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# Power Plant Maintenance Scheduling using Dependency Structure Matrix and Evolutionary Optimization

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*Abstract*—**With the growth of demand for electrical energy, it is a common practice in the power industry to shorten the maintenance duration and often to postpone maintenance tasks. Maintenance or overhaul of generating units is one of the crucial factors in delivering reliable electrical energy. A large part of the overhaul work is to examine the condition of the mechanical and the electrical elements. This examination can highlight faults in some components requiring management of new activities. This paper presents a method using a dependency structure matrix for managing schedules within uncertain conditions of information dependency. The matrix is optimized using an evolutionary algorithm for scheduling overhaul and planned outages at hydro power plants. The dependency between tasks or the information flow between activities is formulated in a structural matrix with the objective to minimize the total completion time. The method is used to examine the staff scheduling of a twelve years overhaul at one of Landsvirkjun's hydro power units. Staff scheduling or rostering is a large scale constrained optimization problem. Using the Dependency Structure Matrix (DSM) and evolutionary methods (GA) to optimize the order of activities shows improvements in the overhaul operational plan.**

*Index Terms*—**Maintenance, optimization, outage, staff scheduling, dependency structure matrix.**

## I. Introduction

ICELAND as the world's largest electricity producer per capita, generates 99% of its energy from hydroelectric and geothermal sources. Landsvirkjun, the largest power company in Iceland, operates 16 power stations all over the country. Installed capacity is 2.1 GW produced by 38 hydro turbines and 5 steam turbines. At Landsvirkjun, preventive maintenance is planned as a comprehensive overhaul every 12 years. The outages process is both costly and time consuming due to its number of activities, equipment, spare parts, teams or staff with different skills and experience, and the dependency relationship between tasks and activities.

This paper describes a hybrid method using an evolutionary algorithm for optimizing a Dependency Structure Matrix (DSM) that includes activities or tasks for a 12 years overhaul of a hydro turbine at Hrauneyjarfoss power station. Conventional project management tools like Gantt charts, CPM and PERT are often used for planning overhaul projects by graphic representations of task flows. These tools can model both dependent and independent tasks in time but are not used to analyze the dependency between tasks or the information flow between activities. In this paper, the dependency of activities and the information flow is used to schedule jobs with the objective to minimize the total completion time and the total cost. A large part of the overhaul work is to examine the condition of the mechanical and the electrical elements. This examination can highlight faults in some components requiring management of new activities. Due to dependences and relations between activities, the approach discussed in this paper uses a Dependency Structure Matrix (DSM) in order to minimize the total outages time and the overhaul cost.

Maintenance management has been the subject of many articles during the last decades, where thorough discussion on maintenance optimization models, maintenance techniques, scheduling, performance models, information systems and policies can be found [1]. The maintenance techniques can be classified as preventive maintenance, condition based, total productivity (TPM), reliability centered (RCM), computerized management systems (CMMS), predictive maintenance, outsourcing, effectiveness centered maintenance, and strategic and risk based maintenance [2]. Many different approaches for measuring maintenance performance have also been discussed in various papers [3]. Maintenance scheduling is another interesting area that needs more investigation [4]. The stochastic nature of the maintenance work makes it a challenging problem and distinguishes it from many production scheduling.

The Design or Dependency Structure Matrix (DSM) methodology is widely known and has been used to handle dependences and relations between activities for large design projects. It's a compact, matrix representation of a project and it has been used for representing and analyzing information flow as well as to analyze development projects modeled at the task level. The method was originally developed by Donald V. Steward in 1981 [5] but it was not until in the 1990s that it received wide spread attention, due to MIT's research in the design process modeling arena [6].

Evolutionary algorithms are population based metaheuristic optimization algorithms which use principles of biological evolution, such as reproduction, mutation, recombination and natural selection, to search for optimal solutions. It has been shown, by many authors, that a GA is an efficient and a robust technique that can be applied to both continuous and discrete optimization problems. The main advantages of a GA in the present study are their efficiency and robustness and their ability to operate on mixed integer-order based problems.

The Dependency Structure Matrix is described in section II and Evolutionary Algorithm in section . In section IV, the maintenance procedure for a hydro turbine power unit is

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explained and the results are presented in section V. The paper concludes with a general discussion and a summary.

## II. DEPENDENCY STRUCTURE MATRIX

Managing hydro turbine overhauls involves a determination of many interdependent activities which together define a project plan. The precedence order of the tasks and the information flow between these activities require coupling because some of the tasks can not be determined unless information from other tasks are first known or assumed.

Conventional planning techniques do not handle the circuits inherent in the project planning but the Dependnecy Structure Matrix (DSM) is a useful tool to develop an effective project plan showing how these iterations are handled, where estimates are to be used as well as showing the information flow during the work. The matrix contains a list of all constituent activities and the corresponding information exchange patterns. In a DSM model, each project task is defined by a row of a matrix and a corresponding identically ordered column. The task's dependencies are represented by placing marks in that particular row in the corresponding columns to indicate the other tasks (columns) on which it depends. Therefore, reading across a row for a specific task reveals all of the tasks whose output is required to perform the task corresponding to that row. Similarily, reading down a column reveals which tasks receive information from the task in that column. Fig. 1 shows an example of a DSM with sequential, parallel and coupled tasks.

The design structure matrix in Fig. 1 shows two marks in row D; in column B and column C. Thus, according to the matrix the output or information from tasks B and C is required to perform task D. Then, task A transfers information to tasks E and F since column A has marks in those rows.

The matrix in Fig. 2 , shows three basic building blocks for describing the relationship among the tasks: parallel (or concurrent), sequential (or dependent) and coupled (or interdependent). In order to improve the maintenance process, the activities in the matrix are reordered and the same reordering is made of the rows and columns. The objective is to reorder the activities so that the matrix is lower triangular, i.e., all marks are either on or below the diagonal. Then, proceeding in this order, the acivities could be determined one at a time. As each activity is determined, all its required predecessors would be to the left of the diagonal and thus already known. The following algorithm can be used to sequence the tasks [6]:

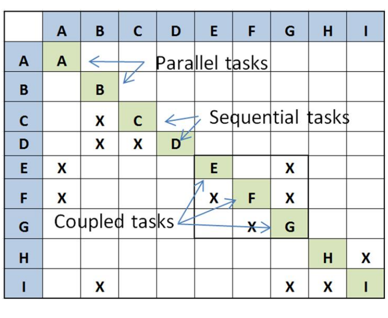


Fig. 1. Dependency structure matrix with sequential, parallel and coupled tasks.

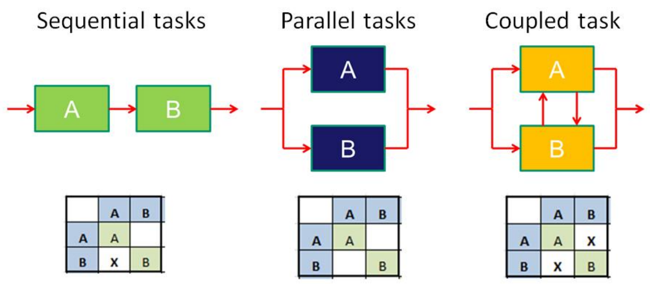


Fig. 2. Basic building blocks descriping the relationship among tasks.

1) All empty rows are moved to the top.
2) All empty columns are moved to the end.
3) All loops are collapsed and scheduled as above.
4) Steps 1)-3) are repeated until all tasks and loops are sequenced.

This kind of reordering is unfortunately rarely possible due to the coupling of activities. However, the tasks can be reordered by a process known as partitioning, so as to confine the marks in the matrix to appear either below the diagonal or within square blocks on the diagonal. All the tasks that occur in a circuit will then be found in the same block and the blocks represent all the smallest sets of tasks that must be determined jointly.

Once the blocks are found, they are sequenced by the following algorithm [7]:

1) A block which no variable has a predecessor in another unnumbered block is found.
2) The block is assigned the next number.
3) Points 1) and 2) are repeated until all blocks are numbered.

This process is used to order the blocks but the relative ordering of the variables within each block is arbitrary. The order of the activities affects the marks, which are above the diagonal and show where estimates are required to start an iteration. A process known as tearing can be used to choose a set of marks representing where estimates might be made, to obtain an ordering so that the marks represent reasonable estimates. Then, when having made these estimates, no additional estimates should need to be made [8]. Thus, when marks that have been chosen from the block have been removed and the block has been reordered

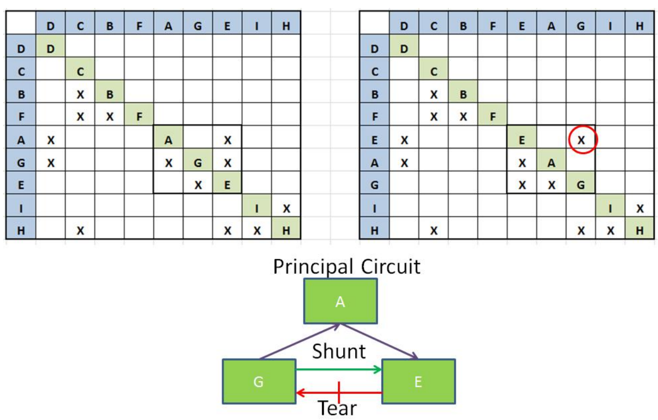


Fig. 3. Reordered DSM and tearing.

by partitioning, no marks should appear above the diagonal. Fig. 3 shows an example of tearing. The square with tasks A, G and E in Fig. 3 shows a block with circuits where task A requires information from task E, task G requires information from tasks A and E, and task E needs output from task G. There are two circuits, one between G and E, and another one between A, G and E. In order to break both of the circuits, tearing is performed between G and E, which results in a lower triangular matrix. The block that is reordered without the marks removed is called the reduced block and the removed marks are called tears. The block with the tear marks restored is called the torn block, and if the reduced block is lower triangular, the torn block has only tear marks above the diagonal. Thus, every circuit contains a mark that is torn and the reduced matrix has no circuit. When tearing, the first choice of marks to tear are the predecessors that already have been well estimated or can be poorly estimated without significantly affecting the variables they precede. The choices are given numbers where high numbers indicate the better places to tear and lower numbers indicate where estimates are harder to make. The marks with the highest level number are torn first, then the variables are reordered in the block by partitioning, and then the marks with the next higher level numbers are torn [9]. Once the estimates are made of how many times each block is to be iterated and how long the tasks are to take in each iteration, a critical path schedule can be developed [10].

Numerical DSMs contains an attributes that provide information on the relationships between the different elements of the system such as the overlapping ratio of the duration time [11]. The duration of each activity is also included as the diagonal cell of the matrix. The dependency structure matrix methodology provides therefore a representation of the schedule that can be optimized using evolutionary methods.

## III. EVOLUTIONARY ALGORITHM

It has been shown, by many authors, that a GA is an efficient and a robust technique that can be applied to both continuous and discrete optimization problems. The main advantages of a GA in the present study are their efficiency and robustness and the ability to operate on mixed integer-order based problems. Genetic algorithms have been widely used to solve or optimize scheduling problems. These GA methods vary in their representation or encoding schemes, the genetic operators, and methods for solution evaluation. The method, maintain a population of encoded tentative solutions that are manipulated by applying some variation operators in the search of global optimum. A general GA goes as follows,

1) Initial generation chosen randomly
2) Individuals in the initial generation evaluated
3) For number of generations
    (a) The fittest individuals chosen
    (b) Crossover
    (c) Mutation
    (d) All individuals in the generation evaluated
4) Results

GA individuals store the decision variables in a coded representation. The decision variables coded as integer are the order of tasks and the assignment of staff to tasks. The tournament selection is a widely used selection method for GA where a number of n-individuals is chosen randomly from the population and the best individual from the group is copied to the intermediate population. This is repeated as often as the number of individuals in a generation. The size n is called the tournament size. Increasing the tournament size results in loss of diversity and increasing selection intensity [6]. Genetic Algorithms implicitly maintain statistics about the search space through the population. It has been proposed to use this implicit statistics to explicitly enhance GA's performance. Inspired by this idea a statistics based non-uniform crossover method has been proposed

In order to get a good coverage of the search space random bits in the resulting individuals from the crossover are mutated with a probability of pm. Low mutation rate speeds up convergence but increases the risk of the algorithm getting stuck in a local minimum, whereas high mutation rate works in the opposite direction.

## IV. HYDRO TURBINES OVERHAULS AND OUTAGES

The first step in the overhauls and outages of hydro turbines is the management process. The outage is planned and each activity is scheduled. Here the DSM is used as a managing tool for preliminary analysis. In this formulation the maintenance supervisor (P) is also a planner and a scheduler. The supervisor manages a group of staff and contractors with different skills and experiences. The group consists of mechanics (M), electricians (E), and workmen (W). The type of work that is performed can be defined as, Planning (P), Controlling (C), Dismantling (D), Inspection (I), Cleaning (L), Testing (T), Repairing (R) and Reassembling (A) as shown in Table II. After the planning, scheduling and staffing process, the safety and environmental issues are considered.

The planned overhaul usually begins with a visual inspection before the shutdown. First, the condition of the foundation, anchor bolts, piping, flanges and valves is examined. Also, before the dewatering process the leakage is checked at accessible areas, for example at the main valve, the penstock and the turbine. Then, the safety and environmental programs and standards are listed for each maintenance unit. The main units are shown in Fig. 4 and listed in Table I. For each unit, there are a number of tasks to perform and each task has a resource requirement as shown in Table II.

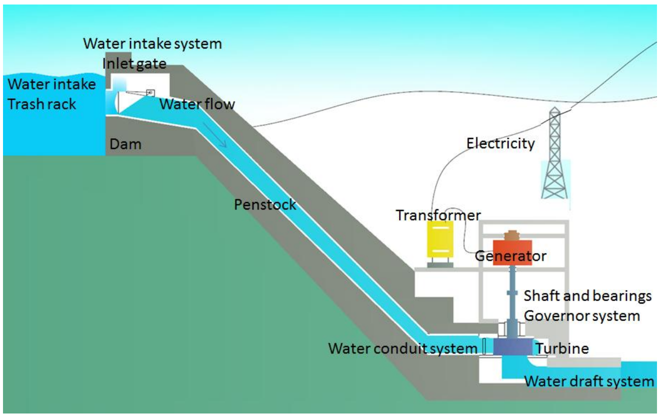


Fig. 4. Hydro Power Plant.

At the water intake for the power plant there is a trash rack and an inlet gate. The gate is used for cutting off the water supply to the turbine when the unit is shut-down and dewatering is required to permit access for maintenance of the connecting penstocks. The intake has a motor lifted, gravity lowered gate and valve, with an automatic release operated by an excess flow device if a burst occurs in a pipe line. Main inlet valves at the turbine are opened by an oil servomotor. The penstock and the inlet valve system are defined as the water conduit system. From the inlet valve the water flows in Francis turbines through the spiral case, stay vain and wicket gates to the runner. The governor is the speed/load control of the turbine and the main controller in which it adjusts, by guide vanes and wicket gate, the flow of water through the turbine to balance the input power with the load. From the runner, the water flows through the water draft system. The turbine is connected to the generator with a shaft that has one thrust bearing, two guide bearings on each side of the generator and the turbine bearing. The main parts of the generator are the stator, rotor and excitation system. From the generator, the electricity is transmitted through the generator terminal and breakers to the unit transformer.

## V. RESULTS

The case studied here is the Hrauneyjarfoss power plant unit 1 and the total workload for this overhaul project is estimated as 1672 man-hours, as shown in Table I. The planner or supervisor uses 8 to complete his part, based on an eight hour work day, but a team of mechanics, electricians and workmen are assigned to each task as shown in Table II. Allowable resources are one planner that is assigned to all tasks, seven mechanics, seven electrician and three workmen.

The order of activities and the dependencies between activities for main maintenance units are shown in Table III. This permutation is based on best practice and is the same as the order of the work previously performed and Fig. 5 shows Gantt charts with couplings between activities. The make span is 30 days and the staff includes 6 mechanics, 6 electrician and 2 workmen. The outages are planned from day 5 and will last for 25 days.

The dependencies rules are used as discussed in chapter II, to sequence the tasks and the activities. The activities are reordered by the following partitioning process:

1) All empty rows are moved to the top.
2) All empty columns are moved to the end.
3) All loops are collapsed and scheduled as above.
4) Steps 1)-3) are repeated until all tasks and loops are sequenced.

Table IV, shows the dependency structure matrix after the partitioning process. At least four blocks need to be considered. The first block is the switchgear and the transformer system, the next one is the draft and the turbine system and then it is the water intake and the conduit system. The last block is the auxiliary, the hydro generator and the shaft bearings system. The blocks are are sequenced by the following algorithm:

1) A block which no variable has a predecessor in another unnumbered block is found.
2) The block is assigned the next number.
3) Points 1) and 2) are repeated until all blocks are numbered.

TABLE I
TASKS ASSIGNED TO EACH ACTIVITY, TYPE OF WORK AND ESTIMATED WORKLOAD ON DIFFERENT SKILLS

| Activities: | Tasks: | ID | # | Type | Total | P | M | E | W |
|---|---|---|---|---|---|---|---|---|---|
| Managing Process: | Safety and preparatory planning | MP | 1 | P | 16 | 16 | | | |
| | Safety and enviromental control | MP | 2 | PC | 16 | 8 | 4 | 4 | |
| | Shutdown and dewatering process | MP | 3 | PC | 14 | 6 | 4 | 4 | |
| | | SUM | | | 46 | 30 | 8 | 8 | 0 |
| Water Intake System: | Safety and preparatory work | WI | 1 | PCL | 44 | 2 | 6 | 6 | 30 |
| | Trash rack and inlet gates | WI | 2 | ITRC | 86 | | 48 | 38 | |
| | Hydraulic system and control unit | WI | 3 | ITR | 50 | | 20 | 30 | |
| | Bracket, foundation and pensock | WI | 4 | IT | 24 | | 12 | 8 | 4 |
| | | SUM | | | 204 | 2 | 86 | 82 | 34 |
| Water Conduit System: | Safety and preparatory work | WC | 1 | PCL | 6 | 2 | 2 | 2 | |
| | Pensock and inlet valve | WC | 2 | IT | 4 | | 2 | 2 | |
| | Inlet valve control and hydraulic system | WC | 3 | IT | 4 | | 2 | 2 | |
| | | SUM | | | 14 | 2 | 6 | 6 | 0 |
| Turbine System: | Safety and preparatory work | TS | 1 | PCL | 84 | 4 | 20 | 20 | 40 |
| | Head cover, spiral case and stay vain | TS | 2 | AIT | 24 | | 12 | 12 | |
| | Turbine runner, wicket gate and packing | TS | 3 | IT | 80 | | 40 | 40 | |
| | Control system | TS | 4 | IT | 12 | | 6 | 6 | |
| | Frame and foundation | TS | 5 | IT | 8 | | 4 | 4 | |
| | | SUM | | | 208 | 4 | 82 | 82 | 40 |
| Draft System: | Safety and preparatory work | DS | 1 | PCL | 2 | | 2 | | |
| | Draft tube and gate | DS | 2 | IT | 4 | | 4 | | |
| | | SUM | | | 6 | 0 | 6 | 0 | 0 |
| Shaft and Bearings: | Safety and preparatory work | SB | 1 | PCL | 8 | 4 | 2 | 2 | |
| | Upper guide bearing | SB | 2 | DIL | 30 | | 18 | 12 | |
| | Middle guide and thrust bearing | SB | 3 | DIL | 34 | | 20 | 14 | |
| | Turbine bearing | SB | 4 | DIL | 26 | | 16 | 10 | |
| | Guide and turbine bearing oil system | SB | 5 | IT | 40 | | 20 | 20 | |
| | Thrust bearing oil system | SB | 6 | DIL | 12 | | 6 | 6 | |
| | Shaft and flange coupling | SB | 7 | IT | 8 | | 6 | 2 | |
| | | SUM | | | 158 | 4 | 88 | 66 | 0 |
| Governor System: | Safety and preparatory work | GO | 1 | PC | 16 | 4 | 4 | 2 | 6 |
| | Wicket gate mechanism and servomotor | GO | 2 | IT | 30 | | 20 | 10 | |
| | Wicket hydraulic and control system | GO | 3 | ITL | 96 | | 46 | 50 | |
| | | SUM | | | 142 | 4 | 70 | 62 | 6 |
| Hydro Generator: | Safety and preparatory work | HG | 1 | PCL | 34 | 8 | 8 | 8 | 10 |
| | Stator and rotor | HG | 2 | TIL | 326 | | 142 | 142 | 42 |
| | Excitation Automatic Voltage Regulator | HG | 3 | TI | 16 | | 8 | 8 | |
| | Brushes and split-ring commutator | HG | 4 | DR | 34 | | 10 | 8 | 16 |
| | Aircooler | HG | 5 | IT | 216 | | 90 | 90 | 36 |
| | Breaking and jacking system | HG | 6 | IT | 26 | | 14 | 12 | |
| | Frame and foundation | HG | 7 | I | 8 | | 4 | 4 | |
| | | SUM | | | 660 | 8 | 276 | 272 | 104 |
| Switchgears and Breakers: | Safety and preparatory work | SG | 1 | PC | 6 | 2 | 2 | 2 | |
| | Generator terminal and breakers | SG | 2 | I | 42 | | 16 | 26 | |
| | High voltage room and control system | SG | 3 | IT | 22 | | 10 | 12 | |
| | | SUM | | | 70 | 2 | 28 | 40 | 0 |
| Unit Transformer: | Safety, preparatory and finishing work | UT | 1 | PCL | 26 | 2 | 2 | 2 | 20 |
| | Pollution prevention and safety system | UT | 2 | TC | 4 | | 2 | 2 | |
| | Transformer oil and cooling system | UT | 3 | ITR | 10 | | 4 | 6 | |
| | Switchgear, control and protection system | UT | 4 | IT | 16 | | 8 | 8 | |
| | Frame and foundation | UT | 5 | I | 8 | | 4 | 4 | |
| | | SUM | | | 64 | 2 | 20 | 22 | 20 |
| Auxiliary Systems: | Cooling water river system | AS | 1 | IT | 100 | 4 | 46 | 46 | 4 |
| | Compressors | AS | 2 | IT | | | 8 | 8 | |
| | | SUM | | | 100 | 4 | 54 | 54 | 4 |
| | | | | | | | | | |
| | | | | | 1672 | 62 | 724 | 694 | 208 |

TABLE II
MAINTENANCE UNITS AND ESTIMATED MAN-HOURS

| Unit no | Maintenance units | | Estimated man-hour for 12 years overhaul | | | | Staff | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Planner | Mechanics | Electrician | Workman | Mechanics | Electrician | Workman | Days |
| 1 | Managing Process: | MP | 30 | 8 | 8 | 0 | 1 | 1 | 0 | 3,8 |
| 2 | Water Intake System: | WI | 2 | 86 | 82 | 34 | 1 | 1 | 0 | 5,0 |
| 3 | Water Conduit System: | WC | 2 | 6 | 6 | 0 | 1 | 1 | 1 | 2,8 |
| 4 | Turbine System: | TS | 4 | 82 | 82 | 40 | 3 | 3 | 2 | 11,5 |
| 5 | Draft System: | DS | 0 | 6 | 0 | 0 | 1 | 1 | 0 | 8,8 |
| 6 | Shaft and Bearings: | SB | 4 | 88 | 66 | 0 | 1 | 1 | 0 | 11,0 |
| 7 | Governor System: | GO | 4 | 70 | 62 | 6 | 1 | 1 | 1 | 0,8 |
| 8 | Hydro Generator: | HG | 8 | 276 | 272 | 104 | 2 | 2 | 1 | 3,4 |
| 9 | Switchgears, Breakers: | SG | 2 | 28 | 40 | 0 | 2 | 2 | 0 | 5,1 |
| 10 | Unit Transformer: | UT | 2 | 20 | 22 | 20 | 1 | 1 | 1 | 0,8 |
| 11 | Auxiliary Systems: | AS | 4 | 54 | 54 | 4 | 2 | 2 | 0 | 5,4 |
| | Total (man-hours): | | 62 | 724 | 694 | 208 | | | | |
| | Total (man-days): | | 8 | 91 | 87 | 26 | | | | |

By using tearing, the dependency structure matrix can be decoupled and solved or optimized seperately. The main objective is to reduce the tasks above the diagonal and to reduce the distance from the diagonal to the tasks above it. The order of activities was changed as shown in Table IV. The most notable changes are the connections of the four iteration blocks in the matrix. Tearing is performed for one connection as shown with a red mark in the table and the total distance for coupling of activities above the digonal of the matrix

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TABLE III
DEPENDENCY STRUCTURE MATRIX PRIOR TO SEQUENCING AND PARTITIONING PROCESS.

| Maintenance units | | | 1 MP | 2 WI | 3 WC | 4 TS | 5 DS | 6 SB | 7 GO | 8 HG | 9 SG | 10 UT | 11 AS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Managing Process: | MP | 46 | | | | | | | | | | |
| 2 | Water Intake System: | WI | X | 204 | X | | | | | | | | |
| 3 | Water Conduit System: | WC | X | X | 14 | X | | | X | | | | X |
| 4 | Turbine System: | TS | X | | X | 208 | X | X | X | X | | | X |
| 5 | Draft System: | DS | X | | | X | 6 | X | | | | | |
| 6 | Shaft and Bearings: | SB | X | | | X | | 158 | X | X | | | |
| 7 | Governor System: | GO | X | | | X | | X | 142 | X | | | |
| 8 | Hydro Generator: | HG | X | | | | | X | X | 660 | X | | |
| 9 | Switchgears and Breakers: | SG | X | | | | | | | X | 70 | X | |
| 10 | Unit Transformer: | UT | X | | | | | | | X | X | 64 | |
| 11 | Auxiliary Systems: | AS | X | | X | X | | X | | X | | | 116 |

| Task | Days 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MP | MP | MP | MP | MP | MP | | | | | | | | | | | | | | | | | | | | | | | | | |
| WI | | | | | | WI | WI | WI | WI | WI | WI | | | | | | | | | | | | | | | | | | | |
| WC | | | | | | WC | WC | | | | | | | | | | | | | | | | | | | | | | | |
| TS | | | | | | | | | | | | TS | TS | TS | TS | TS | TS | | | | | | | | | | | | | |
| DS | | | | | | | | | | | | DS | DS | | | | | | | | | | | | | | | | | |
| SB | | | | | | | | | | | | | | SB | SB | SB | SB | SB | SB | SB | SB | SB | SB | SB | SB | | | | | |
| GO | | | | | | | | | | | | | | GO | GO | GO | GO | GO | GO | GO | GO | GO | GO | | | | | | | |
| HG | | | | | | | | | | | | | | | | | | HG | HG | HG | HG | HG | HG | HG | HG | HG | HG | HG | HG | HG |
| SG | | | | | | | | | | | | | | | | | | SG | SG | SG | SG | SG | SG | | | | | | | |
| UT | | | | | | | | | | | | | | | | | | | | | | | | UT | UT | UT | UT | | | |
| AS | | | | | | | | | | | | AS | AS | AS | AS | | | | | | | | | | | | | | | |
| Staff | 1 | 1 | 1 | 1 | 2 | 7 | 7 | 4 | 4 | 4 | 4 | 12 | 12 | 13 | 13 | 8 | 8 | 14 | 14 | 14 | 14 | 14 | 14 | 13 | 13 | 11 | 11 | 8 | 8 | 8 |

Fig. 5. Gantt chart for schedule based on dependency structure matrix in Table III.

TABLE IV
DEPENDENCY STRUCTURE MATRIX AFTER SEQUENCING AND PARTITIONING PROCESS.

| Maintenance units | | | 1 MP | 9 SG | 10 UT | 8 HG | 7 GO | 6 SB | 5 DS | 11 AS | 4 TS | 3 WC | 2 WI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Managing Process: | MP | 46 | | | | | | | | | | |
| 9 | Switchgears and Breakers: | SG | X | 70 | X | | | | | | | | |
| 10 | Unit Transformer: | UT | X | X | 64 | X | | | | | | | |
| 8 | Hydro Generator: | HG | X | X | | 660 | X | X | | | | | |
| 7 | Governor System: | GO | X | | | X | 142 | X | | | X | | |
| 6 | Shaft and Bearings: | SB | X | | | X | X | 158 | | | X | | |
| 5 | Draft System: | DS | X | | | | | X | 6 | | X | | |
| 11 | Auxiliary Systems: | AS | X | | | X | | X | | 116 | X | X | |
| 4 | Turbine System: | TS | X | | | X | X | X | X | X | 208 | X | |
| 3 | Water Conduit System: | WC | X | | | | X | | | X | X | 14 | X |
| 2 | Water Intake System: | WI | X | | | | | | | | | X | 204 |

| Task | Days 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MP | MP | MP | MP | MP | MP | | | | | | | | | | | | | | | | | | | |
| SG | | | | | | SG | SG | SG | SG | SG | SG | | | | | | | | | | | | | |
| UT | | | | | | UT | UT | UT | UT | | | | | | | | | | | | | | | |
| HG | | | | | | HG | HG | HG | HG | HG | HG | HG | HG | HG | HG | HG | HG | HG | | | | | | |
| GO | | | | | | GO | GO | GO | GO | GO | GO | GO | GO | GO | GO | | | | | | | | | |
| SB | | | | | | | | | | SB | SB | SB | SB | SB | SB | SB | SB | SB | SB | SB | SB | | | |
| DS | | | | | | | | | | | | | | | | | | | | | | DS | DS | |
| AS | | | | | | | | | | | | | | | | AS | AS | AS | AS | | | | | |
| TS | | | | | | | | | | | | | | | | | | | TS | TS | TS | TS | TS | TS |
| WC | | | | | | | | | | | | | | | | | | | | | | WC | WC | |
| WI | | | | | | | | | | | | | | | | | | | WI | WI | WI | WI | WI | WI |
| Staff | 1 | 1 | 1 | 1 | 2 | 15 | 15 | 15 | 15 | 14 | 14 | 12 | 12 | 12 | 12 | 15 | 15 | 15 | 15 | 10 | 10 | 14 | 14 | 8 |

Fig. 6. Gantt chart for schedule based on dependency structure matrix in Table IV.

is reduced. When the blocks are coupled, the efficiency of the maintenance team can be increased, reducing the total makespan of the work outages and shortening the outages as shown in Fig. . By using these blocks and adding one workman to the staff the make span reduce to 24 days as shown in Fig. . The outages last for 19 days and the total period of the 12 years overhaul has been reduced without increasing the cost.

## VI. CONCLUSION

This paper introduces a novel approach for designing a planning and a scheduling methodology using a Dependency Structure Matrix (DSM). The method was successfully tested by scheduling a 12 years overhaul and outages for a hydro turbine at Landsvirkjun power plant in Iceland. One of the premises for a successful use of the DSM methodology is that the data used is of high quality, i.e. the task breakdown has a reasonable granularity and that the relationships of these tasks is known with a high level of certainty. The data used to create the matrix for this project did not fully meet these requirements. Although a large part of the tasks have sufficient granularity and their relationships with other tasks is known, other tasks lack these important properties.

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