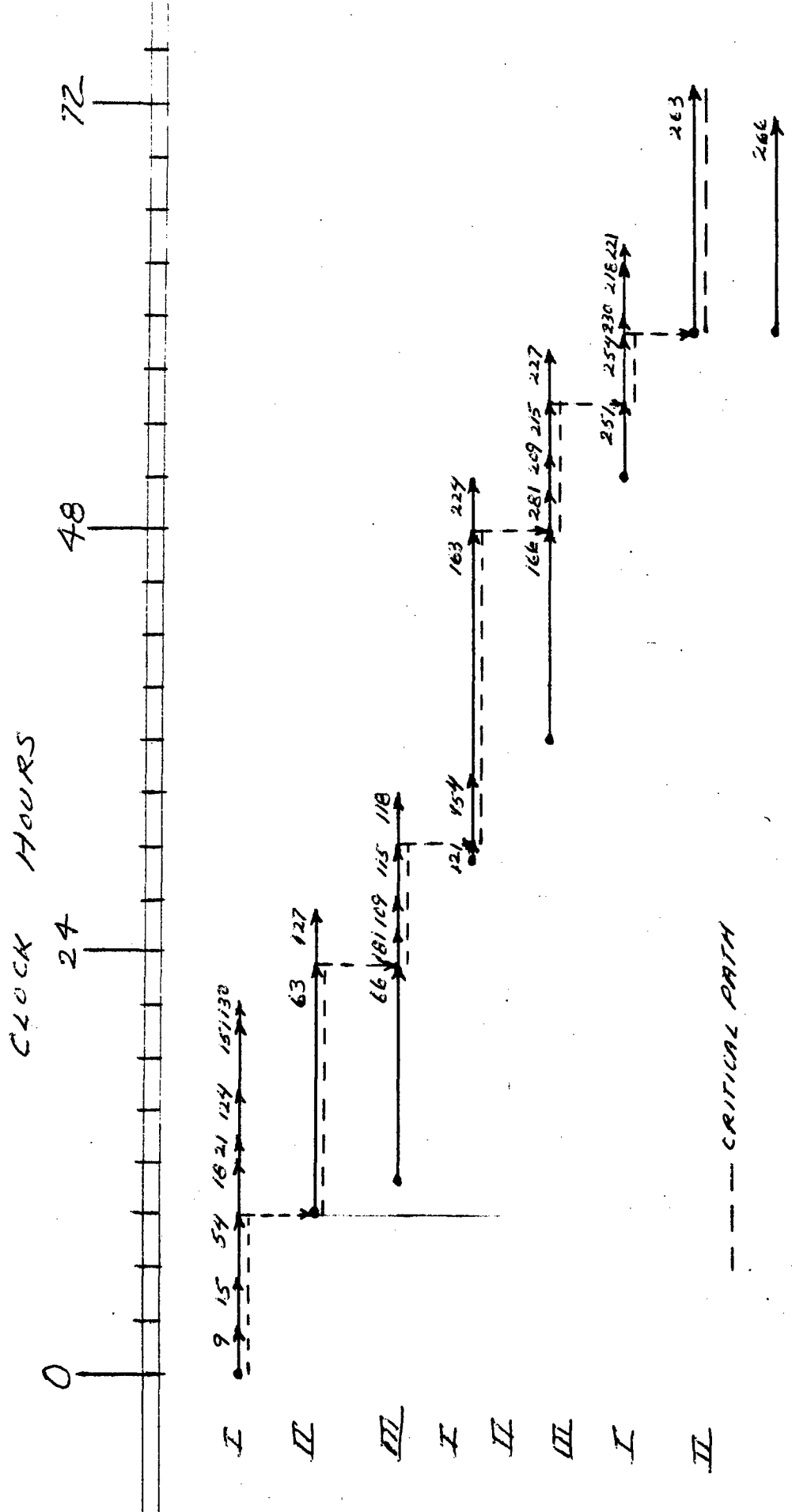
Possible Assignment and Sequence of Activities  
(22 Hours Cycle Time)

| Station<br>Number/<br>Computer<br>(Number) | Activities<br>Assigned             | Time (Hours)<br>Assigned -<br>Remaining (-)                              |
|--|------------------------------------|--|
| I<br>(I)                                   | 9, 15, 54, 18, 21, 124<br>151, 130 | 2, 3, 4, 3, 1, 3<br>(20), (17), (13), (10), (9), (6)<br>4, 1<br>(2), (1) |
| II<br>(II)                                 | 63, 127                            | 14, 3<br>(8), (5)  |
| III<br>(III)                               | 66, 181, 109, 115, 118             | 12, 2, 2, 3, 3<br>(10), (8), (6), (3), (0)                               |
| IV<br>(I)                                  | 121, 154, 163, 224                 | 1, 4, 14, 3<br>(21), (17), (3), (0)                                      |
| V<br>(II)                                  | 166, 281, 209, 215, 227            | 12, 2, 2, 3, 3<br>(10), (8), (6), (3), (0)                               |
| VI<br>(III)                                | 251, 254, 230, 218, 221            | 4, 4, 1, 3, 1<br>(18), (14), (13), (10), (9)                             |
| VII<br>(I)                                 | 263                                | 14<br>(8)  |
| VIII<br>(II)                               | 266                                | 12<br>(10)   |

TABLE 6

Possible Assignment and Sequence of Activities  
(22 Hours Cycle Time)

GANTT CHART



### III. Example of the Critical Path Method Procedure (cont...)

#### e. Interpretation and Evaluation (Steps 6 and 9)

The interpretation and evaluation has been deferred at this time until the above technique has been applied to a real network with real data. Some of the performance parameters under consideration for such an evaluation are as follows:

##### (1) Performance Parameters

Quantity of late jobs

Total late time

Total early time (slack time)

Total process time

Total maintenance time

Maximum late time per late job

Minimum late time per late job

Quantity of on-time jobs

Total quantity jobs

##### (2) Optimization Criteria

Many criteria are possible for optimization.

The performance, of course, will vary according to which criteria is optimized. A few examples of possible criteria are as follows:

(a) Minimize quantity of late jobs.

(b) Minimize quantity of high priority jobs that are late.

(c) Minimize total late time for jobs.

(d) Minimize quantity of jobs on a computer. (Essentially will minimize scheduled idle time between job change-overs).

### III. Example of the Critical Path Method Procedure (cont...)

(e) Minimize quantity of late jobs first and minimize total late time for jobs second.

(f) Minimize "make-span": Determine a schedule that causes the latest-finishing job to be completed at the earliest possible time.

(g) Given  $n$  jobs,  $m$  machines, for each machine there is a maximum available time. What jobs should be assigned to which machine in order to minimize the idle time on each of the machines. Assume certain jobs can be processed only on certain (not all) machines.

CRITICAL PATH METHOD  
CPM

(Project Planning and Scheduling)

IV. Glossary of Relevant Terms, Concepts, and Techniques

Gantt Chart: Planning and scheduling are presented simultaneously and are inseparable.

CPM: Planning and scheduling can be done independently.

Planning: The act of stating what activities must occur in a project and in what order these activities must take place.

Scheduling: The act of producing project time tables in consideration of the plan and costs.

Planning: Concerns itself with the structural characteristics of a project. It describes the precedence among project jobs, operations, or activities and is represented and facilitated by the use of a graphic technique, the arrow diagram or network representation.

Network: Is a graphical representation of a project plan, showing the interrelationships of the various activities.

Cyclical Network: Is a network which has a number of cycles or group of activities. Such a network can be composed of several condensed networks.

Detailed Network: Is a network in which activities are defined on a level of considerable detail thereby resulting in a relatively large network.

Condensed Network: Is a summarized version of a detailed network.

Glossary of Relevant Terms, Concepts, and Techniques (cont...)

Activity: Is a task or job within a project that cannot begin until certain other activities are completed. They involve a time - or other resource consuming element of the project.

Event: Is the beginning or ending of an activity.

Activity on Node Network: Is a network in which the activities are graphically represented by the nodes. The arrows are used to represent only the dependency relationships among the nodes.

Event Oriented Network: Is a network in which the activities are graphically represented by arrows. The nodes represent either start or complete events. At merge and burst points, dummy activities are introduced in the network to avoid ambiguities.

Critical Activity: Is an activity that if delayed will affect all other activities following it and will thus affect the completion of the overall project. If they are not completed at given points in time an overall project delay is incurred. (They have no float).

Critical Path(s): One or more contiguous path(s) of critical activities through any project arrow diagram.

Float: A certain amount of leeway or float is associated with all the non-critical activities.

Timely Control: Of a project requires awareness of both the critical path(s) and the amount of leeway or float available for each activity.

Types of Float: Three types can be identified: total float, free float, and independent float.

Glossary of Relevant Terms, Concepts, and Techniques (cont...)

Total Activity Slack (or Float): It is the amount of time that the activity completion time can be delayed without affecting the earliest start or occurrence time of any activity or event on the network critical path. It is computed by taking the latest allowable time of the activity's successor event minus the earliest finish time of the activity in question. (The largest of the three floats).

Free activity Slack (or Float): It is the amount of time that the activity completion time can be delayed without affecting the earliest start or occurrence time of any other activity or event in the network. Computed by taking the earliest expected time of the activity's successor event minus the earliest finish time of the activity in question.

Independent Float: Is the leeway available no matter where preceeding or succeeding activities are placed within their intervals of float.

Ready-Time: The earliest time at which processing can begin.

Processing-Time: The amount of time required on the machine.

Due-Time: The time by which completion is desired.



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## APPENDIX A

### ALGORITHM

#### To Minimize the Number of Work Stations for a Given Cycle Time

(Hedgeson and Bernie)

1. Select the work unit with the highest positional weight and assign it to the first work station. (It is assumed that one would not try to balance the line to a cycle time smaller than the time of the largest work element on the line, therefore the first assignable work unit can always be assigned to an empty work station.)
2. Calculate the unassigned time for the work station by calculating the cumulative time of all work units assigned to the station and subtract this sum from the cycle time.
3. Select the work unit with the next highest positional weight and attempt to assign it to the work station after making the following checks:
  - a. Check the list of already assigned work units. If the "immediate precedent" work unit has been assigned, precedence will not be violated; proceed to step 3b. If the "immediate precedent" has not been assigned proceed to step 4.
  - b. Compare the work unit time with the unassigned time. If the work unit time is less than the work station unassigned time, assign the work unit and recalculate unassigned time. If the work unit time is greater than the unassigned time, proceed to step 4.

APPENDIX A (cont...)

4. Continue to select, check, and assign if possible until one of two conditions has been met:

- a. All work units have been assigned.
- b. No unassigned work unit remains that can satisfy both the precedence requirement and the "less than the unassigned time" requirement.

5. Assign the unassigned work unit with the highest positional weight to the second work station, and proceed through the preceding steps in the same manner.

6. Continue assigning work units to work stations until all work units have been assigned. At that time a solution to the assembly line balancing problem will have been found.

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| 13. ABSTRACT<br>This report presents by example the application of the critical path method (CPM) for the planning and scheduling of jobs on a computer. It provides a step-by-step preparation and analysis of a network representation of a computer system application. Also, included is a glossary of relevant terms and a fairly comprehensive bibliography on the subject of CPM/PERT, scheduling and sequencing. |  |   |                       |

| 14. KEY WORDS       | LINK A |    | LINK B |    | LINK C |    |
|---------------------|--------|----|--------|----|--------|----|
|                     | ROLE   | WT | ROLE   | WT | ROLE   | WT |
| Job scheduling      |        |    |        |    |        |    |
| Scheduling          |        |    |        |    |        |    |
| CPM                 |        |    |        |    |        |    |
| Computer Scheduling |        |    |        |    |        |    |
| PERT                |        |    |        |    |        |    |