Analysis of NATM tunneling method using CYCLONE modeling and simulation tools

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Abstract. The NATM or New Austrian Tunneling Method became a popular method for tunneling in Indonesia recently, since at least two strategic and huge construction projects utilized it. It is considered as a new method introduced to the Indonesian construction industry and therefore it is interesting to be studied and anticipated for the implementation. This paper discusses modeling the operation of the NATM and then simulation of the model for finding the productivity, effectiveness, and problems that may come in the implementation. The CYCLONE modeling and three simulation tools, i.e., WebCYCLONE, COST, and Symphony.Net, were utilized for this purpose. Data used for durations of tasks associated with the method were gathered from previous work in the field of different projects and literature. The results of this analysis then compared to other similar analyses but for a different project. A comparison of those two analyses was used to identify the most important tasks that will determine the performance of the method with a safety-first requirement in mind. The sensitivity analysis identified secondary resources such as a concrete wet sprayer; the shotcrete team and the formwork team are considered sensitive to improve the performance of the NATM.

1. Introduction
The development of science and technology in all aspects of the scientific field is a continuous process. Technological developments in the construction sector will contribute directly to the performance of a work operation in the project, where the objectives can be achieved with optimal conditions. The optimal condition means each resource, the existing constraints, and their objectives can be well controlled according to their purpose and are effective. Productivity is important in construction activities, which will have a direct impact on the final cost of project completion. Important control activities in construction operations to achieve expected effectiveness and efficiency, control efforts can be carried out by operating simulation activities designed in such a way as to be able to describe the real conditions in the field.

The object of this study is a tunnel section with a diameter of 12-14 meters, as some segment of the overall project that will be used by the transportation fleet. A mega project of the railway with the total investment in this project amounted above 50 trillion rupiahs, a slight delay would potentially result in...
a large cost overrun, which need to be avoided. In infrastructure projects in Indonesia, tunneling is still rarely found while in this overall project the portion of tunnel work is 15.23% of the total project length, therefore thorough planning was required. Tunneling is a complex job with high uncertainty such as soil conditions that are at risk of erosion while vertical digging is being done. Although tunneling is complex, the operation can be repetitive so that the modeling simulations can be carried out. The construction method used is the New Austrian Tunneling Method. Cyclone modeling is used for the construction operations modeling in this study and the simulations are conducted with the help of three simulation tools, namely WebCYCLONE, COST, and Simphony.NET.

The purposes of this research are to develop tunneling simulation models in tunnels that are part of the train project, analyze the productivity of the tunneling method used based on the model that has been made, compare the simulation results which is the productivity of tunnel construction operation to the previous research on the construction operation of Cisumdawu toll road tunnel and last but not least is to determine the effect of resource variations on the modeled productivity system.

1.1. New Austrian tunneling method

New Austrian Tunneling Method (NATM) is a method developed to make tunnel construction, especially for tunnels made in soft soil conditions. Soft soil categories are lands that require the use of structural support, either to maintain balance or to limit the displacement of land around the tunnel construction area. The purpose of the NATM method is to provide safe and economical support for tunnels where the type of soil unable to support their own weights - for example, crushed rocks, debris, and even soil. Structural support can be obtained by mobilizing any strength with hard rock equivalent strength. This structural support can be obtained by using surface stabilization such as thin shotcrete layers and other reinforcement for example steel rib, inverted arch lining, and so on [1].

![Figure 1. Tunnel excavation.](image1)

![Figure 2. Division of tunnel section.](image2)

1.2. Modeling of construction operation

Models are representations of real situations. The purpose of modeling a construction process is to find out more about the actual situation of a construction process occurring in the field by analyzing and investigating. Basics symbols of cyclic operations network systems modeling developed from the [2] as in table 1. The procedure in modeling the construction process involves four basic steps [2], namely:

- Identify the resource flow, at this stage a number of resources are related to the implementation of the construction operation. Related resources include workers, equipment, materials, workspace, and access to information;
- Develop the cycle of resource flow, develop each of the stage’s cycle which includes several type and number of resources;
- Integrate the flow unit cycle, each cycle that represents each stage of the work is then integrated into a system that describes the stages of the overall operation;
Flow unit Initiation, to analyze the model made, each flow unit needs to be named and numbered in the logical sequence.

### Table 1. Basic elements of CYCLONE modeling [2].

| No | Symbol | Name       | Description                                                                 |
|----|--------|------------|-----------------------------------------------------------------------------|
| 1  | ![Normal Activity (NORMAL)](image) | Normal Activity (NORMAL) | The normal work task modeling element, which is unconstrained in its starting logic and indicates active processing of (or by) resource entities |
| 2  | ![Combination Activity (COMBI)](image) | Combination Activity (COMBI) | The constrained work task modeling element, which is logically constrained in its starting logic, otherwise similar to the normal work task modeling element |
| 3  | ![Queue Node (QUEUE)](image) | Queue Node (QUEUE) | The idle state of a resource entity symbolically representing a queueing up or waiting for use of passive state of resources |
| 4  | ![Accumulator (COUNTER)](image) | Accumulator (COUNTER) | The countermeasures the modeled system’s production rate |
| 5  | ![Arrows](image) | Arcs | The resource entity directional flow modeling element |

Besides, the model developed must be modified to provide control for system performance. Simulations in construction operations are needed to provide information on work performance with existing conditions.

### 1.3. Simulation of construction operation

Simulation is a modeling of a process or system to mimic the original system of events that occur at a certain time [3]. Simulation is done to determine the condition of the system, to determine the system response and the imbalance between resources. This imbalance can have an impact on bottlenecks and inefficiencies that must be avoided or minimized [2]. The steps taken in conducting the simulation are: defining the system, modeling the system, analyzing input and output, as well as validation and verification.

Based on the previous study [4], the development of simulation techniques for repetitive construction operations has been going on for a long time, namely since the 1970s where Daniel W. Halpin developed CYCLONE modeling. Until now, a web-based simulation technique has been developed called WebCYCLONE. Some simulation techniques for repetitive construction operations that have been developed are Insight (Kalk 1980), RESQUE (Chang 1986), UM-CYCLONE (Loannou 1989), MicroCYCLONE (Halpin 1990), COOPS (Liu 1990), CIPROS (Odeh et al. 1992), DISCO (Huang 1994), STROBOSCOPE (Martinez 1996), SIMPHONY (AbouRizk and Mohamed 2000), COST (Cheng et al. 2000), RISim (Chua and Li 2002), and WebCYCLONE (Halpin et al. 2003).

In this study, three soft wares are used in the simulation, namely WebCYCLONE, COST, and Simphony.NET. The use of each software is quite different in terms of input and output data. In WebCYCLONE, the users must input the model in a particular programming language, while in COST, input data is a parameter of each element in the model. Unlike the two soft wares mentioned earlier, Simphony.NET uses input data in the form of images so that the result is easier to see. Apart from being
different in terms of inputting data, the output given by these three softwares is also different, table 2 shows the comparative output of each software.

| Table 2. The comparative output of each softwares. |
|-----------------------------------------------|
| Output                                       | Web Cyclone | COST | Symphony.NET |
| Productivity graph                           | ✓            | ✓    | ✓             |
| Event list                                   | ✓            | ✓    | ✓             |
| Chronological list                           | ✓            | ✓    | ✓             |
| Productivity per time unit                   | ✓            | ✓    | ✓             |
| Trace chart/ Time chart for every que         | ✓            | ✓    | ✓             |
| % que occupied                               | ✓            | ✓    | ✓             |
| Waiting time for que                         | ✓            | ✓    | ✓             |
| % occupied graph for que                     | ✓            |     |               |
| % busy graph for normal & combi              | ✓            |     |               |
| Emission report                              | ✓            |     |               |
| Cost report                                  | ✓            | ✓    |               |
| Histogram and CDF for each element           | ✓            |     |               |

2. Methodology
The methodology begins with conducting a preliminary study of the construction operations in a project. This preliminary process is carried out to see how repetitive operating processes in construction projects can be examined using Cyclone modeling to obtain productivity values with work tasks and available resources. Then a literature study was conducted regarding the use of NATM (New Austrian Tunneling Method) in tunnel construction operations, and identifying the objectives of the research, followed by field observations for tunneling projects and collecting data in the form of interviews with parties who carry out operations in the field. The data is also obtained by analyzing the simulation video of the work made by the contractor. To complete the simulation, secondary data from the previous studies [4] are used to cover the data that could not be obtained from the construction project.

The study was continued by using the data obtained to make the Cyclone model using work tasks that have a significant influence on tunneling operations, along with data on the number of resources and the duration that has been obtained during data collection. The model will be run using Webcyclone, COST, and Symphony.NET software, if there is a failure in running the model, the model will be made to re-check the existing model. The use of three softwares is intended to obtain results that can be compared between one software with another software.

The results of the simulation will be analyzed regarding the value of productivity which will then be compared with previous studies which will then be analyzed for the causes of the differences. The next step is sensitivity analysis, sensitivity analysis is used to compare several possible uses of resources with different amounts and then will produce a number of different productivity results with the same operating cycle, those results then will be considered as suggestions for the most efficient use of resources. All results of analysis then used as a basis for making conclusions and recommendations.

3. Results and discussion
Construction operation can be defined as a collection of specific work tasks, where work tasks are the basic elements of work, each work task will be related to the technology and tools that support it and the resources involved in it [2]. The simulation model is intended to be able to describe the real conditions, it is expected that by modeling the results of the output values achieved will be close to the real output results in the field. Simulations can describe resources that will move from one work task to another in accordance with the task definition of each resource. Identification of resources, elements of
the work task, and how the flow of resources between work tasks is the basic rational modeling that is carried out.

3.1. Work task and duration identification
The work task is a readily identifiable component of a construction process or operation whose description to a crew member implies what is involved in and required [2], thus work task identification in the model is the selection of work groupings that have significant value-added to the progress of the work. The duration of each work task affects the work task productivity value. There are two types of duration distributions in each work task in the study. The first type is a uniform distribution, where each value of the random variable has the same probability to be selected and the type of triangular distribution is a continuous opportunity distribution with 3 parameters, they are minimum value, most likely value, and maximum value, respectively.

Table 3 shows a list of work tasks in tunneling operations that are reviewed and their respective durations, the duration of which comes from a previous study [5,6] regarding tunneling on the Cisumdawu Toll Road project with adjustments. The assumption for the duration is the length of time needed to complete the work until the secondary lining for 10.5 meters has finished, thus defined as one operating cycle.

3.2. Identification of resource needs
Resource requirements used in tunnel work activities are Drilling Machine, Pneumatic Drill, Anchor Pump, Excavator, Loader, Dump Truck, Labor (work team), Concrete Wet Sprayer, Ready Mix, Concrete Pump, Inverse Arc Hydraulic model, Multi-function Laying Trolley-Formwork Platform, Crane, and Traveler Concrete Formwork. Resource requirements for each work task in tunnel construction activities are shown in table 4.

3.3. Cyclone model development
Modeling development based on the work breakdown structure of tunnel work. A model was developed to get the possibility of improvements in terms of productivity. Assume that in modeling, three-bench conditions in the excavation are considered to have occurred, operations are running in series stages where there are no parallel jobs that occur, this may not be accurate when compared to the actual conditions but with limited resources, it needs to be considered.

Figure 3 illustrates how a tunneling operation cycle works, simply explained as follow, assume the three bench condition (figure 1) has been achieved, preparation and reinforcement were conducted first to prevent the upper soil from collapsing, excavation then begins from the top-level then continued with the initial reinforcement immediately, excavation and initial reinforcement of the middle and bottom level then carried out sequentially (top, middle, and bottom level of the tunnel shown by number 1, 2, and 3 respectively in figure 1), the next step is excavation, reinforcement, and lining for the inverted section, the last part is the reinforcement and lining of the tunnel section (above the inverted part which was previously lining). Black dots that are assumed to be the initial condition for resources will move in its path to carry out the task, then return again to its initial condition. The Cycle is counting as one cycle of this operation when the resources pass the counter element, then the cycle time will stop counting as the result of cycle duration.

| ID  | Work Task            | Duration (Hours) | Type   | Parameter |
|-----|----------------------|------------------|--------|-----------|
| WT1 | Assessment           | uniform          | 0.5    | 1         |
| WT2 | Advanced Support     | uniform          | 1.5    | 2         |
| WT3 | Excavation Phase 1   | triangular       | 9      | 10 11     |
WT4 Initial concrete Spray uniform 20 22
WT5 Anchor Installation + Wire Mesh + H beam + temporary Support uniform 6 8
WT6 Shotcrete 30 cm uniform 20 22
WT7 Excavation Phase 2 triangular 9 10 11
WT8 Initial concrete Spray uniform 20 22
WT9 Anchor Installation + Wire Mesh + H beam + Temporary Arc uniform 6 8
WT10 Shotcrete uniform 20 22
WT11 Excavation Phase 3 triangular 9 10 11
WT12 Excavation Phase 4 uniform 7 9
WT13 H beam arc triangular 5 6 7
WT14 lean Concreting h Beam pouring uniform 3 6
WT15 Inverted Rebar work + Formwork uniform 21 23
WT16 Inverted Lining uniform 18 20
WT17 Instal Geotextile triangular 22 23 24
WT18 Rebar work + Formwork triangular 32 40 48
WT19 Concrete Lining triangular 10 13 16

Figure 3. Cyclone model of tunneling.

Table 4. Integration flow units’ cycle and initial resource.

| Integration Flow units’ cycle | Initial Resource | Work Task |
|-------------------------------|------------------|-----------|
| Drilling Machine             | R1 1 Unit        | ✓         |
| Pneumatic Drill              | R2 1 Unit        | ✓         |
### Table of Equipment

| Equipment                  | R   | Quantity | Status |
|----------------------------|-----|----------|--------|
| Anchor Pump                | R3  | 2 Unit   | ✓      |
| Excavator                  | R4  | 2 Unit   | ✓ ✓ ✓ ✓ |
| Loader                     | R5  | 2 Unit   | ✓ ✓ ✓ ✓ |
| Dump Truck                 | R6  | 3 Unit   | ✓ ✓ ✓ ✓ |
| Labour                     | R7  | 1 Team   | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| Concrete Wet Sprayer       | R8  | 1 Team   | ✓ ✓ ✓ ✓ |
| Ready-mix                  | R9  | 3 Unit   | ✓ ✓ ✓ |
| Concrete Pump              | R10 | 1 Unit   | ✓ ✓ ✓ |
| Inverse Arc                | R11 | 1 Unit   | ✓ ✓ ✓ |
| Hydraulic model            |     |          |        |
| Multi-function             |     |          |        |
| Platform Laying            |     |          |        |
| Trolley-Formwork           | R12 | 1 Unit   | ✓ ✓ ✓ ✓ |
| Crane                      | R13 | 1 Unit   | ✓ ✓ ✓ ✓ |
| Traveller Concrete Formwork| R14 | 1 Unit   | ✓ ✓ |

#### 3.4. Simulation result analysis

The simulation of tunneling operations is carried out for 100 cycles. With this number, the system has reached a stable state, as in figure 4 for simulation using WebCyclone, figure 5 for simulations using Symphony.Net software, and figure 6 for simulations using COST software. The steady states show that the process has reached equilibrium conditions, where changes in time do not affect the value of productivity.

**Figure 4.** Simulation result using WebCyclone.  **Figure 5.** Simulation result using Symphony.NET.  **Figure 6.** Simulation result using COST.

The operating simulation results produce output values of productivity (or production rate, it’s the same just different in the term used in the software) as units produced in unit time (hour in this case). In
this simulation, 1 production unit is defined as 10.5 meters of the part that has been done secondary lining, with the 12 hours of working hours in one day, the time needed to produce 10.5 meters of the tunnel can be calculated using equation (1).

\[
\text{Dur. for 1 unit prod. (days)} = \frac{1}{\text{Working hours assumption} \times \text{Productivity (unit/hour)}}
\]  

**Table 5.** Productivity value from simulations.

| Productivity                  | WebCyclone | Symphony.NET | COST |
|-------------------------------|------------|--------------|------|
| Productivity (Unit/hour)      | 0.0067     | 0.006        | 0.007|
| Productivity (meter/day)      | 0.84       | 0.76         | 0.88 |
| Duration for 1 unit production (days) | 12.4       | 13.9         | 11.9 |

The simulation output in the form of productivity in table 5 shows that to produce 10.5 meters of the tunnel it takes around 12-14 days. There is a gradual change in the value of productivity when running simulations before finally achieving productivity in a steady state.

**Table 6.** The idleness percentage of resources.

| Resources                        | Percentage of Idleness (%) | WebCyclone | Symphony.NET | COST |
|----------------------------------|----------------------------|------------|--------------|------|
| Anchor Pump (node 5)             | 99.98%                     | 100.00%    | 100.00%      |      |
| Concrete Pump (node 42)          | 91.36%                     | 91.30%     | 91.29%       |      |
| Concrete Truck (node 30)         | 100.00%                    | 100.00%    | 100.00%      |      |
| Crane (node 19)                  | 77.22%                     | 62.40%     | 77.20%       |      |
| Dump Truck (node 9)              | 99.98%                     | 100.00%    | 100.00%      |      |
| Excavator (node 11)              | 95.76%                     | 94.30%     | 94.38%       |      |
| Formwork Team (node 18)          | 20.46%                     | 20.30%     | 20.11%       |      |
| Geological Drilling rig (node 2) | 97.98%                     | 99.50%     | 99.51%       |      |
| Inverse Arch Model (node 33)     | 84.64%                     | 85.30%     | 85.23%       |      |
| Lining Trolley (node 43)         | 91.36%                     | 91.30%     | 91.29%       |      |
| Loader (node 10)                 | 95.76%                     | 94.30%     | 94.38%       |      |
| Multifunction Work Platform (node 38) | 57.89%             | 57.80%     | 57.69%       |      |
| Pneumatic Drill (node 6)         | 95.26%                     | 98.80%     | 98.82%       |      |
| Second liner Team (node 29)      | 75.67%                     | 75.50%     | 75.69%       |      |
| Shotcrete Team (node 14)         | 0.82%                      | 1.00%      | 1.03%        |      |
| Spray Robot (node 15)            | 0.82%                      | 1.00%      | 1.03%        |      |

The idleness percentage of most resources in table 6 shows that there is a high waiting time in the system (model), this can occur due to the dependency from one work task to another so that the work sequence in the system is sequential (series), there are too many resources available, or there are too many work tasks that use these resources.

### 3.5. Sensitivity analysis

The low idleness percentage shows that the resource works continuously. It can occur because the resource is used in many work tasks and/or the amount is too little, therefore the addition of the number of resources (which has a low percentage) is considered to increase system productivity value. Based on the simulation results shown in table 6, resources that have a low percentage and are considered to need additional resources, namely the Formwork Team, Shotcrete Team, and Concrete Wet Sprayer. The
alternative number of configurations is made from these three resources for the sensitivity analysis process. Sensitivity analysis to find out the number of resources can be done using WebCyclone. For modeling on tunnel construction operations, variations in resources are as follows:

- **Formwork team**: 1 to 3 teams
- **Shotcrete team**: 1 to 3 teams
- **Concrete Wet Sprayer**: 1 to 3 units of equipment

Based on the results of the sensitivity analysis, the system (model) productivity value increases with the addition of certain resources. The addition of each of them to the Shotcrete Team, Concrete Wet Sprayer, and the Formwork Team to be 2, led to almost twice the productivity increase (6.5 days for production of 10.5 meters) but the addition of each of these resources to 3 has not increased productivity significantly. An increase in the number of resources could lead to additional cost, even though cost analysis were not conducted its logical to conclude that the optimal amount of Shotcrete Team, Concrete Wet Sprayer, and Formwork Team are 2 for each resource (the decision ultimately depend on the project needs). Table 7 is a resume of the sensitivity results analysis, alternative 1 with 1 resource each, alternative 2 with 2 resources each, and alternative 3 with 3 resources each. The addition of a number of resources causes the idleness percentage of all three resources to increase, but unlike other resources, the percentage of the idle formwork team increases dramatically.

**Table 7.** Comparison of the productivity value and the percentage of each alternative condition.

| Name               | % Idleness | Alternative 1 | Alternative 2 | Alternative 3 |
|--------------------|------------|---------------|---------------|---------------|
| SHOTCRETE TEAM     | 0.78       | 5.78          | 8.79          |
| SPRAY ROBOT        | 0.78       | 5.78          | 8.79          |
| FORMWORK TEAM      | 20.45      | 39.56         | 68.63         |
| **Productivity (unit/hour)** | **0.006709** | **0.012945**  | **0.01496**  |

3.6. **Comparison with previous research**

Comparisons in the result are made to previous studies [5]. The total duration of the tunneling work can be calculated using equation (2), both previous study and this study has a different length of the tunneling work path (608 meters in this study), so that has an impact on total duration. Moreover, in the previous study [5], the working hours in one day were 8 hours, while in this study the working hours in one day were assumed to be 12 hours because the project needs to meet the completion target.

\[
\text{Total duration (day)} = \frac{\text{Total length of tunnel (m)}}{\text{Productivity (m/day)}} \tag{2}
\]

**Table 8.** The comparison of productivity value.

| Description       | Previous study [5] | Current study |
|-------------------|--------------------|---------------|
| Tunneling Method  | NMT                | NATM          |
| Productivity (m/day) | 0.554             | 0.84          |
| Total Duration (day) | 653               | 724           |

As shown in table 8, the results of each study are displayed based on the construction method, the value of work productivity, and the total duration needed to complete the work. There are differences in the tunnel construction method used as the object of study, in the previous study [5] that simulated...
tunneling operations on the construction of Cisumdawu toll road, Norwegian Method of Tunneling (NMT) were used in the project, while this study used the New Austrian Tunneling Method (NATM).

4. Conclusion
The conclusion of this study are as follows:
- The tunneling operation in this study can be modeled with Cyclone to figure out the system’s condition and the response based on the simulation conducted;
- The productivity value obtained from the simulation results is around 12 days for 10.5 m, assuming the working hours are 12 hours a day. Meanwhile, according to interviews in the field, tunneling work has a productivity of 1.2 meters per day, which means that the work methods in the field are better than the simulated methods. This can be caused by the assumption of working hours used in the model might be different from the project;
- Compared to the previous study of tunneling at Cisumdawu toll road, there are differences in the value of productivity, this is due to differences in tunneling construction methods; and
- Sensitivity analysis results that the resource concrete wet sprayer, shotcrete team, and formwork team are quite sensitive in influencing system productivity, where the addition of the number of those resources influences the increase in productivity, with the optimum number of two resources for each of concrete wet sprayer, shotcrete team, and formwork team.

Some recommendations based on this research were given as follows:
- The duration of modeling used should come from project data that is being reviewed, if possible, use data from field observations to obtain a more reliable duration; and
- The construction operation process used in the modeling assumptions should be adjusted to the actual conditions, namely by observing directly (if possible) and interviewing the construction implementers in the field and validate the model with the expert on the project.

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