NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

ANALYSIS OF ENGINEER C2 AS MODELED BY STOCHASTIC, TIMED ATTRIBUTED PETRI NETS

by

Peter J. Tabacchi

September, 1990

Thesis Co-Advisors: William J. Caldwell
Robert R. Read

Unclassified

security classification of this page

REPORT DOCUMENTATION PAGE

1a Report Security Classification Unclassified	1b Restrictive Markings
2a Security Classification Authority	3 Distribution/Availability of Report Approved for public release; distribution is unlimited.
2b Declassification Downgrading Schedule	
4 Performing Organization Report Number(s)	5 Monitoring Organization Report Number(s)
6a Name of Performing Organization Naval Postgraduate School / 6b Office Symbol *(if applicable)* 50	7a Name of Monitoring Organization Naval Postgraduate School
6c Address *(city, state, and ZIP code)* Monterey, CA 93943-5000	7b Address *(city, state, and ZIP code)* Monterey, CA 93943-5000
8a Name of Funding Sponsoring Organization / 8b Office Symbol *(if applicable)*	9 Procurement Instrument Identification Number
8c Address *(city, state, and ZIP code)*	10 Source of Funding Numbers Program Element No / Project No / Task No / Work Unit Accession No

11 Title *(include security classification)* ANALYSIS OF ENGINEER C2 AS MODELED BY STOCHASTIC, TIMED ATTRIBUTED PETRI NETS (Unclassified)

12 Personal Author(s) Peter J. Tabacchi

13a Type of Report	13b Time Covered	14 Date of Report *(year, month, day)*	15 Page Count
Master's Thesis	From To	September 1990	90

16 Supplementary Notation The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

17 Cosati Codes

Field	Group	Subgroup

18 Subject Terms *(continue on reverse if necessary and identify by block number)* land warfare, military planning, military science, petri nets,command and control, combat engineers

19 Abstract *(continue on reverse if necessary and identify by block number)*

Engineer command and control in a mechanized corps is a complex system. The current doctrine for engineer force structures is inadequate. Three command and control alternative force structures, identified in the Engineer Structure Study, are evaluated to determine which structure best supports a mechanized corps. The analysis is based on the results of a Stochastic, Timed, Attributed Petri Net timed stepped simulation. The model used in this simulation was constructed using an interactive graphical design tool, called Modeler, by a team including the software developer ALPHATECH, the U.S. Army Engineer Center, and the Training and Doctrine Analysis Command. This was the Army's first use of Modeler. The C2 performance of the engineer staffs is simulated for each of the three force structures by simulation message traffic and processing for 15 days of war in three settings, offense, defense and transitioning from offense to defense. The force structures are then analyzed by comparing simulation output using three measures of performances: Message Processing Capacity, Message Quality, and Message Processing Speed. The Division Engineer alternative consistently out performs the Base Case and Company Restructure alternatives for each measure of performance and in each of the three settings. Therefore based on these simulations, the Division Engineer alternative is the best force structure to support a mechanized corps.

20 Distribution Availability of Abstract ☒ unclassified unlimited ☐ same as report ☐ DTIC users	21 Abstract Security Classification Unclassified
22a Name of Responsible Individual William J. Caldwell	22b Telephone *(include Area code)* (408) 646-3452 / 22c Office Symbol 55Cw

DD FORM 1473,84 MAR 83 APR edition may be used until exhausted
All other editions are obsolete

security classification of this page
Unclassified

Approved for public release; distribution is unlimited.

Analysis of Engineer C2 as Modeled by Stochastic, Timed Attributed Petri Nets

by

Peter J. Tabacchi
Captain, United States Army
B.S., Geneva College, 1981

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 1990

Author: Peter J. Tabacchi

Approved by: William J. Caldwell, Co-Advisor

Robert R. Read, Co-Advisor

Lyn R. Whitaker, Second Reader

Peter Purdue, Chairman,
Department of Operations Research

ABSTRACT

Engineer command and control in a mechanized corps is a complex system. The current doctrine for engineer force structures is inadequate. Three command and control alternative force structures, identified in the Engineer Structure Study, are evaluated to determine which structure best supports a mechanized corps. The analysis is based on the results of a Stochastic, Timed, Attributed Petri Net timed stepped simulation. The model used in this simulation was constructed using an interactive graphical design tool, called Modeler, by a team including the software developer ALPHATECH, the U.S. Army Engineer Center, and the Training and Doctrine Analysis Command. This was the Army's first use of Modeler. The C2 performance of the engineer staffs is simulated for each of the three force structures by simulation message traffic and processing for 15 days of war in three settings, offensive, defensive and transitional from offensive to defensive. The force structures are then analyzed by comparing simulation output using three measures of performances: Processing Capacity, Message Quality, and Message Processing Speed. The Division Engineer alternative consistently out performs the Base Case and Company Restructure alternatives for each measure of performance and in each of the three settings. Therefore based on these simulations, the Division Engineer alternative is the best force structure to support a mechanized corps.

TABLE OF CONTENTS

I. INTRODUCTION AND BACKGROUND

A. INTRODUCTION

The purpose of this thesis is to determine the best engineer force structure to support a corps composed of armored and mechanized divisions. This corps, called the heavy corps, is the backbone of the defense of Central Europe. A better engineer force structure is necessary because of the acknowledged engineer support problem summarized by Major General Kem, former Commandant of the U.S. Army Engineer Center. "The combat engineer finds himself supporting a rapidly modernizing battlefield with a cumbersome World War II organizational architecture" [Ref. 1].

The nature of the problem can be discussed after describing the three alternatives. These alternatives were developed in the Army study called the Engineer Structure Study (ESS). The three alternative force structures analyzed follow:

- Base Case (BC) - is the current force design which consists of one divisional engineer battalion organic to each division. Additionally, there exists an engineer brigade which provides reinforcing engineer units to the division, as well as support to the rest of the corps.
- Company Restructure (CR) - in this force the line companies of the divisional engineer battalion are strengthened with additional personnel and equipment. These assets are reallocated from corps

units. The corps engineer brigade still retains assets to weight the main effort, and provides support to the rest of the corps.

- Division Engineer (DE) - in this force the divisional engineer assets are completely restructured. Assets taken from the corps are used to form a divisional engineer headquarters with three downsized engineer battalions organic to the division. This provides an organic command and control structure to the division not present in the other alternatives. The corps engineer brigade retains sufficient assets to weight the main effort, and provide support to the rest of the corps.

An understanding of the use of symbols is required to describe the alternatives in greater detail and illuminate the engineer support problem. The unit symbols used to describe the alternatives are defined in FIG(1). The boundaries of a typical four division corps are shown in FIG(2). Since the four division areas are similar, we magnify the engineer organization in the corps. Only the area so surrounded by the use of a dashed line is portrayed in the graphical depiction of the alternatives.

The base case alternative is illustrated in FIG(3). From this figure, one can see that corps engineer units have complicated command and support channels. Also, they are required to provide significant engineer forces to support maneuver operation at the division and brigade level. As a result corps performance may be adversely affected.

Unit Symbols

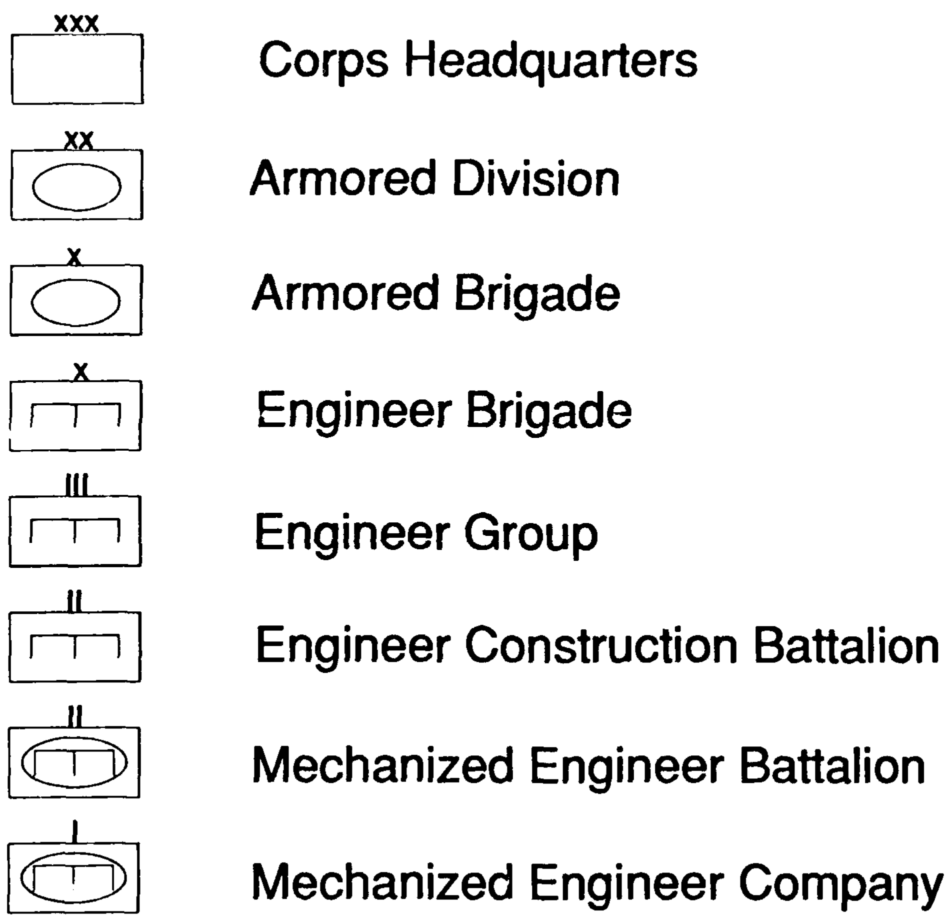


Figure 1

Four Division Corps

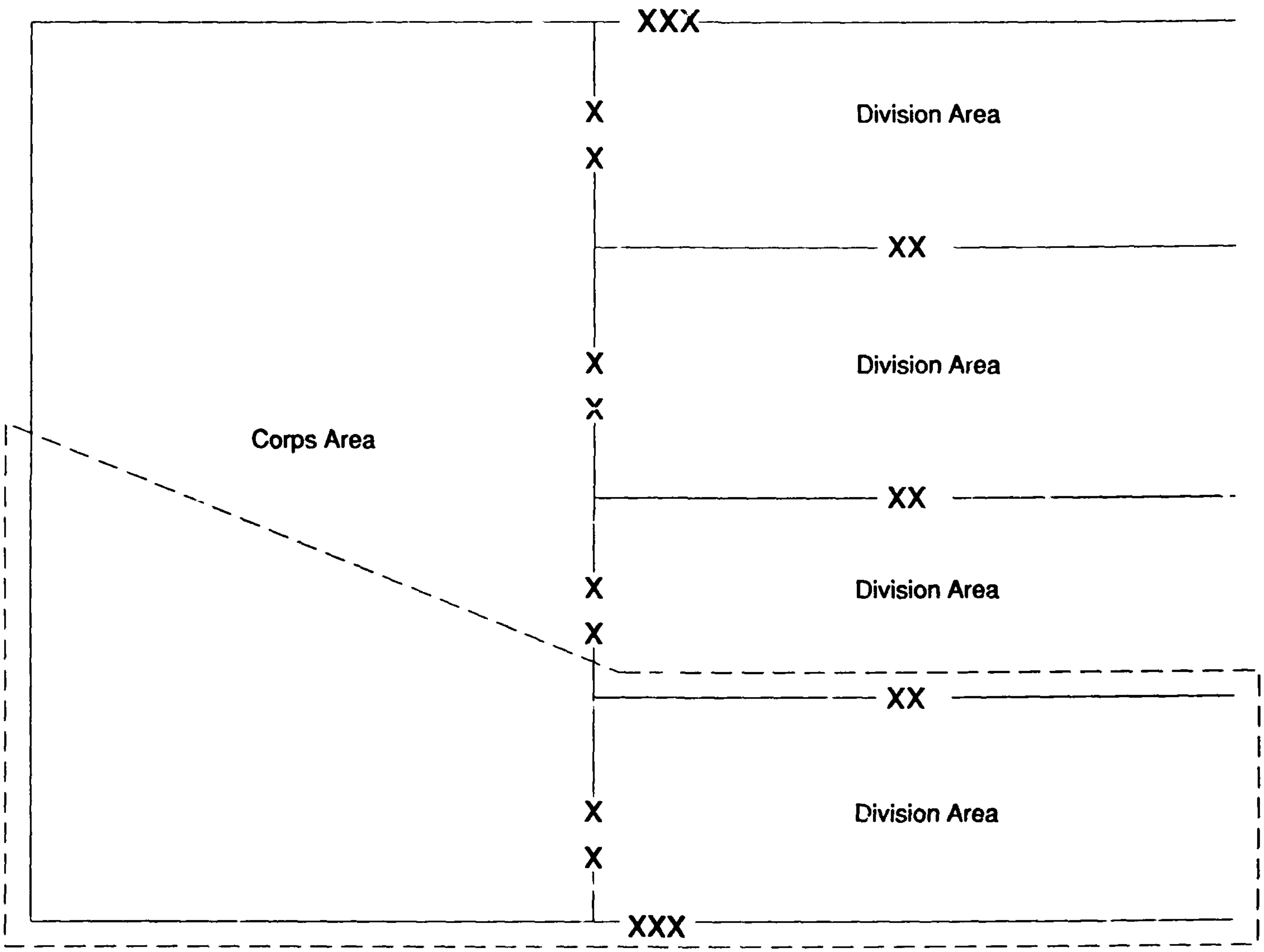


Figure 2

Base Case Alternative

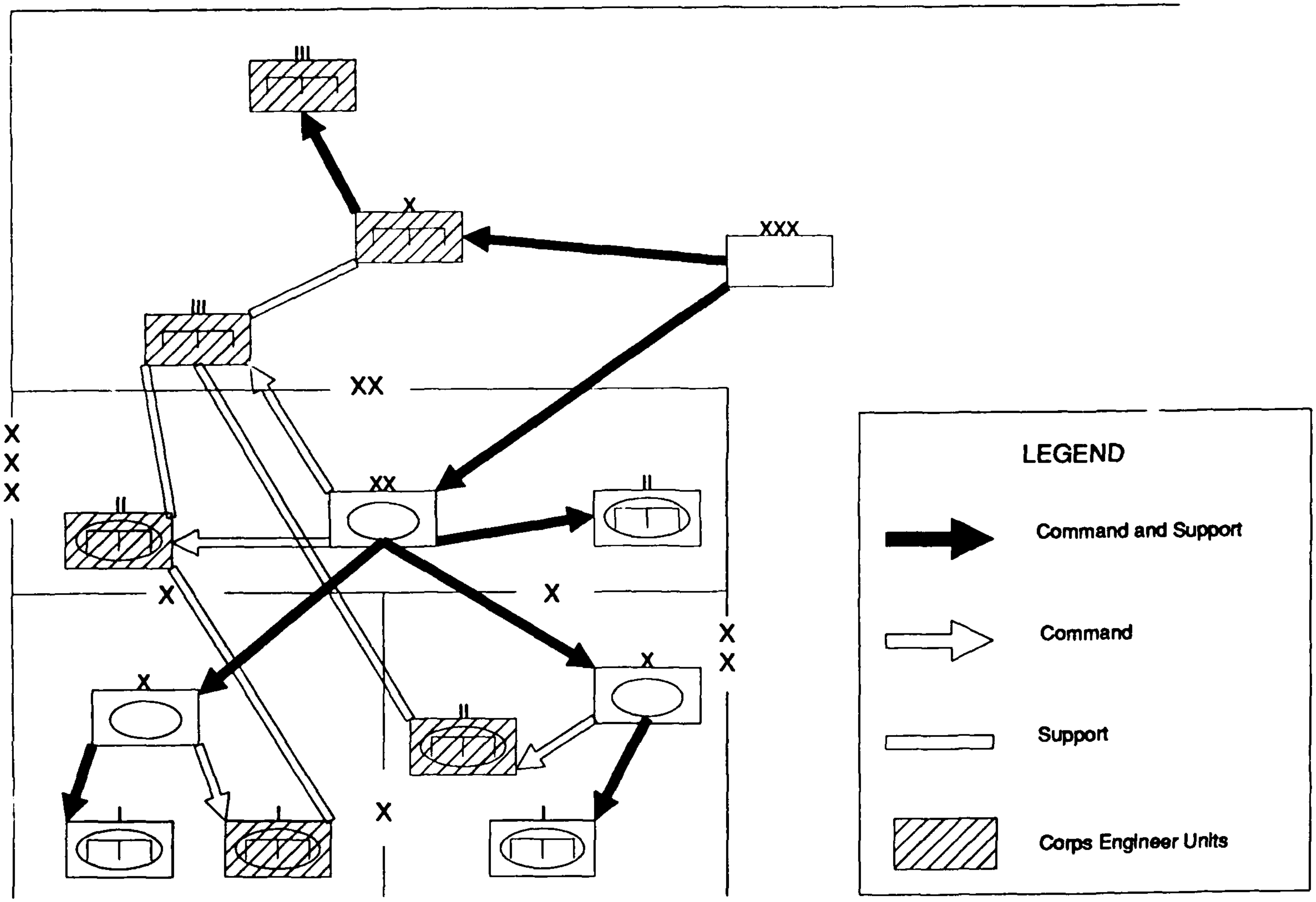


Figure 3

The command and support requirements cause the corps engineer units to communicate with both their parent unit, and the maneuver unit they are supporting. Supplies must go through long channels and must pass through the supported division's area. Under certain conditions orders from maneuver commanders must pass through the corps engineer command channels. This extended and complex command channel can often cause the corps engineer units to be unresponsive to the maneuver commanders.

The reliance of the maneuver brigades on corps engineer units for engineer support operations in the forward battle area leads to additional problems. Corps engineer units have different equipment and standard operating procedures. This leads to difficulties in synchronization, agility and initiative.

The company restructure alternative is very similar to the base case and is illustrated in FIG(4). The main difference is that personnel and equipment are reallocated from corps units into the divisional engineer units. This reduces the need for the maneuver commanders to rely on corps engineer units in the forward battle area, but command and support problems still exist and other problems arise.

It may be seen in FIG(4) that control of the engineers in the forward battle area is less complicated than in the base case. An offsetting feature of

Company Restructure Alternative

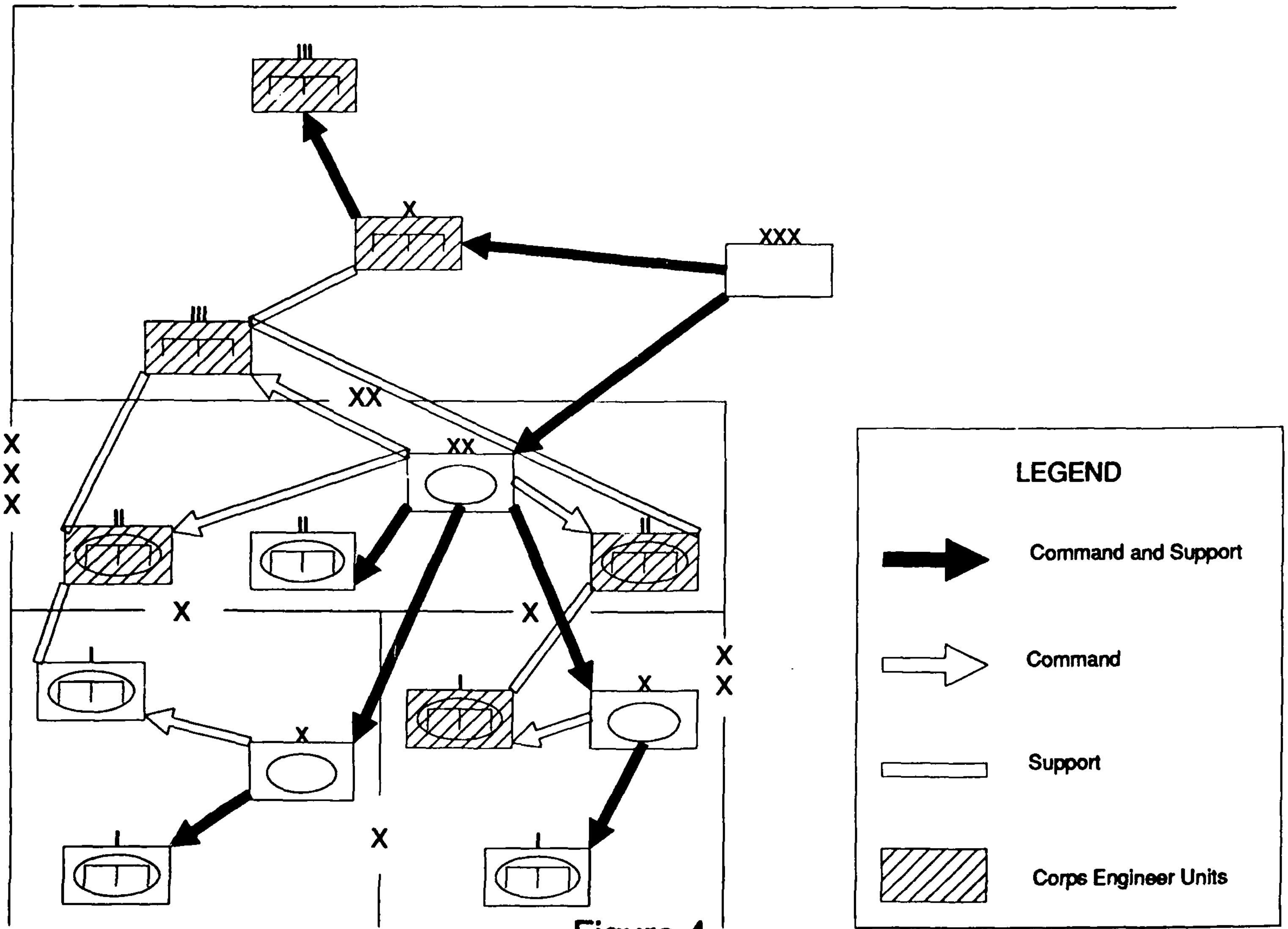


Figure 4

this is that the additional personnel and equipment reallocated to the divisions appears with no additional command and control structure. It is anticipated that the division and brigade engineer staffs will quickly become overwhelmed. This is also indicated in the alternative illustration FIG(4). The command and support appears complicated in the armored division's area.

The third alternative, division engineer, totally restructures the way engineers support the corps. Under this alternative, command and support relationships are simplified, as can be seen in FIG(5). In addition, engineers in the forward battle area are organic to the maneuver divisions, increasing the maneuver commanders ability to rely on engineers in his exploiting of the tenets of AirLand Battle.

Personnel and equipment are held relatively constant in all alternatives. This allows a fair comparison and the foremost alternative will be the one with the best command and control structure.

1. BACKGROUND

As stated earlier, the three alternatives were developed as part of the Engineer Structure Study. Because of the engineer support problem, the Training and Doctrine Command (TRADOC) Commander instructed the United States Army Engineer School (USAES) and TRADOC Analysis Command

Division Engineer Alternative

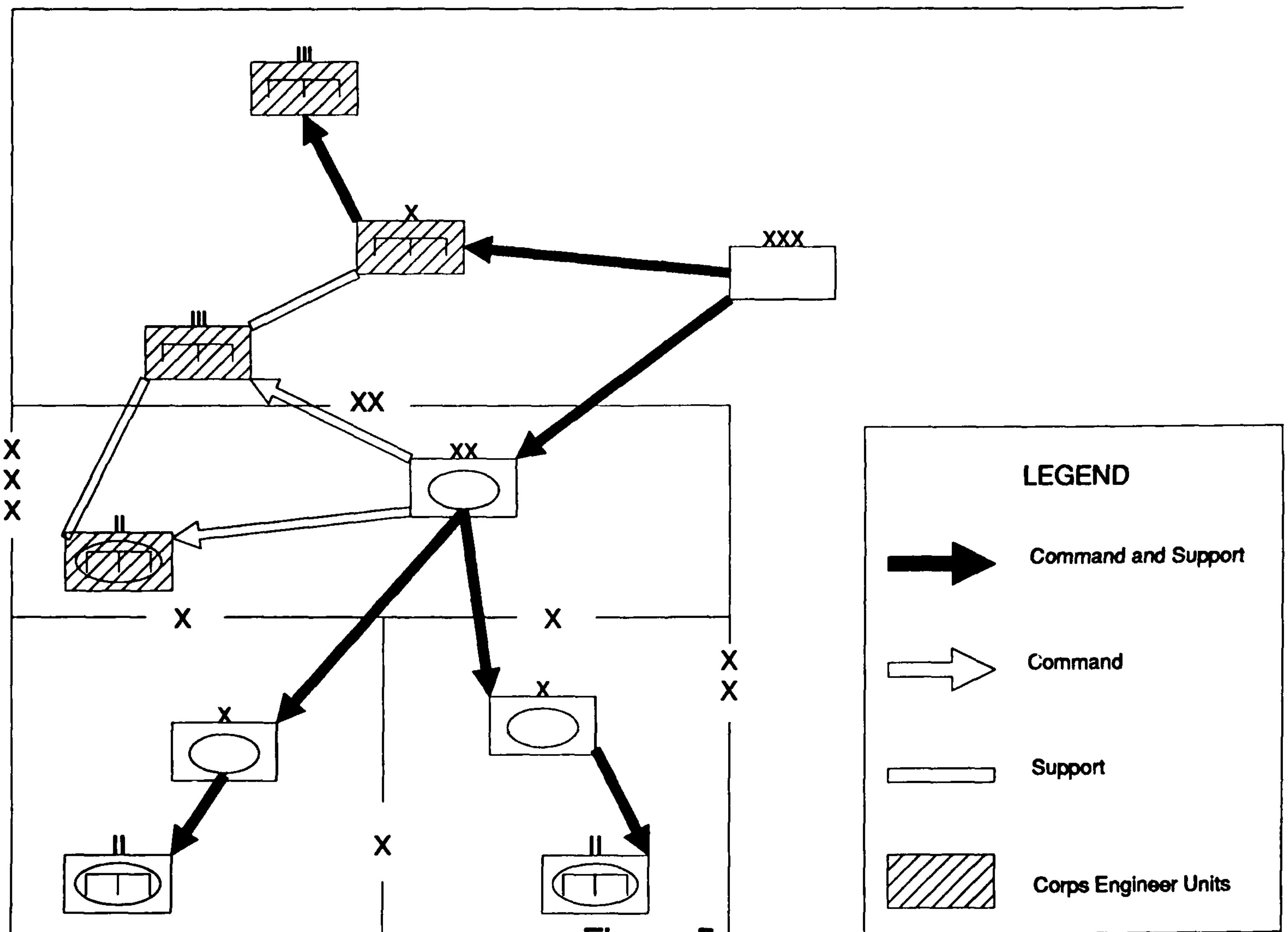


Figure 5

(TRAC) to develop a two phase analytical effort to define and evaluate alternative engineer force structures. The goal was to select an engineer force structure to best support the heavy corps.

2. Phase I

In Phase I four engineer force alternatives were developed and a screening performance analysis was conducted to measure capabilities versus requirements. It recommended the three alternatives described earlier for evaluation in Phase II.

- Base Case (BC)
- Company Restructure (CR)
- Division Engineer (DE)

3. Phase II

Phase II was designed to provide an analytical basis for the selection of a preferred engineer force structure from the three alternatives developed in Phase I. It focused on evaluating the responsiveness of engineer command and control (C2) capabilities and how these capabilities contributed to the corps overall combat effectiveness.

As part of this analysis, a model was built using an interactive graphical design tool named Modeler. This was the first Army analysis to use

Modeler to build a C2 analysis simulation. The intent was to generate C2 time delays for input into CORBAN, a force on force model. A description of Modeler and the model designed with it will be presented in chapter 3.

The results of this C2 analysis model were very successful in terms of providing the time delays for the force on force model. In addition, it was determined that many other C2 insights are available in Modeler's output. This thesis uses the Modeler C2 output to recommend a preferred engineer force structure in the heavy corps.

B. THE THESIS IN OUTLINE

The remainder of the thesis is organized as follows. To enable a better understanding of what is important in a command and control structure, Chapter 2 contains a description of AirLand Battle doctrine. Then the measures of performance for the analysis of the alternatives are developed. To further assist with the understanding of the model, Chapter 3 begins with a review of Petri-Net graphs and their extension in Modeler. Then follows a description of the process of building the Engineer Structure Model and the model itself. In chapter 4, the output of Modeler is examined. The method of calculating the Measures of Performance, MOP'S, are described and the results stated. Chapter 5 reports on historical uses of Modeler and provides additional suggestions for further uses of Modeler by the Army. The conclusions are presented in Chapter 6.

II. MEASURE OF PERFORMANCE DEVELOPMENT

The development of command and control measures of performance requires an understanding of the tenets of AirLand Battle and of the stated purpose of command and control. These are presented in FM 100-5, Operations. A summary of pertinent information appears below.

A. AIRLAND BATTLE

Airland battle is the U.S. Army's basic fighting doctrine. This doctrine describes the Army's approach to generating and applying combat power at the operational and tactical levels. It was developed to allow for the lethality and mobility of modern warfare, the dynamics of combat power, and the application of the principles of war. It is based on securing and retaining the initiative and aggressively accomplishing the mission. The Army must adhere to the four tenets of Airland Battle if it is to be successful on the next battlefield. These tenets, taken from FM 100-5 Operations, are:

1. Initiative

Initiative is the setting or changing of the terms of battle by action. It requires a willingness and ability of individuals and leaders to act independently. This requires commanders at all levels and subordinates to be well informed.

2. Agility

Agility is the ability of friendly forces to act faster than the enemy. This quickness permits the rapid concentration of friendly strengths against enemy vulnerabilities. This in turn requires a commander to communicate quickly with superiors and subordinates.

3. Depth

Depth is the extension of operations in terms of space, time and resources. This requires the commander to plan past his horizons. Operations in depth degrade the enemies capabilities by attacking him before his forces join the battle. Commanders must plan ahead, actively seek information and employ every asset available. This requires a staff capable of doing detailed planning.

4. Synchronization

Synchronization is the arrangement of battlefield activities in time, space and purpose in order to produce maximum relative combat power at the decisive point. The product of effective synchronization is maximum economy of force. This is achieved through up-to-date information and quick reliable communication.[Ref. 2]

The purpose of command and control is also clearly stated in FM 100-5, Operations: "the only purpose of command and control is to implement the commander's will in pursuit of the unit's objective." Since it is the corps engineer's command and control structure being studied, and the fact that engineers are a support arms, it is clear that engineer C2 must be evaluated from the corps commander's perspective.

"The ultimate measure of command and control effectiveness is whether the force functions more effectively and more quickly than the enemy." (op. cit.)

In summary, to support the tenets of AirLand Battle and to fulfill the stated purpose of command and control, a C2 structure must be reliable and fast; it must collect, analyze, and present information; and it must issue orders rapidly and accurately.

B. MEASURES OF PERFORMANCE

Three things must be examined in order to evaluate the ability of differing C2 structures to support the maneuver commanders. Firstly, which alternative has the greatest capacity to process information. Secondly, which alternative can provide the most accurate and reliable information. And thirdly, which alternative can process information with the greatest speed.

1. MOP 1: Processing Capacity

Processing capacity is the ability of the alternative to process the required information. This MOP impacts the alternatives ability to reliably collect, analyze, and present information. An alternative can not present reliable information if it doesn't have access to a majority of available information.

2. MOP 2: Message Quality

Message quality is the accuracy and the reliability of the information passed. Two items determine the accuracy and reliability of the staff output. These are the experience level of the staff and the amount of time available to process the information.

3. MOP 3: Processing Speed

Processing Speed is the speed at which messages are processed and orders issued. This relates directly to the ultimate measure of effectiveness of functioning more quickly than the enemy. It also evaluates the ability of staffs to collect, analyze, and present information rapidly.

II. MODEL DESCRIPTION

The ESS C2 model was built using Modeler I which is an interactive, graphical modeling tool based on stochastic timed attributed Petri-Nets. A rudimentary understanding of Petri-Net concepts and definitions is required in order to fully understand the ESS model.

A. PETRI NET GRAPH CONCEPTS AND DEFINITIONS

Petri-Nets have emerged as an important tool for the study and analysis of systems. They allow a mathematical depiction of the system and are effective at modeling dynamic systems.

A Petri-Net graph is a bipartite directed multigraph consisting of places and transitions. Places are visually depicted with circles FIG(6). Transitions are depicted by rectangles and represent activities in the model. Places and transitions are connected by directed arcs.

Data flow carriers are called tokens and are represented by dots. The number and distribution of tokens control the execution of a Petri-Net. A Petri-Net executes by firing transitions, this occurs when a transition is enabled.

A transition is enabled when each of its input places has a token. A transition fires by combining all the enabling tokens from its input places, executing any statements required by the transition, and then depositing the tokens into each of the output places. Execution of the Petri-Net will continue as long as at least one transition is enabled.[Ref. 3]

A simple example of a message center model for illustrating a Petri-Net graph is shown in FIG(6) through FIG(9). In FIG(6) there is only one staff member. His purpose is to decode incoming messages. He waits for the arrival of a message (token depicted by a dot) to the place, Message Awaits Staff Member. In FIG(7) a message has arrived which enables the transition Decode Message. While the message is being decoded, another message arrives FIG(8), and must wait for the staff member to complete the decoding before the transition is enabled again. After an appropriate time delay (needed to decode the message) the transition fires. The decoded message is then placed in the Outbox place and the staff member returns to the place Staff Member enabling the Decode Message transition again FIG(9). This Petri-Net will continue to fire until messages stop arriving.

Petri Net Example

Staff Member Awaits Message

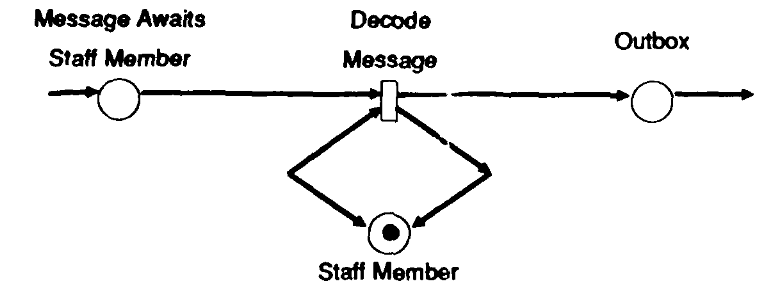


Figure 6

Transition Enabled

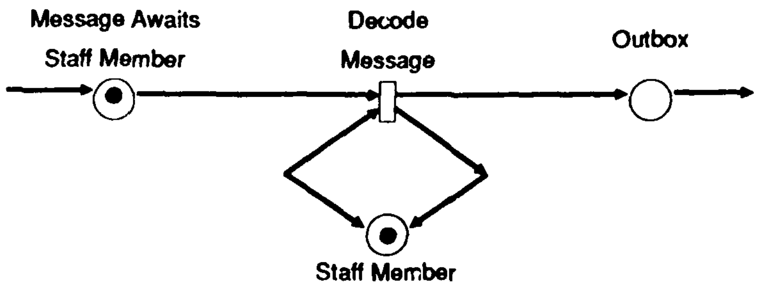


Figure 7

Message Awaits Staff Member

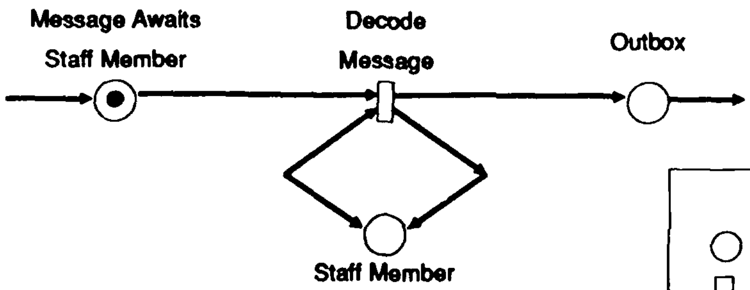
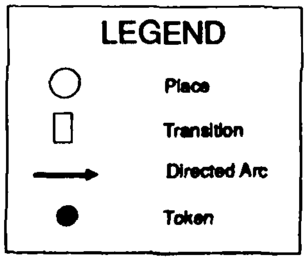


Figure 8



Transition Enable Again

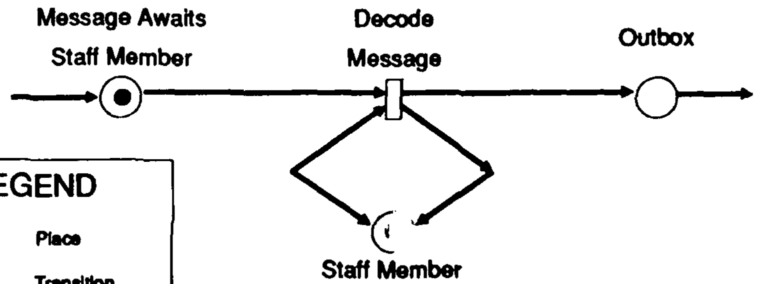


Figure 9

B. MODELER

Modeler uses the Stochastic Timed Attributed Petri-Net (STAPN) modeling language to graphically build a model. In Modeler, places model facilities, transitions model processes, and tokens model objects acted on by processes. Modeler has some extensions of Petri-Nets that are used in the ESS model.

Places may provide inputs to more than one transition. In Modeler all transitions can be enabled or a decision rule can be used to determine which transition is enabled. These decision rules can be described in terms of probabilities, priorities, or functions. They allow the modeling of alternatives.

Time delays can be assigned to transitions. These times can be drawn randomly from parameterized distributions, assigned a constant or can be calculated. The time that processes require is represented in this way.

In Modeler tokens can be assigned attributes. It is through these attributes that models from Modeler are connected with real world data.

In addition to the standard directed arc, Modeler has two special arcs. The first is the inhibit arc represented by an arc with an unfilled circle at the head. A place connected to a transition by a inhibit arc will not allow the transition to fire if a token is in the place. The enable arc represented by an arc with a filled circle at the head, allows a transition to fire but does not consume the token. The enable arc is the one used in the ESS model. [Ref. 4]

For the model description, places can represent facilities, holding areas for tokens, or a decision point in the model flow. Transitions will represent activities that can consume time and/or do calculations. Tokens will represent messages or a control as to how a message is processed. If the token represents a message, it will be referred to as a message.

The description of Modeler provided is sufficient to understand the Modeler model used in the ESS. Many additional features are presented in Modeler, and the reader is referred to the users manual.

C. THE ESS MODEL

1. Model Development

The ESS model was built using Modeler I by personnel from ALPHATECH (a contractor), TRAC Ft. Leavenworth and U.S. Army Engineer School (USAES). Because no C2 data existed, a panel, selected by the Commanding General of USAES, of Subject Matter Experts (SME) was formed to provide this data. They followed a structured process for generating the data. The model was built iteratively with the SME's reviewing each step and providing additional input and guidance. [Ref. 5] In addition the SME's examined the command and control situations for each of the three alternatives selected from Phase I: (Base Case (BC), Company Restructure (CR),and Division Engineer (DE)).

The panel identified three cases under which to analyze the three alternatives.

a. Three Cases:

- Offense - Corps attacking.
- Defense - Corps in the defensive.
- Transition - Corps going from the offensive to the defensive.

The panel then reviewed the alternatives and identified eleven engineer staffs that needed to be modeled. It was determined that the staffs function similarly and could be modeled with same model structure but with differing input parameters to account for differences in the staffs.

b. Eleven Engineer Staffs:

- Forward Divisional Engineer Battalion (EBF-DIV).
- Forward Corps Engineer Battalion (EBF-COR).
- Rear Corps Engineer Battalion (ENBN-R).
- Division Engineer Headquarters (DIVEHQ).
- Engineer Group Forward (ENGP-F).
- Engineer Group Rear (ENGP-R).

- Engineer Brigade (EN BDE).
- Brigade Engineer Section (BDE EN-S).
- Regimental Engineer Section (ACR).
- Assistant Division Engineer Section (ADE).
- Assistant Corps Engineer Section (ACE).

While in the course of the model development, eight critical information types were identified to represent message traffic in the corps. Numerous other information types exist, but it was decided that these eight would suffice. The first seven types are essential to mission accomplishment, with the other routine message type attempting to capture the additional message traffic. Each message type is modeled concurrently, although the models have the same structure, with different input parameters.

c. ***Eight Information Types:***

- Warning Order (WO)
- Maneuver Operations Order (MO)
- Engineer Operations Order (EO)
- Intelligence Processed Higher to Lower (IN)
- Enemy Information Unprocessed Lower to Higher (EI)
- Requests for Assets (AR)

- Engineer SITREP (ES)
- Other/Routine (OT)

Bubble charts were developed to more clearly depict information flow in the corps. These bubble charts graphically show the flow of C2 information between engineer and maneuver units for all the alternatives and cases. An example is seen in FIG(10).

These bubble charts along with the information types and the engineer staffs, became the foundation for the design of the C2 architecture in Modeler. With this foundation the SME's were able to define the model's structure and provide the necessary inputs.

2. Model Description

The ESS model measures the throughput capability of a headquarters engineering staff by representing that staff as a single queue, multiple server system in which messages are processed based on priority, arrival time, and availability of servers. A separate model was defined for each of the eleven engineer staffs. The structure of the model is the same for each staff, however,

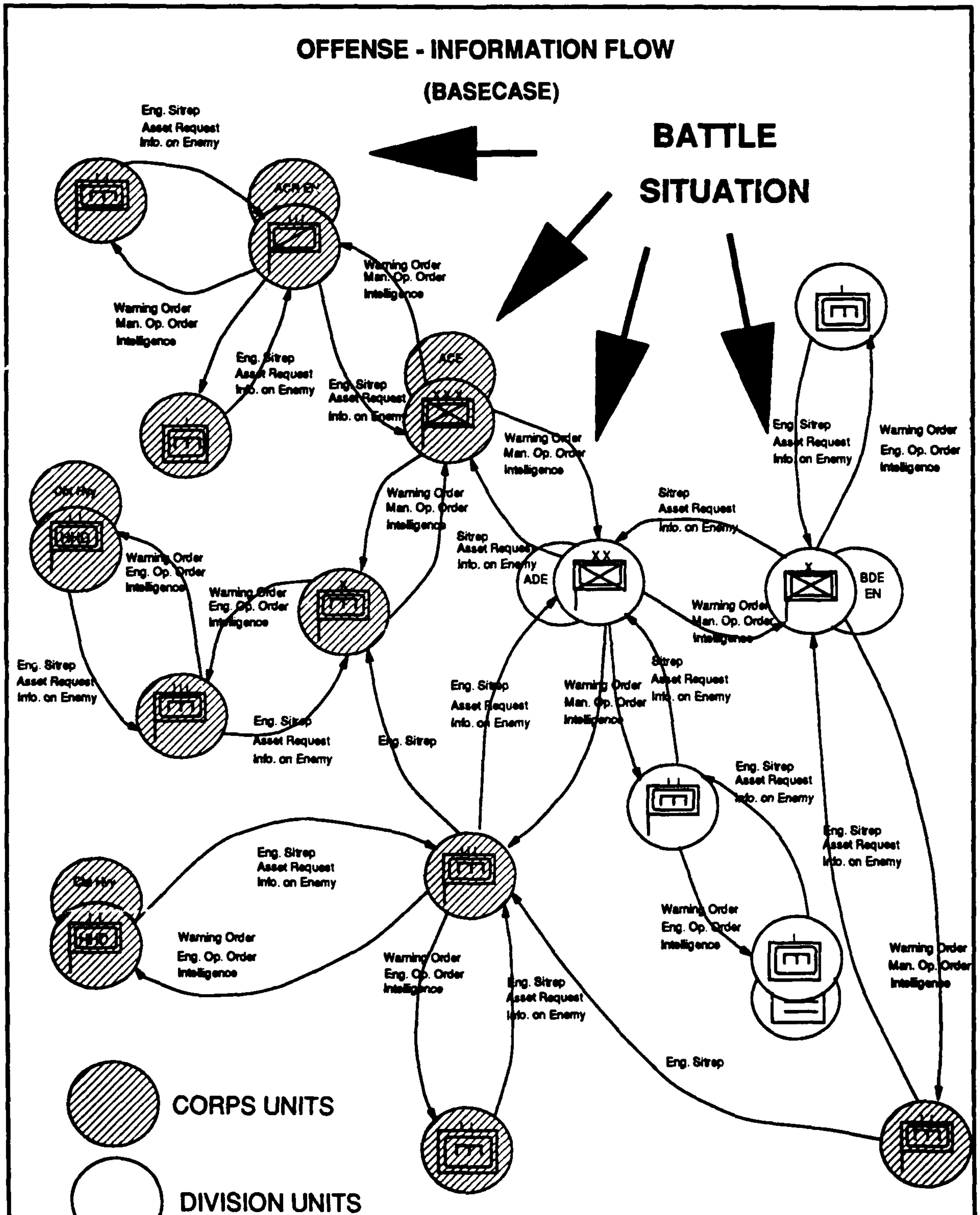

OFFENSE - INFORMATION FLOW
(BASECASE)
BATTLE
SITUATION
Eng. Sitrep
Asset Request
Info. on Enemy
Warning Order
Man. Op. Order
Intelligence
Warning Order
Eng. Op. Order
Intelligence
Sitrep
Asset Request
Info. on Enemy
Eng. Sitrep
ADE
BDE
EN
CORPS UNITS
DIVISION UNITS

Figure 10

the input parameters change depending on the C2 architecture, the command/support relationships, and the situation.

The SME's had to provide the following input parameters for each message type, case and staff. Notice that Modeler notation is introduced. This involves a total of 3336 data points.

- Action Priority - the order in which the staff will process a specific message type when messages are in the queue.
- Rate of Information - The number of information types received at the engineer node within an hour.
- Processing Time Minimum (t_min) - The least amount of time a given staff node can interpret and adequately respond to the information type.
- Processing Time Optimum (t_opt) - The amount of time a given staff node needs to interpret and best respond to the information types.
- Quality Factor Minimum (q_min) - The resultant quality/worth of a processed message type when a staff has only the minimum time to process the information.
- Quality Factor Optimum (q_max) - The resultant quality/worth of a processes message type when a staff has the optimal time to process the information.
- Probability of Retransmit - The likelihood that an engineer staff's dissemination of a given information type will need to be retransmitted before it is received and acknowledged by each receiving unit.

- Time to Retransmit - The time it takes a given staff to disseminate a given information type to the receiving unit given the information had to be retransmitted.

The ESS model consisted of four components: simulation start-up, attribute definition and message generation, node processing, and output statistics. This structure is seen in FIG(11), with each box representing a submodel. The submodels represented by the boxes will be described in detail. The first two components are initialization submodels, with the third component doing the actual dynamic modeling.

The last component calculates the output statistics.

a. Simulation Start-up

The purpose of the simulation start-up submodel is to provide a time delay. This assures the attribute definition and message generation submodel has enough time to generate enough messages to insure the node processing submodel would have an uninterrupted flow of messages during simulation execution.

b. Attribute Definition and Message Generation

The attribute definition and message generation submodels have two primary purposes: they generate messages, and provide an interarrival

Structure of the ESS Model

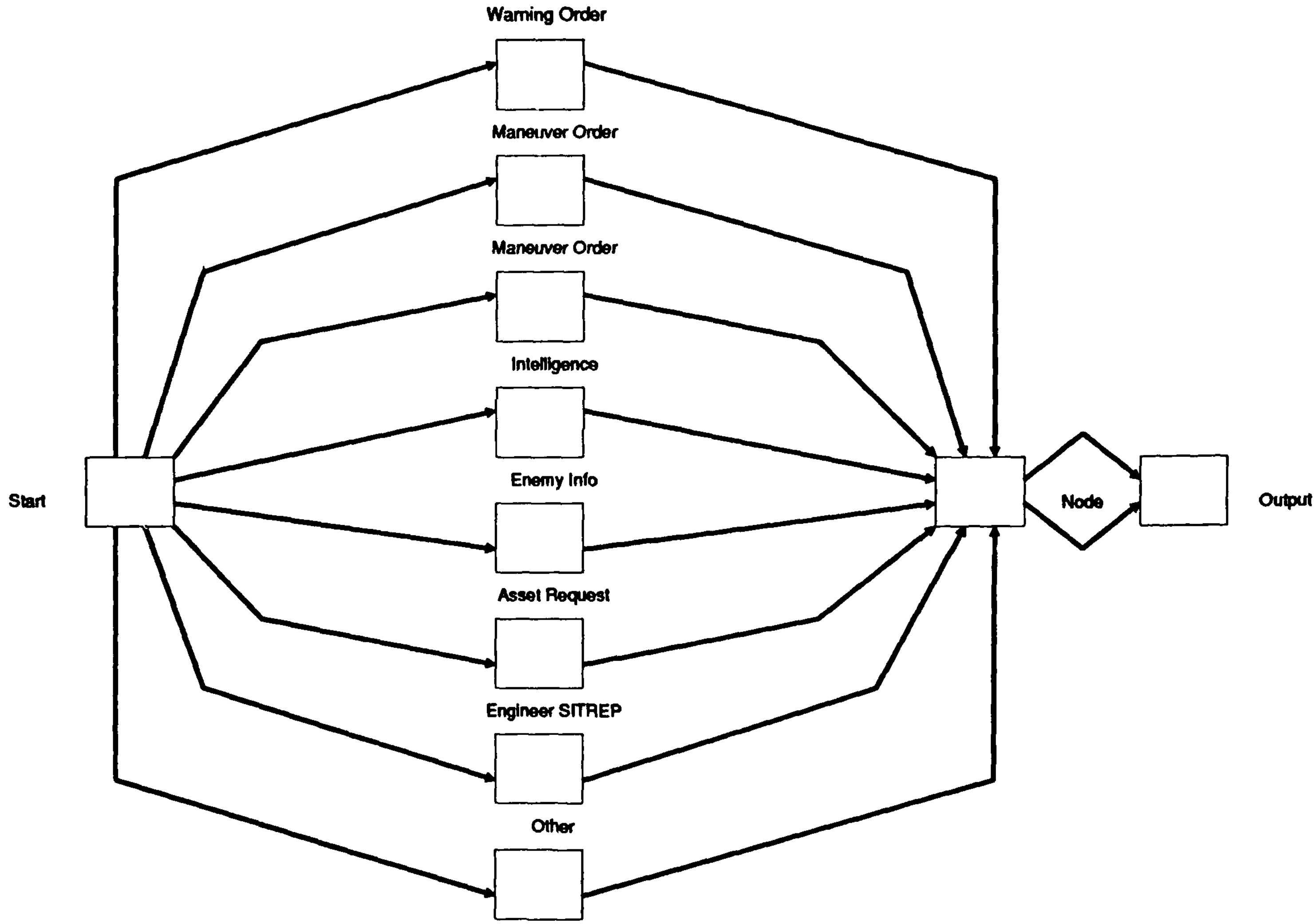


Figure 11

time delay of the message type to the node processing submodel. They generates messages by entering static attributes and calculating three additional attributes.

We will follow a message through the (Warning Order) submodel in the order of execution in order to describe the execution of the submodels in this component. An example of the Warning Order portion of the submodel is seen in FIG(12). Each of the information type's submodels has the same structure as this one and executes concurrently with the Warning Order submodel, this is shown in FIG(11).

Three places have been assigned tokens when the simulation is started. The place cycle has only one token, which ensures only one message's attribute calculations is done at a time. Another token exists in the place init_mssg_attribs which stamps each token with the initial attributes (input parameters) defined by the SME's. The third token comes from the place max_num_mssgs which calculates how many messages for a given staff will occur during the time of the simulation. This is calculated by the simulation time (15 days for ESS) divided by the average rate of arrival as defined by the SME's. This place will determine how many times the create_init_mssgs transition will fire. Thereby it determines how many times this submodel is executed.

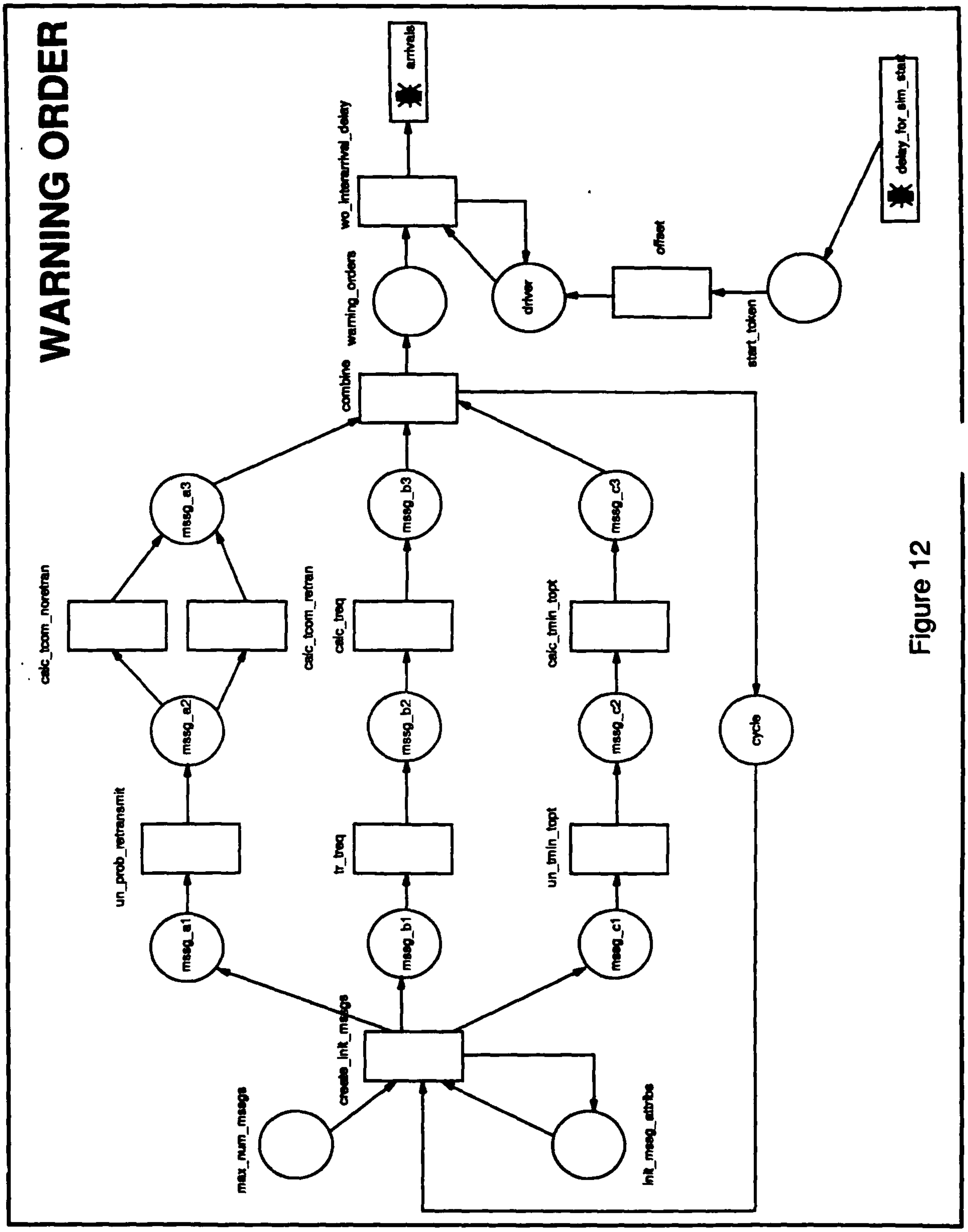

WARNING ORDER
max_num_msgs
create_init_msgs
init_msg_attribs
msg_a1
msg_b1
msg_c1
un_prob_retransmit
tr_treq
un_tmin_topt
msg_a2
msg_b2
msg_c2
calc_tcom_noretran
calc_tcom_retran
calc_treq
calc_tmin_topt
msg_a3
msg_b3
msg_c3
cycle
combine
warning_orders
wo_interarrival_delay
arrivals
driver
offset
start_token
delay_for_sim_start

Figure 12

The transition create_init_mssgs fires immediately, this creates a warning order message. This message then has three attributes calculated in parallel. These attributes will be used in the node processing submodel. The three attributes calculated are: time to transmit (t_com), time required to process this message, (tr_treq), and a processing time between the minimum processing time and the optimum processing time (un_tmin_topt).

The time to retransmit (t_com) is the time to retransmit a message and receive back an acknowledgement from the receiving headquarters. It's value is determined as stated below:

$$t\_com = \begin{cases} 0 \text{ if a random variable} \leq \text{input parameter} \\ t\_retran \text{ otherwise (SME input data)} \end{cases}$$

The time required to process the message (tr_reg) is the time to process the message, plus the time to communicate it, if no retransmisson is needed, plus the time to receive back an acknowledgement from the receiving headquarters.

The time to process our message (tr_reg) is drawn from a triangular distribution. The minimum value of the distribution is equal to the minimum processing time plus the time to communicate the message. The maximum value of the distribution is equal to the maximum time that will be taken to process plus the time to communicate the message. The mode is calculated as stated below:

$$\text{mode} = \min + .25\,(\max - \min) \quad \text{(offense)}$$
$$= \min + .75\,(\max - \min) \quad \text{(defense)}$$
$$= \min + .5\,(\max - \min) \quad \text{(transition)}$$

The different modes are described in this way because of the urgency of the information under the different corps missions.

The processing time will be a random uniform draw between the minimum processing time (t_min) and the optimum processing time (t_opt). This time will be used in the node processing submodel if the time available to process the message is greater than the time until the message is due. This is done to capture the notion that staffs do not spend all available time processing every message.

The transition combine will fire once all the attributes are calculated. This will enable create_init_mssgs again if max_num_mssgs has not been reached and will put our message in the place warning_orders. The messages will accumulate in warning_orders until the time delay from the simulation start_up submodel expires.

At the end of the delay from the simulation start_up, the transition offset will fire giving a one time delay of the first message to assure there is a time separation between the arrival of the first message of each information type.

Once offset has fired, the transition wo_interarrival_delay will fire sending messages to the node processing submodel according to the distribution of interarrival times defined by the SME's. Our message will then go to the node processing submodel.

c. *Node Processing*

In the node processing submodel all messages for the engineer staff are processed. It is in this submodel that the dynamics of the system are described. A graphical depiction of the model as it appears in Modeler is seen in FIG(13). We will again examine how this submodel functions by following a message through the model.

As our message is generated from one of the eight message type interarrival_delay transitions it enables the transition receive_mssgs. It is stamped with the time it was received and the time it is due is calculated. The message is then prioritized according to the SME's input and it's time of arrival in the place mssg_q. Here it waits for an available staff member. The

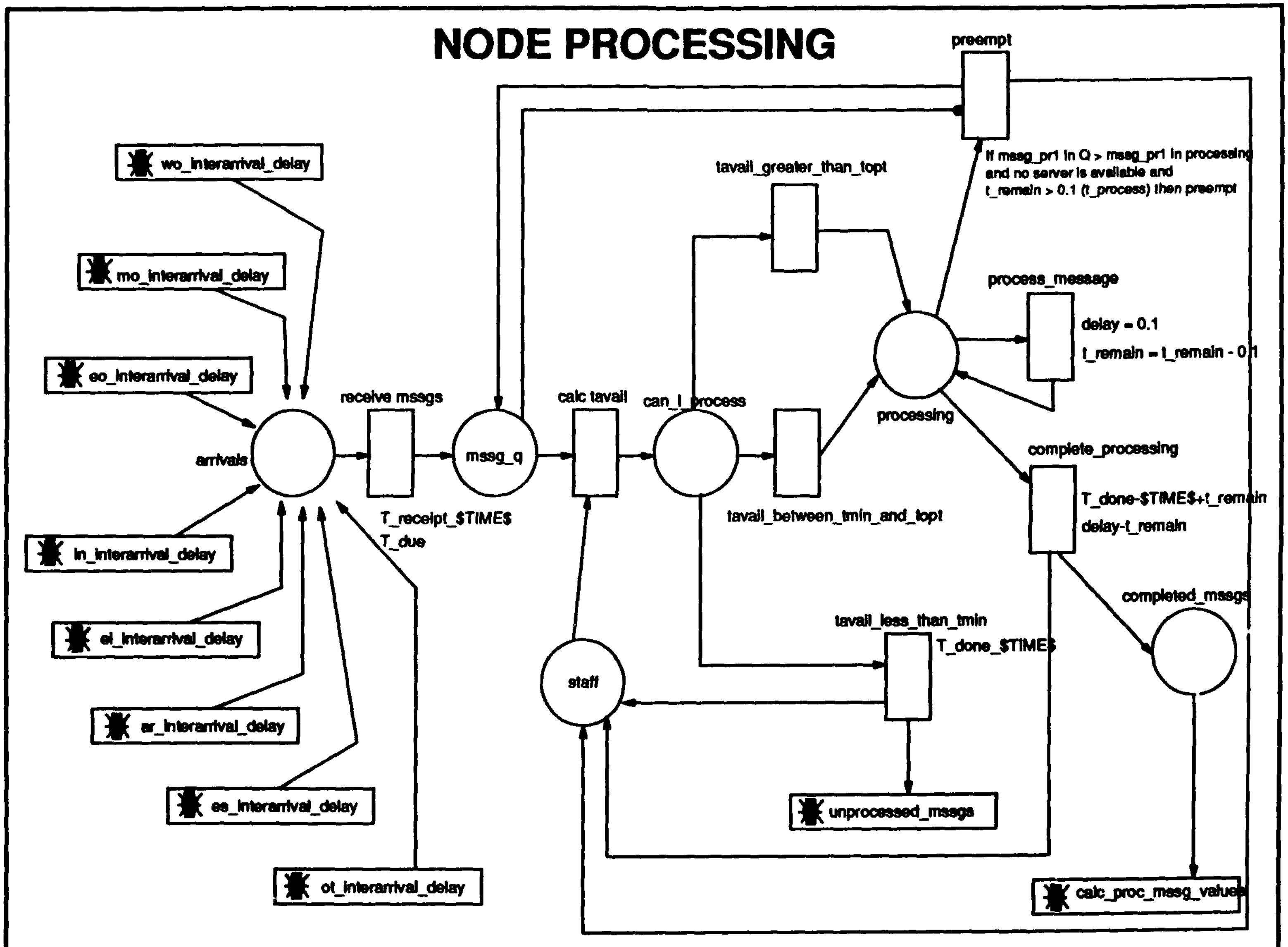

NODE PROCESSING
wo_interarrival_delay
mo_interarrival_delay
eo_interarrival_delay
in_interarrival_delay
ei_interarrival_delay
ar_interarrival_delay
es_interarrival_delay
ot_interarrival_delay
arrivals
receive mssgs
T_receipt_$TIME$
T_due
mssg_q
calc tavail
can_I_process
staff
tavail_greater_than_topt
tavail_between_tmin_and_topt
tavail_less_than_tmin
T_done_$TIME$
unprocessed_mssgs
preempt
If mssg_pr1 in Q > mssg_pr1 in processing
and no server is available and
t_remain > 0.1 (t_process) then preempt
processing
process_message
delay = 0.1
t_remain = t_remain - 0.1
complete_processing
T_done-$TIME$+t_remain
delay-t_remain
completed_mssgs
calc_proc_mssg_values

Figure 13

number of tokens in the place staff is determined by the size of the engineer staff thus determining how many messages can be processed simultaneously.

Once a staff member is available the transition calc_tavail fires calculating how much time is available to process our message. A decision rule at the place can_i_process determines which of the three paths our message will take based on the time available (t_avail) to process the message.

If there is not enough time to process our message, the transition tavail_less_than_tmin fires. The message is stamped with its completion time and the time it waited to be processed. It is then placed in the output box. The staff member then returns to the place staff and is then available to process another message.

If the time available is greater than the optimal (maximum) time it takes to process our message, (i.e. there is more time available then the staff will use), the transition tavail_greater_than_topt fires. The SME's decided that a staff would not normally take the maximum time to process a message even if it is available. To model this, the time to process a message when the time available is greater than the maximum time required is drawn from a uniform distribution with the minimum value equal to the minimum processing time (t_min) plus the communication time, and the maximum value equal to the optimal processing time.

If the time available is greater than the minimum processing time, but less than the optimal processing time, the time to process the message (t_process) will equal the time available (t_avail). This models a staff person working under a time constraint and getting what ever information he has out when it is needed.

After the processing time has been calculated our message proceeds to the logical place processing. It will remain in this place having the time remaining to process decreased by the transition process_mssg until the message is preempted or until the message is 90% processed. The value 90% was selected as the point were a person would just finish what he was doing rather than put it down to start a new message. There are two paths by which our message can escape this place.

Our message will get preempted if there is a message in the queue with a higher priority, no staff member is available, and less than 90% of the message has been processed. This is modeled in Modeler by the enable arc (the arc from mssg_q and the transition preempt). The preempted message will be marked and the time spent will be recorded. It will then be put back into the queue and the staff member will become available for the higher priority message.

Once our message is 90% completed, it will enable the complete_processing transition. This transition stamps the message with its completion time and places it in the output box. The staff member becomes available after the message is completely processed. The message then enters the last submodel and has it's output attributes calculated.

When the submodel is finished, all messages are either processed or unprocessed. The last submodel then completes output calculations.

d. Output Statistics

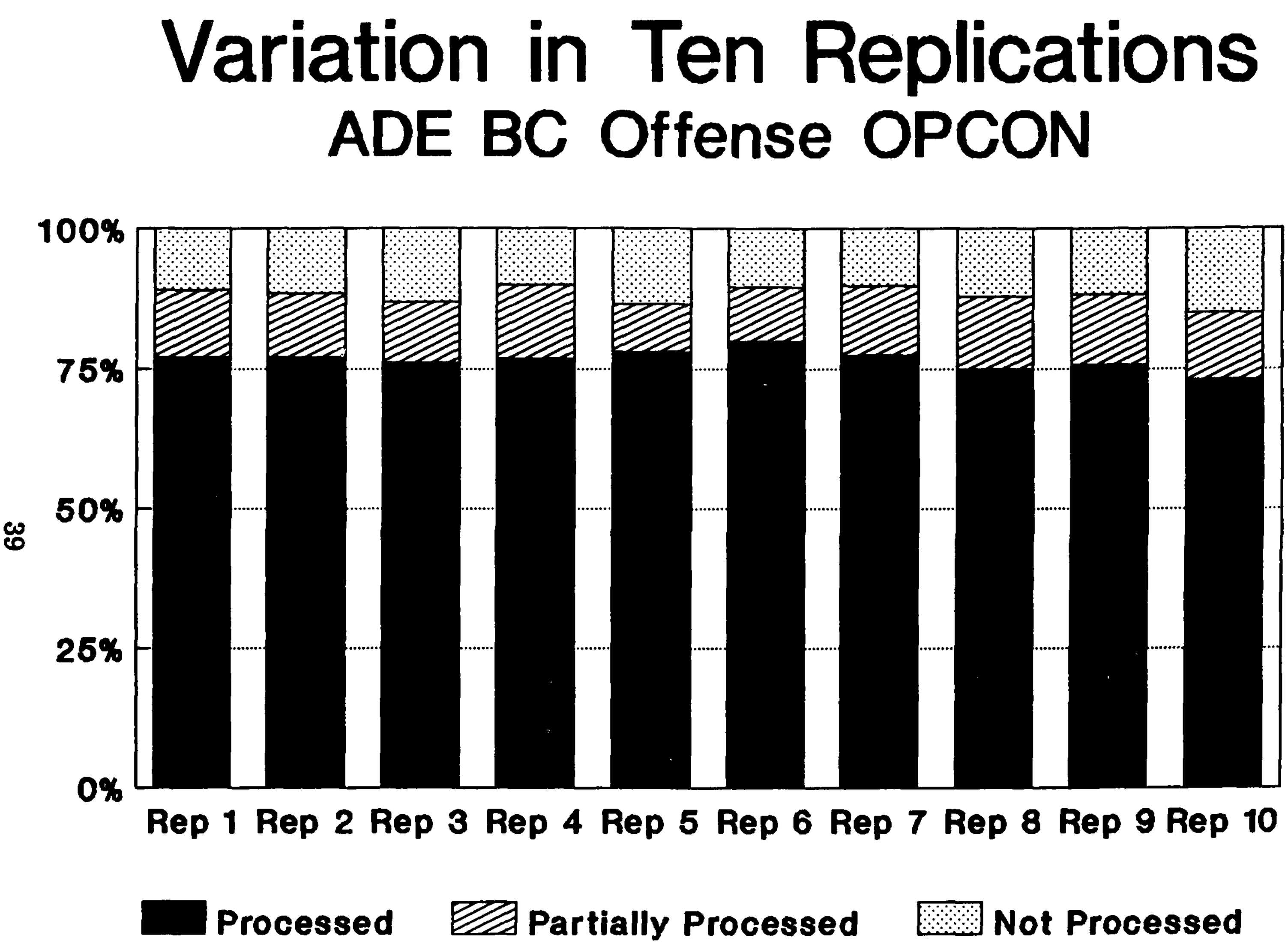
In the output statistics submodel the messages are sorted and output statistics are calculated. The output from MODELER consisted of:

- Processing time delay- (minimum, maximum, and average) time it took to process messages of a specific message type.
- Waiting time delay- (minimum, maximum, and average) time a message waits to be processed.
- Quality factor- (minimum, maximum, and average) the quality of a processed message at each staff by type based on the time it took to process the message.
- Total time delay- (minimum, maximum, and average) sum of the processing time, waiting time, and transmission time to the receiving staff.
- The number of processed, partially processed, and unprocessed messages by type and staff.

The model is stochastic so the variability of its output was examined by running 10 replications of the ADE base case offense. FIG(14) is a graphical presentation of the number of messages processed, partially processed and unprocessed for each run. In addition, a 95% confidence interval was constructed around the sample mean of the total time delay for each message type using the t-statistic with 9 degrees of freedom.

The length of the largest confidence interval was ± 5% of the sample mean. The lack of variation is attributed to the limits placed on the processing time, the required time, and the interarrival times.

Due to time constraints, the purpose of the study, and the results above, it was decided that a single replication of each case was sufficient.



Variation in Ten Replications
ADE BC Offense OPCON
100%
75%
50%
25%
0%
Rep 1
Rep 2
Rep 3
Rep 4
Rep 5
Rep 6
Rep 7
Rep 8
Rep 9
Rep 10
Processed
Partially Processed
Not Processed

Figure 14

IV. ANALYSIS OF THE THREE C2 ALTERNATIVES

A. INSIGHTS FROM THE DATA

The output from Modeler is not in a form that can be used to evaluate the three alternatives. The data represents how each staff performed, not how the command performed as a whole. This can be seen in FIG(15) where there is no direct comparison of nodes.

In this figure, the engineer battalion forward divisional, (EBF-DIV) is compared in each of the three alternatives. Yet this battalion is distinctly different in each alternative. Under the Base Case and Company Restructure alternative, the battalion supports a division; while under the Division Engineer alternative it supports a brigade.

Additionally each node contributes differently to the corps. As an example, in the Base Case there is only one engineer brigade (EN-BDE) but, the number of brigade engineer sections (BDE EN-S) is dependent on the number of divisions in the corps. In our notional four division corps there would be twelve brigade engineer sections. There are, however, some insights that can be drawn from the data.

Message Processing by Node

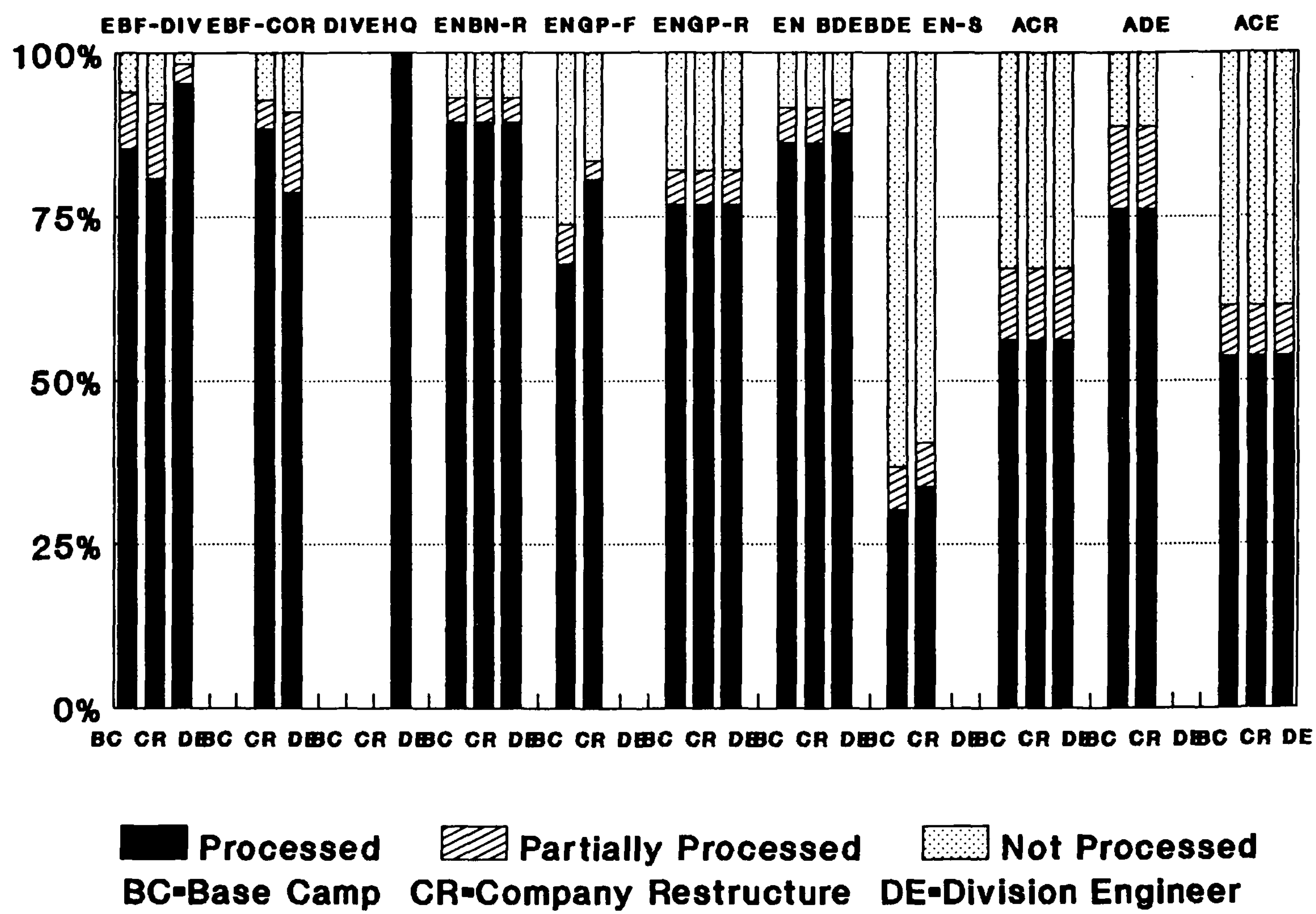


Figure 15

The goal of any staff is to process all incoming messages. The performance of each staff in each case can be seen in FIG(16) through FIG(18). From the figures one can see only the division engineer headquarters in the offense case was able to process all incoming messages. In addition, there are certain staffs that perform noticeably poorer than the others. These staffs are: the brigade engineer section, the armored calvary's engineer section, and the assistant corps engineer section. These three staff's performances must be improved under any alternative selected.

Further evaluation of the alternatives is impossible with the data in its present form. There is no staff to staff comparison between the alternatives and some staffs have different functions in each alternatives.

B. ANALYSIS METHODOLOGY

The model output must be manipulated so the MOP's derived earlier are viable. One of the keys to evaluating the alternatives is to view them from the corps commander's perspective. To fully understand his perspective, the effects of the different engineer C2 structures on the corps commander's primary maneuver commanders must be understood. These maneuver commanders are his division commanders and the brigade commanders.

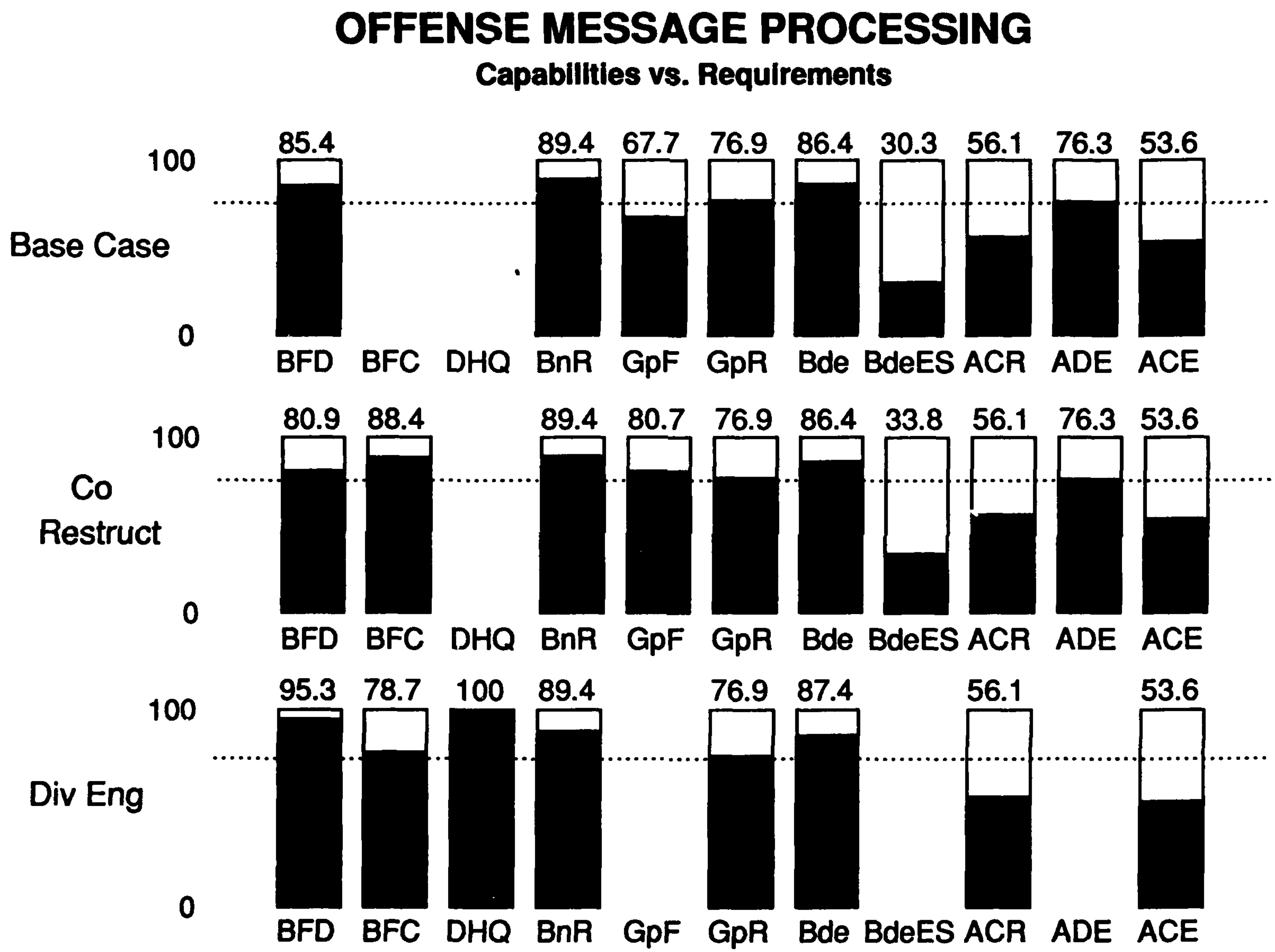

OFFENSE MESSAGE PROCESSING
Capabilities vs. Requirements
Base Case
Co Restruct
Div Eng
100
0
85.4 89.4 67.7 76.9 86.4 30.3 56.1 76.3 53.6
80.9 88.4 89.4 80.7 76.9 86.4 33.8 56.1 76.3 53.6
95.3 78.7 100 89.4 76.9 87.4 56.1 53.6
BFD BFC DHQ BnR GpF GpR Bde BdeES ACR ADE ACE

Figure 16

DEFENSE MESSAGE PROCESSING

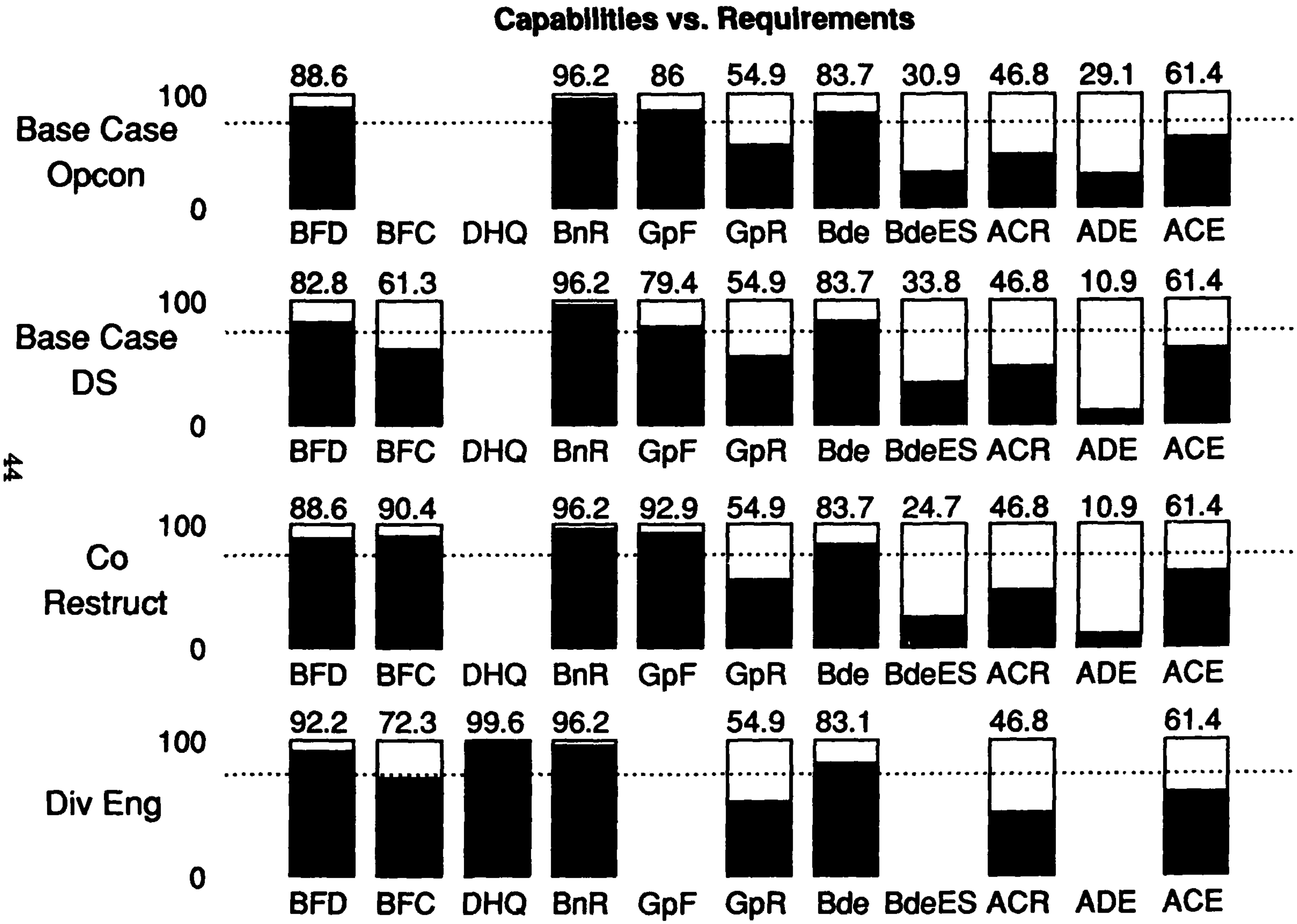


Figure 17

TRANSITION MESSAGE PROCESSING

Capabilities vs. Requirements

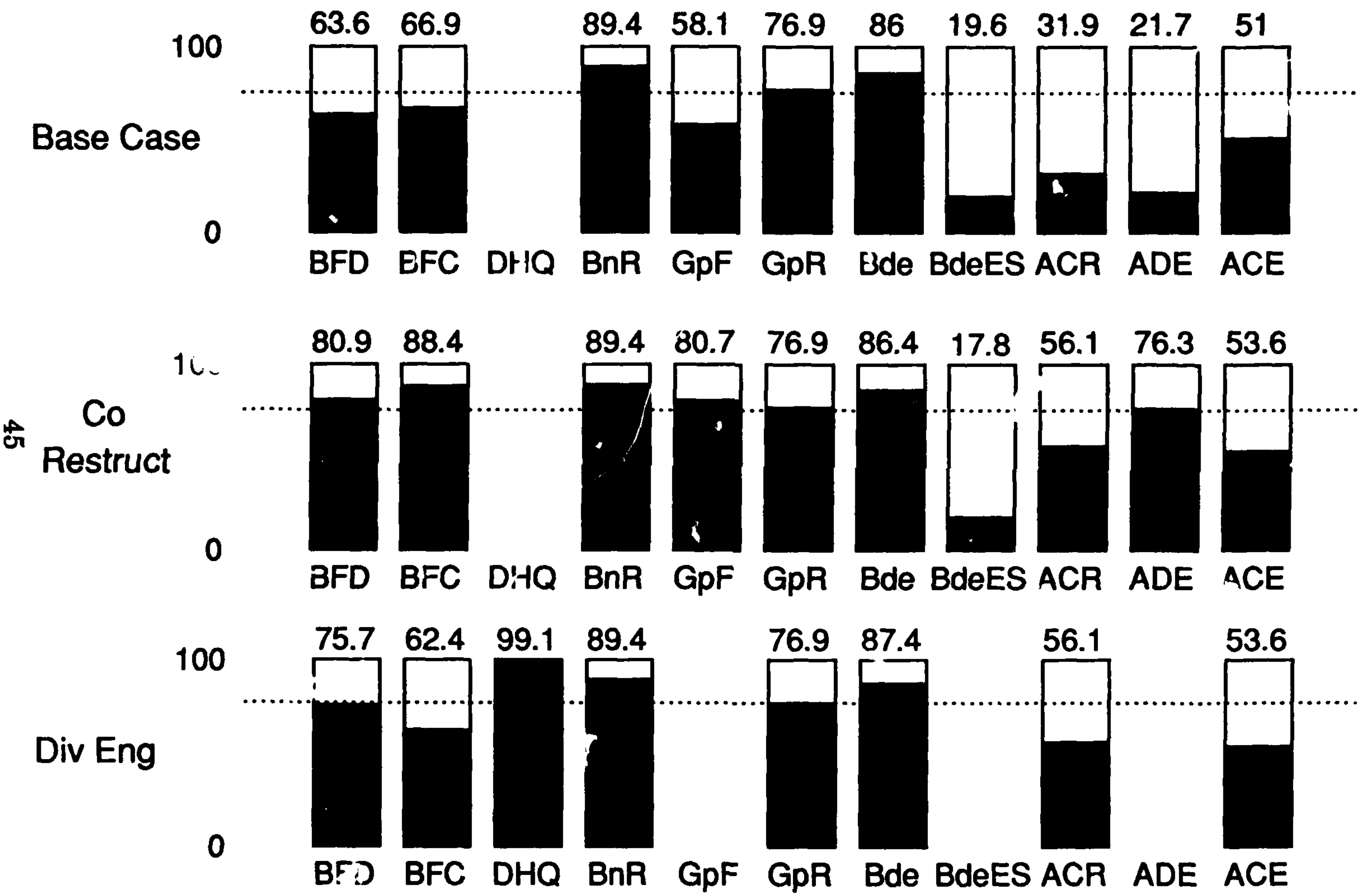


Figure 18

Phase I allocation rules, which dictate how many engineer units are assigned to a corps, were used to determine each engineer staffs contribution to a notional four division corps. The engineer organization of the notional corps is shown in Table 1. Divisional and brigade task organization are shown in Table 2 and Table 3 respectively.

The average output data from Modeler was used to further build the alternatives. It is reasonable to believe that the simulation reached steady state since it simulated 15 days of war. This methodology allows a direct comparison of the alternatives. Each of the MOP's developed earlier will utilize this methodology.

TABLE 1

NUMBER OF ENGINEER STAFFS IN THE CORPS BY ALTERNATIVE

	EBF DIV	EBF COR	DIVEHQ	ENBN R	ENGP F	ENGP R	EN BDE	BDE EN-S	ACR	ADE	ACE
BASE CASE	4	8	0	5	3	1	1	12	1	4	1
COMPANY RESTRUCTURE	4	4	0	7	3	1	1	12	1	4	1
DIVISION ENGINEER	12	5	4	5	0	3	1	0	1	0	1

TABLE 2

NUMBER OF ENGINEER STAFFS IN THE DIVISIONS BY ALTERNATIVE

	EBF DIV	EBF COR	DIVEHQ	ENBN R	ENGP F	ENGP R	EN BDE	BDE EN-S	ACR	ADE	ACE
BASE CASE	4	8	0	4	3	0	0	12	0	4	0
COMPANY RESTRUCTURE	4	4	0	3	3	0	0	12	0	4	0
DIVISION ENGINEER	12	4	4	2	0	2	0	0	0	0	0

TABLE 3

NUMBER OF ENGINEER STAFFS IN THE BRIGADES BY ALTERNATIVE

	EBF DIV	EBF COR	DIVEHQ	ENBN R	ENGP F	ENGP R	EN BDE	BDE EN-S	ACR	ADE	ACE
BASE CASE	0	8	0	0	0	0	0	12	0	0	0
COMPANY RESTRUCTURE	0	4	0	0	0	0	0	12	0	0	0
DIVISION ENGINEER	12	0	0	0	0	0	0	0	0	0	0

C. OFFENSIVE CASE RESULTS

1. MOP 1: Processing Capacity

Processing capacity is the ability of the alternative to process the required information. This MOP examines each alternatives ability to collect, analyze, and present information. It is the percentage of messages processed at each maneuver level for each of the cases, and is calculated as follows:

LET i = 1,2,...,11 represent the staffs EBF-DIV, EBF-COR, ENBN-R, DIVEHQ, ENGP-F, ENGP-R, EN BDE, BDE EN-S, ACR, ADE, ACE.

DEFINE for i = 1,2,...,11

X_i = the number of type i engineer staff in the command.

Y_i = the number of messages processed per type i engineer staff.

Z_i = the total number of messages generated per type i engineer staff.

PERCENT OF MESSAGES PROCESSED FOR EACH ALTERNATIVE

$$\frac{\sum_i X_i Y_i}{\sum_i X_i Z_i} \text{ for each alternative } i = 1,2,\ldots,11.$$

An example of this calculation for the Base Case offense for the brigade's warning orders is (8 corps engineer battalions * 20 warning orders processed per corps battalion + 12 brigade engineer sections * 19 warning orders processed per section / 8 corps engineer battalions * 20 warning orders generated per corps battalion + 12 brigade engineer sections * 20 warning orders generated per section) * 100 = (160 + 228 / 160 + 240) * 100 = 97% warning orders processed in the corps's maneuver brigades.

MOP1 is calculated for each message type and each alternative with corps, division and brigade level. The following table contains these results.

TABLE 4

		OFFENSE CASE PROCESSING CAPACITY PERCENT MESSAGES PROCESSED								
			BRIGADE			DIVISION			CORPS	
MESSAGE PRIORITY	MESSAGE TYPE	BASE CASE	CO RESTRUC	DIV ENG	BASE CASE	CO RESTRUC	DIV ENG	BASE CASE	CO RESTRUC	DIV ENG
1	Warning Order	97.0	100.0	100.0	98.0	100.0	100.0	97.2	98.9	98.7
2	Maneuver Order	100.0	100.0	100.0	100.0	100.0	100.0	95.7	93.7	92.4
3	Engineer Order	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
6	Intell Annexes	48.0	50.4	98.3	65.5	68.6	94.1	68.5	73.7	93.3
4	Enemy Info	88.2	37.0	100.0	82.4	70.6	94.7	82.1	72.8	92.1
5	Asset Requests	77.5	76.1	98.4	84.2	82.1	98.5	85.6	84.7	98.4
7	Engineer SITREPs	48.0	11.7	98.7	88.1	58.9	89.7	88.4	80.2	85.6
8	Other Routine	31.5	28.4	86.7	48.5	45.0	83.5	50.6	51.9	80.4

From this table we can see the effects of the prioritization of the message types. All three alternatives at each of the three levels of command perform well on the three highest priority message types. After the three highest priorities the base case and company restructure alternatives perform noticeably poorer than the division engineer alternative.

The effects of moving more equipment and personnel into the divisions without providing for additional command and control degrades the company restructure alternative performance. This is evident in the company restructures extremely poor performance in the lowest priority messages at the brigade level.

By summing over all the message types we get the over all processed percentage for each of the levels of command by alternative. These results can be seen in FIG(19). Clearly the Division Engineer alternative out performs the other two.

2. MOP 2: Message Quality

Message quality is the accuracy and the reliability of the information passed. Message quality is scored on a scale of 0 to 1. Quality is determined by the experience of the staff (SME Input) and the amount of time available to process the message. Message quality will be summarized by computing a command average.

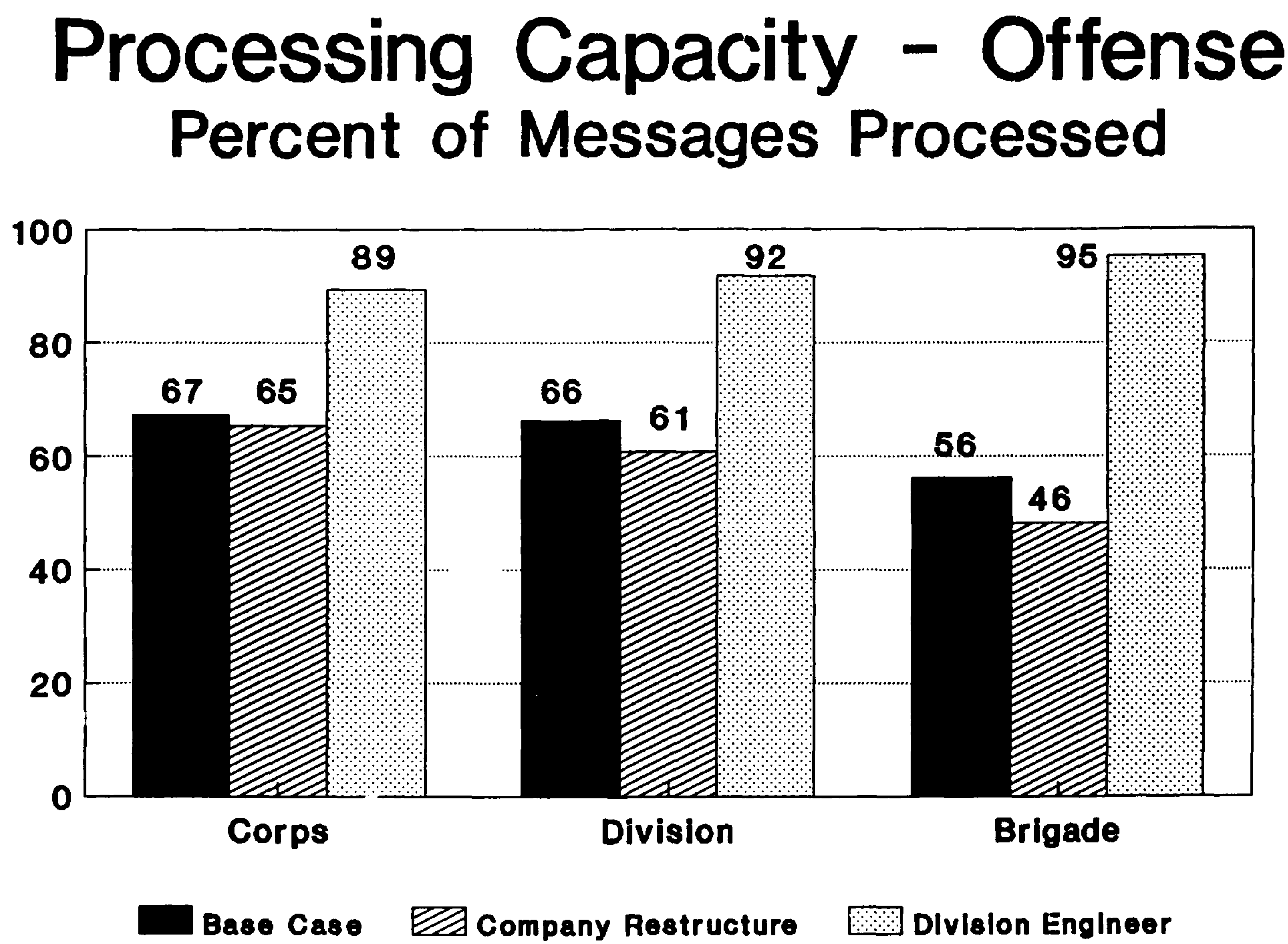

Processing Capacity - Offense
Percent of Messages Processed
100
80
60
40
20
0
67
65
89
66
61
92
56
46
95
Corps
Division
Brigade
Base Case
Company Restructure
Division Engineer

Figure 19

LET i = 1,2,...,11 represent the staffs EBF-DIV, EBF-COR, ENBN-R, DIVEHQ, ENGP-F, ENGP-R, EN BDE, BDE EN-S, ACR, ADE, ACE.

DEFINE for i = 1,2,...,11

X_i = the number of type i engineer staff in the command.

Y_i = the number of messages processed per type i engineer staff .

Z_i = the average quality value of the messages processed by type i engineer staff.

AVERAGE MESSAGE QUALITY IN THE COMMAND

$$\frac{\sum_i X_i Y_i Z_i}{\sum_i X_i Y_i} \text{ for each alternative } i = 1,2,...,11.$$

An example of this calculation for the Base Case offense for the brigade's warning orders is (8 corps engineer battalions * 20 warning orders processed per corps battalion * 0.54 the average message quality in a corps battalion + 12 brigade engineer sections * 19 warning orders processed per section * 0.42 the average message quality in the brigade engineer section / 8 corps engineer battalions * 20 warning orders processed per corps battalion + 12 brigade engineer sections * 20 warning orders processed per section) = (86.4 + 95.76 / 160 + 228) = 0.4695 average message quality in the corps's maneuver brigades.

This is done for each message type and each alternative with the results in the following table at corps, division and brigade level. The following table contains these results.

TABLE 5

			OFFENSE CASE PROCESSING SPEED OF MESSAGES PROCESSED							
			BRIGADE			DIVISION			CORPS	
MESSAGE PRIORITY	MESSAGE TYPE	BASE CASE	CO RESTRUC	DIV ENG	BASE CASE	CO RESTRUC	DIV ENG	BASE CASE	CO RESTRUC	DIV ENG
1	Warning Order	2.96	3.88	0.82	2.56	3.01	1.26	2.59	2.94	1.44
2	Maneuver Order	5.47	5.32	0.86	5.22	5.34	1.84	5.35	5.53	2.22
3	Engineer Order	3.37	2.72	2.35	4.31	4.58	3.97	4.79	4.93	4.08
6	Intell Annexes	2.31	2.00	1.07	2.58	2.43	1.96	2.60	2.49	2.14
4	Enemy Info	2.13	1.87	0.71	2.22	2.22	0.99	2.21	2.15	1.12
5	Asset Requests	2.40	2.55	1.12	2.33	2.38	1.57	2.56	2.55	1.78
7	Engineer SITREPs	2.49	2.80	2.32	2.94	3.27	2.87	3.10	3.33	3.01
8	Other Routine	3.03	3.09	3.19	3.01	3.07	2.99	3.16	3.14	3.08

From the table it is clear that Division Engineer produces higher quality messages at every command level and for each message type.

We then sum over all the message types to get the over all message quality for each of the levels of command by alternative. These results can be seen in FIG(20). The Division Engineer attains higher message quality scores than the other alternatives.

3. MOP 3: Processing Speed

Processing Speed is the speed at which messages are processed and orders issued. This MOP examines how fast each alternative is able to collect, analyze, present information and issue orders.

LET i = 1,2,...,11 represent the staffs EBF-DIV, EBF-COR, ENBN-R, DIVEHQ, ENGP-F, ENGP-R, EN BDE, BDE EN-S, ACR, ADE, ACE.

DEFINE for i = 1,2,...,11

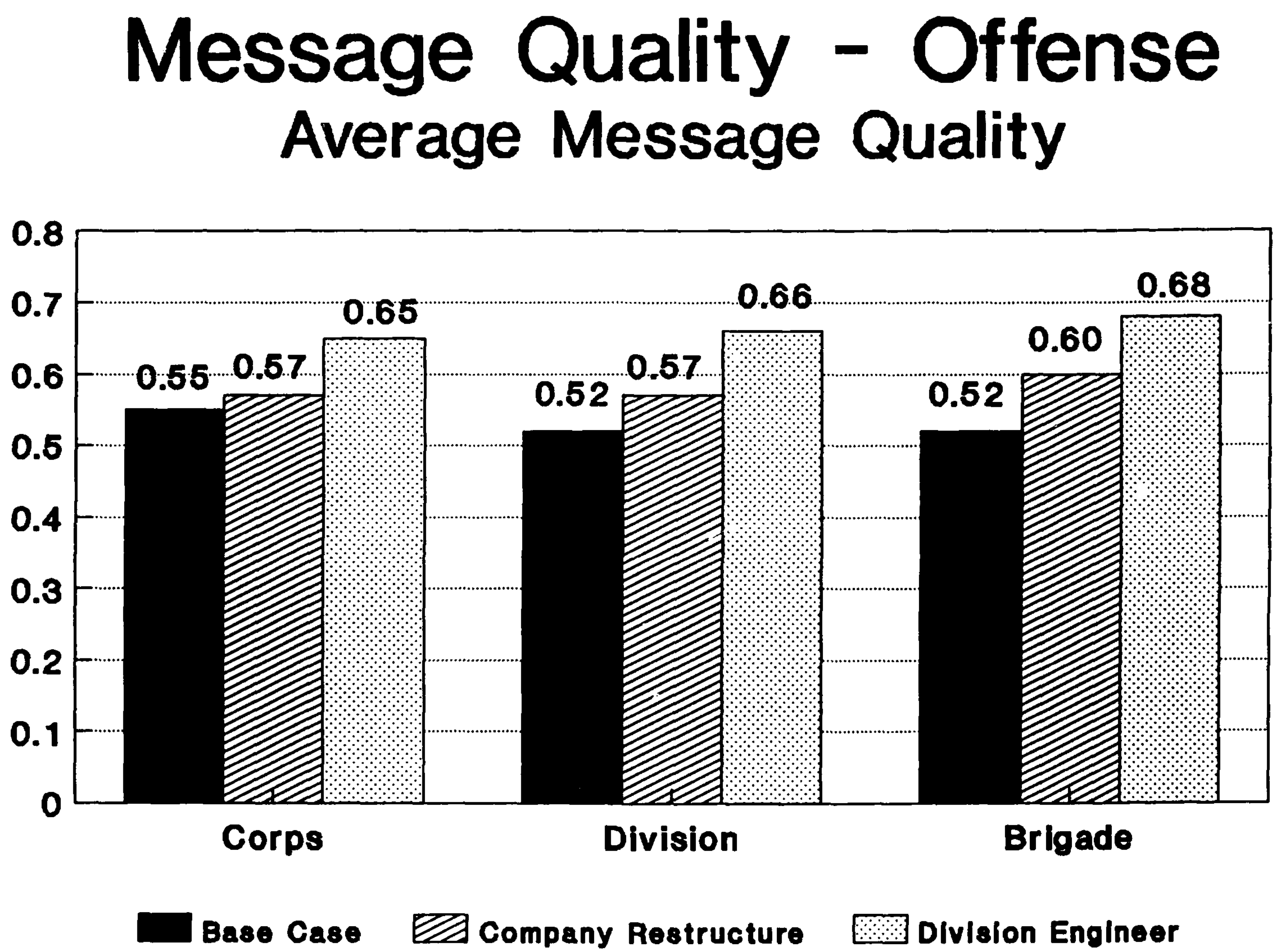
X_i = the number of type i engineer staff in the command.

Y_i = the number of messages processed per type i engineer staff.

Z_i = the average total delay value of the messages processed by type i engineer staff.

AVERAGE MESSAGE TOTAL DELAY IN THE COMMAND

$$\frac{\sum_i X_i Y_i Z_i}{\sum_i X_i Y_i} \text{ for each alternative } i = 1,2,\ldots,11.$$



Message Quality - Offense
Average Message Quality
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.55
0.57
0.65
0.52
0.57
0.66
0.52
0.60
0.68
Corps
Division
Brigade
Base Case
Company Restructure
Division Engineer

Figure 20

The results of these calculations are shown in the following table.

TABLE 6

			OFFENSE CASE PROCESSING SPEED OF MESSAGES PROCESSED							
			BRIGADE			DIVISION			CORPS	
MESSAGE PRIORITY	MESSAGE TYPE	BASE CASE	CO RESTRUC	DIV ENG	BASE CASE	CO RESTRUC	DIV ENG	BASE CASE	CO RESTRUC	DIV ENG
1	Warning Order	2.96	3.06	0.82	2.56	3.01	1.28	2.59	2.94	1.44
2	Maneuver Order	5.47	5.32	0.89	5.22	5.34	1.84	5.35	5.53	2.22
3	Engineer Order	3.37	2.72	2.36	4.31	4.58	3.97	4.79	4.93	4.08
6	Intell Annexes	2.31	2.00	1.07	2.58	2.43	1.96	2.60	2.49	2.14
4	Enemy Info	2.13	1.87	0.71	2.22	2.22	0.99	2.21	2.15	1.12
5	Asset Requests	2.40	2.55	1.12	2.33	2.36	1.57	2.56	2.55	1.78
7	Engineer SITREPs	2.49	2.80	2.32	2.94	3.27	2.87	3.10	3.33	3.01
8	Other Routine	3.03	3.00	3.19	3.01	3.07	2.99	3.16	3.14	3.08

Processing speed measures how fast a staff can collect, analyze, and provide the information to those who need it. This is extremely critical in the forward battle area, where the situation changes rapidly. The Division Engineer alternative excels at providing information rapidly at all levels of command, but most notably in the forward battle area. This can be seen from the table at the brigade level.

The overall total time delay average for each of the levels of command by alternative can be seen in FIG(21). Again, the Division Engineer alternative achieves superior results.

D. DEFENSIVE CASE RESULTS

There are four alternatives in the Defense Case. In this case the Base Case was modeled using two different command and support relationships. Historically and doctrinally, engineers have been placed in direct support of the maneuver units during defensive operations. This was done to centralize engineer planning and operations. In recent years it became evident that this command and support relationship was not responsive enough for the maneuver commanders. The corps in Europe changed this command and support relationship to operational control. The results here indicate that this was a good decision. Operationally controlled command and support is preferred over the direct support command and support relationship.

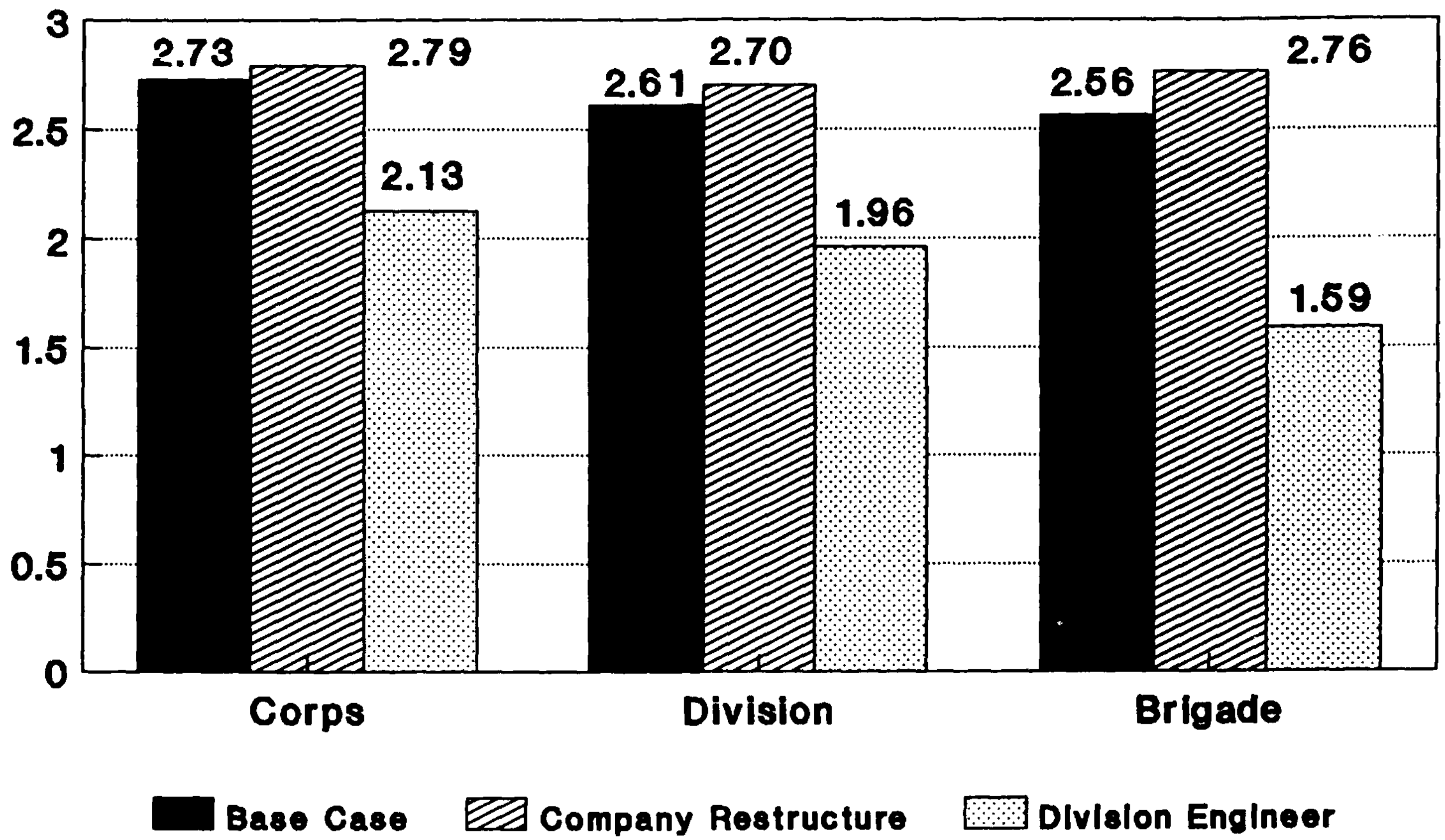
1. MOP 1: Processing Capacity

The results with the corps in the defense are very similar to the Offensive Case. Table 7 contains these results.

The effects of the prioritization of the message types can still be seen. All four alternatives at each of the three levels of command perform well on

Processing Speed - Offense

Time Delay Average



Smaller is Better

Figure 21

TABLE 7

		DEFENSE CASE PROCESSING CAPACITY PERCENT MESSAGES PROCESSED											
		BRIGADE				DIVISION				CORPS			
MESSAGE PRIORITY	MESSAGE TYPE	BC OPCON	BC DS	CO RESTRUC	DIV ENG	BC OPCON	BC DS	CO RESTRUC	DIV ENG	BC OPCON	BC DS	CO RESTRUC	DIV ENG
1	Warning Order	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.4	97.4	97.8	97.4	98.0
2	Maneuver Order	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	94.2	93.5	92.7	98.3
3	Engineer Order	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.5
5	Intell Annexes	75.8	68.0	28.3	100.0	85.2	81.0	57.4	94.2	87.1	83.8	88.7	93.6
6	Enemy Info	73.2	46.1	59.9	98.7	65.4	46.1	56.7	96.4	86.0	40.5	61.8	93.2
4	Asset Requests	94.8	90.5	62.8	100.0	96.2	92.0	75.6	98.6	95.3	91.6	78.2	98.3
7	Engineer SITREPs	38.2	27.3	21.3	97.5	55.5	41.7	44.1	85.2	56.1	43.9	50.3	81.2
8	Other Routine	20.5	14.9	19.8	67.3	36.6	28.4	38.9	88.3	38.8	31.7	45.4	86.4

the highest priority message types. Once again, the Base Case and Company Restructure alternatives performed noticeably poorer than the Division Engineer alternative in the lower priority message types.

The overall processed percentage for each of the levels of command by alternative can be seen in FIG(22). Clearly the Division Engineer alternative out performs the others.

2. MOP 2: Message Quality

Message quality is calculated the same in the defense case as in the Offense Case with similar results. Table 8 contains these results.

The overall command average for each of the levels of command by alternatives can be seen in FIG(23). The results are similar to the Offense Case, with Division Engineer out performing the other alternatives in message quality.

3. MOP 3: Processing Speed

The results for processing speed under this case are also similar as shown in Table 9. FIG(24) shows the overall total time delay average for this case.

Processing Capacity - Defense
Percent of Messages Processed

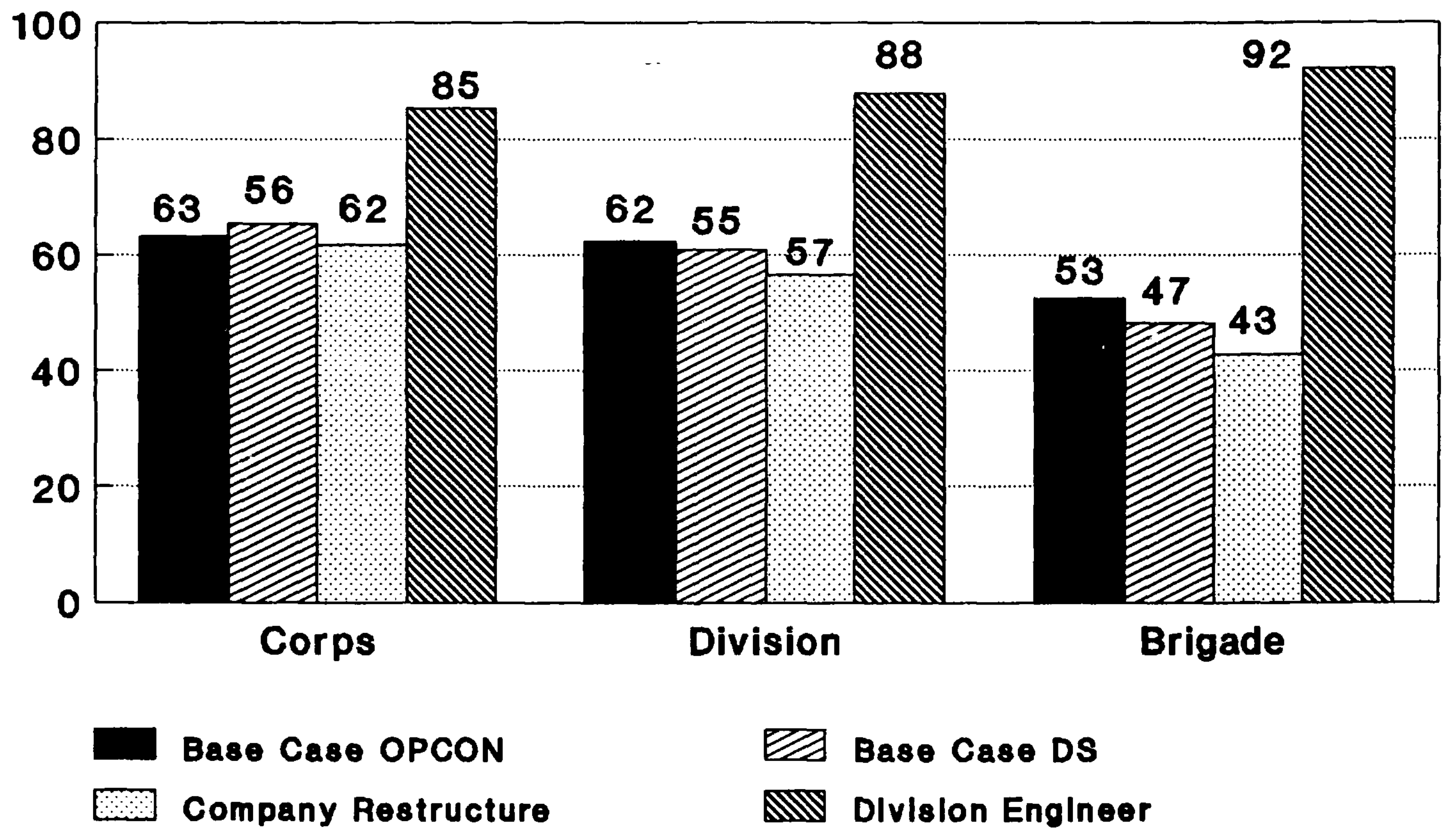


Figure 22

TABLE 8

		DEFENSE CASE PROCESSING SPEED OF MESSAGES PROCESSED											
			BRIGADE				DIVISION				CORPS		
MESSAGE PRIORITY	MESSAGE TYPE	BC OPCON	BC DS	CO RESTRUC	DIV ENG	BC OPCON	BC DS	CO RESTRUC	DIV ENG	BC OPCON	BC DS	CO RESTRUC	DIV ENG
1	Warning Order	0.45	0.46	0.52	0.70	0.50	0.51	0.53	0.67	0.58	0.51	0.54	0.64
2	Maneuver Order	0.52	0.61	0.61	0.69	0.54	0.56	0.60	0.71	0.54	0.66	0.60	0.70
3	Engineer Order	0.58	0.65	0.46	0.61	0.60	0.58	0.58	0.72	0.61	0.58	0.66	0.71
5	Intell Annexes	0.42	0.44	0.55	0.70	0.49	0.50	0.56	0.66	0.53	0.53	0.58	0.64
6	Enemy Info	0.48	0.60	0.50	0.60	0.49	0.50	0.51	0.60	0.60	0.51	0.62	0.68
4	Asset Requests	0.64	0.65	0.63	0.75	0.65	0.66	0.64	0.73	0.65	0.65	0.64	0.71
7	Engineer SITREPs	0.51	0.61	0.59	0.69	0.51	0.50	0.53	0.64	0.51	0.60	0.52	0.61
8	Other Routine												

Message Quality - Defense

Average Message Quality

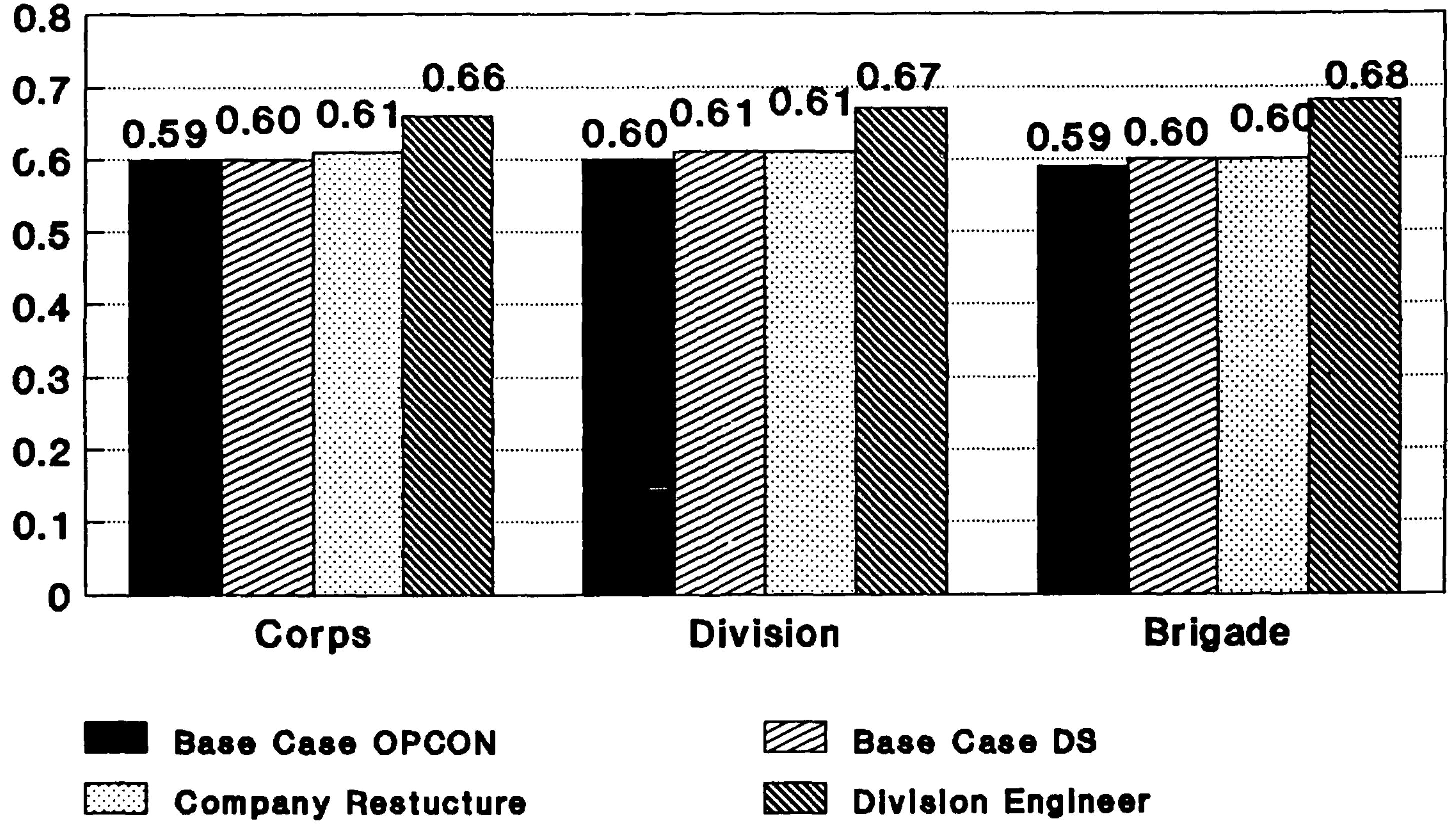
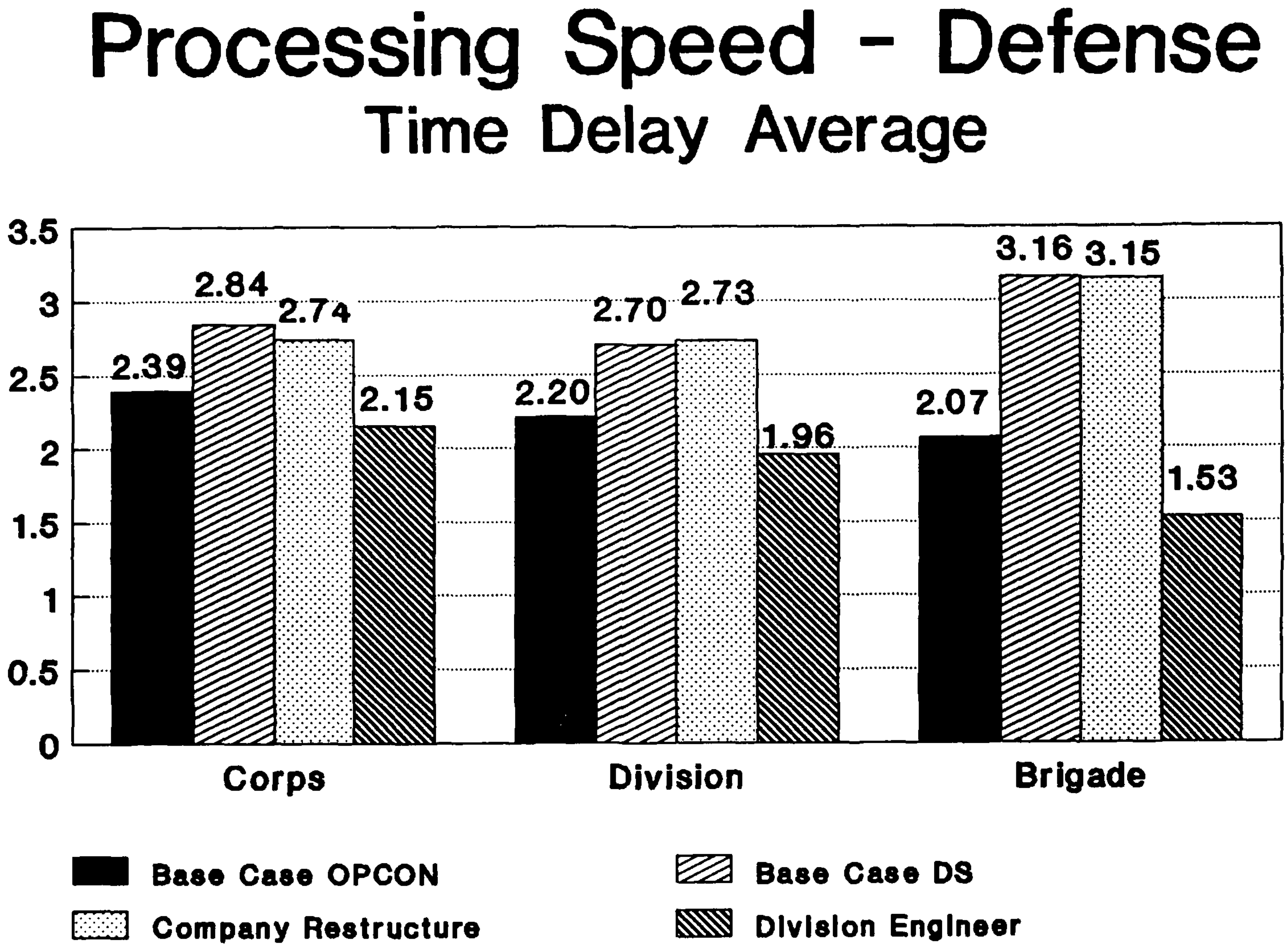


Figure 23

TABLE 9

				DEFENSE CASE PROCESSING SPEED OF MESSAGES PROCESSED									
			BRIGADE				DIVISION				CORPS		
MESSAGE PRIORITY	MESSAGE TYPE	BC OPCON	BC DS	CO RESTRUC	DIV ENG	BC OPCON	BC DS	CO RESTRUC	DIV ENG	BC OPCON	BC DS	CO RESTRUC	DIV ENG
1	Warning Order	2.57	3.17	2.76	0.86	2.21	2.65	2.31	1.36	2.26	2.65	2.27	1.86
2	Manouver Order	4.73	6.02	6.17	2.57	4.89	6.03	5.89	3.46	5.15	6.29	6.16	4.67
3	Engineer Order	5.74	4.19	3.34	3.31	5.83	5.03	5.62	4.86	6.33	5.34	6.09	5.35
5	Intell Annexes	1.74	2.14	1.51	1.25	1.83	2.38	1.91	1.50	1.81	2.22	1.78	1.86
6	Enemy Info	1.22	1.89	1.28	0.79	1.37	1.51	1.28	0.94	1.42	1.54	1.34	1.08
4	Asset Requests	1.48	3.21	3.38	1.06	1.39	2.42	2.40	1.84	1.88	2.80	2.39	1.76
7	Engineer SITREPs	3.31	3.80	3.62	2.22	3.24	3.35	3.40	2.83	3.36	3.40	3.38	3.09
8	Other Routine	4.11	4.29	3.55	4.12	3.77	3.79	3.60	3.40	4.02	4.10	3.77	3.72



Smaller Is Better

Figure 24

E. TRANSITION FROM OFFENSE TO DEFENSE CASE RESULTS

Transitioning from offense to defense is a critical time for engineers. They must quickly consolidate their units, and determine the status of their equipment. They must coordinate plans with maneuver forces and quickly begin work on obstacles and survivability positions. This is crucial because these task are time consuming.

1. MOP 1: Processing Capacity

The performance of all alternatives decrease because of the confusion during this transition. While the Division Engineer alternative's performance decreased somewhat, it's advantages are seen even in the highest priority message types when compared to the other alternatives. This is seen in Table 10.

The overall percentage of processed messages are shown in FIG(25). The Division Engineer alternative is still the best.

2. MOP 2: Message Quality

In this case, the Division Engineer alternative has higher quality messages at all levels of command for all message types. The results for this MOP are shown in Table 11.

TABLE 10

TRANSITION OFFENSE TO DEFENSE CASE PROCESSING CAPACITY PERCENT MESSAGES PROCESSED										
			BRIGADE			DIVISION			CORPS	
MESSAGE PRIORITY	MESSAGE TYPE	BASE CASE	CO RESTRUC	DIV ENG	BASE CASE	CO RESTRUC	DIV ENG	BASE CASE	CO RESTRUC	DIV ENG
5	Warning Order	12.0	27.8	86.0	21.7	57.8	81.9	23.6	63.4	81.5
8	Maneuver Order	4.0	0.0	70.0	5.4	46.0	86.4	6.4	44.7	81.6
7	Engineer Order	45.0	100.0	45.0	44.1	100.0	45.7	45.3	100.0	45.5
3	Intell Annexes	40.2	32.2	90.0	50.7	62.8	83.5	52.7	60.9	84.1
4	Enemy Info	38.1	6.5	90.6	48.2	43.0	86.9	48.9	50.6	85.3
2	Asset Requests	63.9	45.5	96.9	60.1	57.6	96.7	70.0	63.5	96.6
1	Engineer SITREPs	100.0	96.7	100.0	99.8	92.9	98.5	95.8	90.0	94.3
6	Other Routine	11.0	28.2	38.6	21.6	49.4	52.6	26.5	56.1	55.7

TABLE 11

	TRANSITION OFFENSE TO DEFENSE CASE MESSAGE QUALITY OF MESSAGES PROCESSED									
			BRIGADE			DIVISION			CORPS	
MESSAGE PRIORITY	MESSAGE TYPE	BASE CASE	CO RESTRUC	DIV ENG	BASE CASE	CO RESTRUC	DIV ENG	BASE CASE	CO RESTRUC	DIV ENG
5	Warning Order	0.47	0.53	0.70	0.54	0.53	0.70	0.54	0.54	0.67
8	Maneuver Order	0.55	0.0	0.68	0.54	0.60	0.70	0.54	0.60	0.69
7	Engineer Order	0.50	0.53	0.70	0.51	0.56	0.69	0.52	0.56	0.68
3	Intell Annexes	0.55	0.58	0.70	0.55	0.57	0.65	0.55	0.57	0.63
4	Enemy Info	0.50	0.49	0.60	0.49	0.48	0.57	0.48	0.49	0.56
2	Asset Requests	0.62	0.56	0.75	0.61	0.59	0.74	0.61	0.60	0.73
1	Engineer SITREPs	0.57	0.50	0.70	0.65	0.51	0.65	0.55	0.51	0.62
6	Other Routine									

Processing Capacity - Transition

Percent of Messages Processed

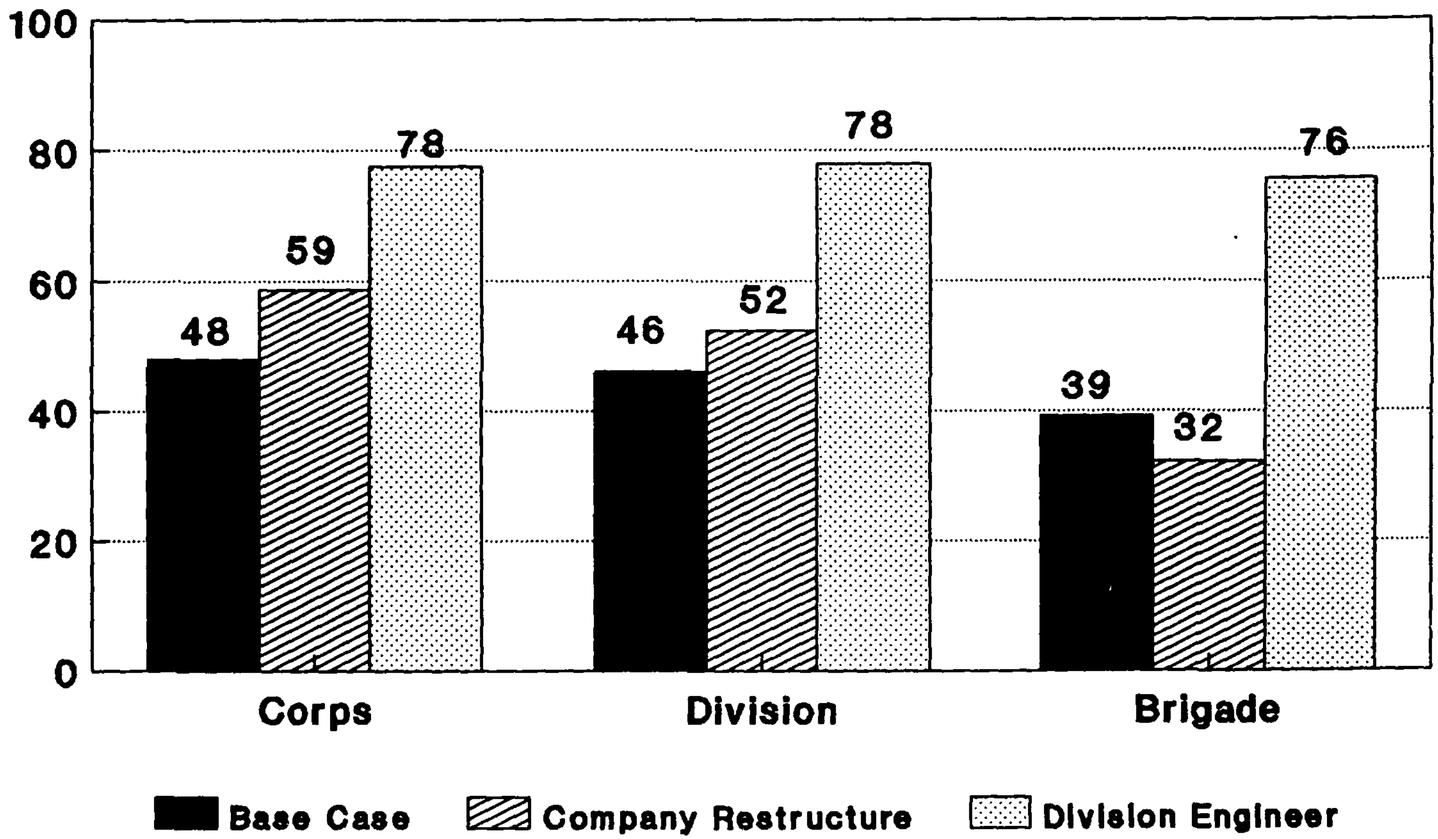


Figure 25

The overall case average message quality, by alternative and level of command is shown in FIG(26).

3. MOP 3: Processing Speed

In this case, Company Restructure has a faster processing speed for two of the lower priority messages. This is due to the small number of these type messages generated and processed in this case.

TABLE 12

	TRANSITION OFFENSE TO DEFENSE CASE PROCESSING SPEED OF MESSAGES PROCESSED									
			BRIGADE			DIVISION			CORPS	
MESSAGE PRIORITY	MESSAGE TYPE	BASE CASE	CO RESTRUC	DIV ENG	BASE CASE	CO RESTRUC	DIV ENG	BASE CASE	CO RESTRUC	DIV ENG
5	Warning Order	6.76	1.49	2.07	5.19	1.64	2.36	5.11	1.84	2.43
8	Maneuver Order	4.96	0.0	4.57	7.08	5.36	5.15	8.45	5.87	5.40
7	Engineer Order	5.28	2.72	4.83	5.82	4.58	5.24	5.76	4.93	5.32
3	Intell Annexes	1.97	2.56	1.45	2.19	2.69	1.99	2.34	2.67	2.12
4	Enemy Info	1.72	1.55	1.03	1.94	2.21	1.40	2.00	2.15	1.52
2	Asset Requests	3.63	3.81	2.20	3.72	3.09	2.44	3.71	3.15	2.55
1	Engineer SITREPs	4.54	4.17	3.17	4.32	3.83	3.48	4.32	3.77	3.53
6	Other Routine	4.13	2.99	3.60	3.38	3.04	3.25	3.60	3.12	3.30

The overall processing speed for the alternatives by level of command is shown in FIG(27). Division Engineer is still noticeably faster.

Message Quality - Transition

Average Message Quality

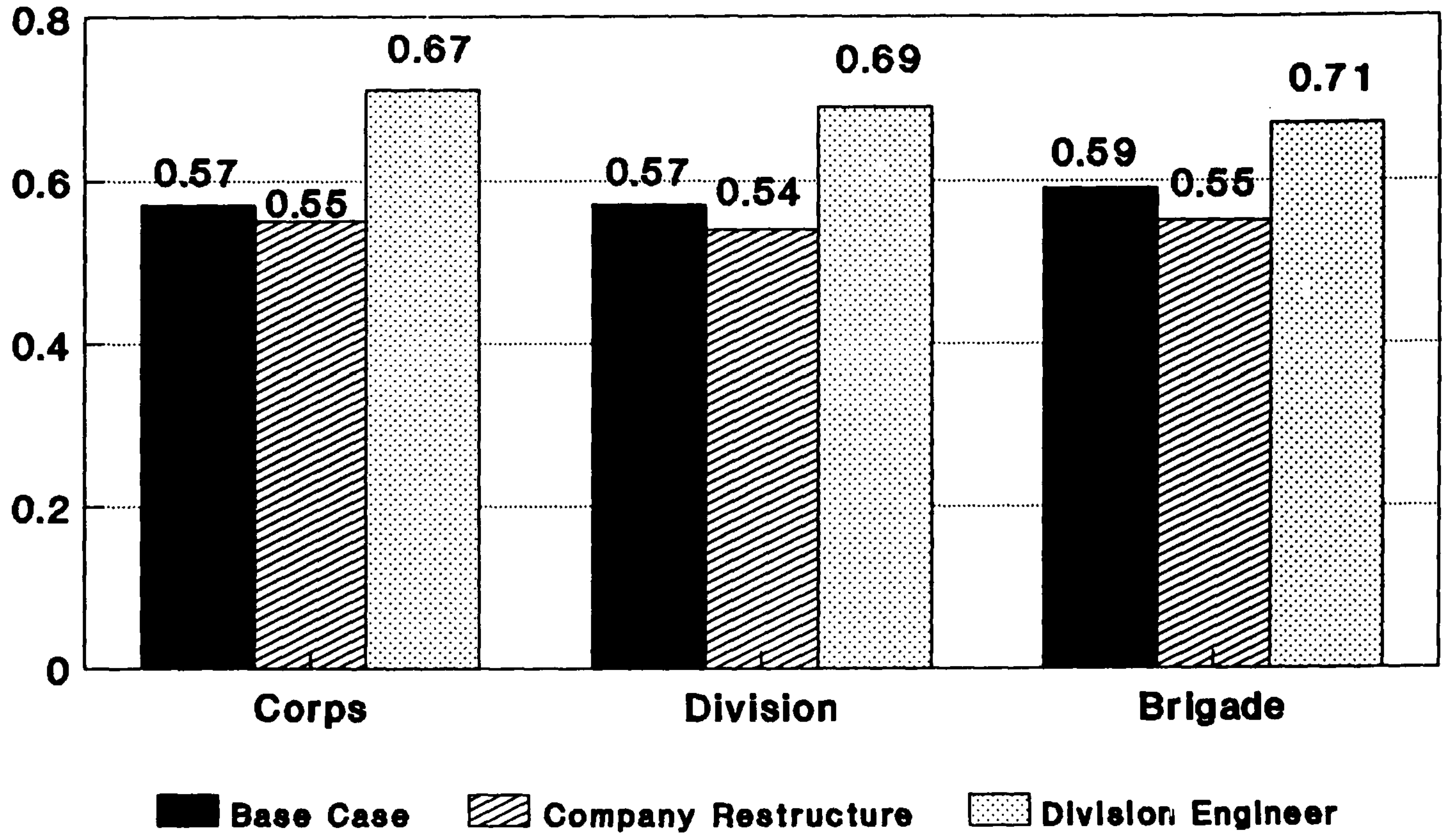
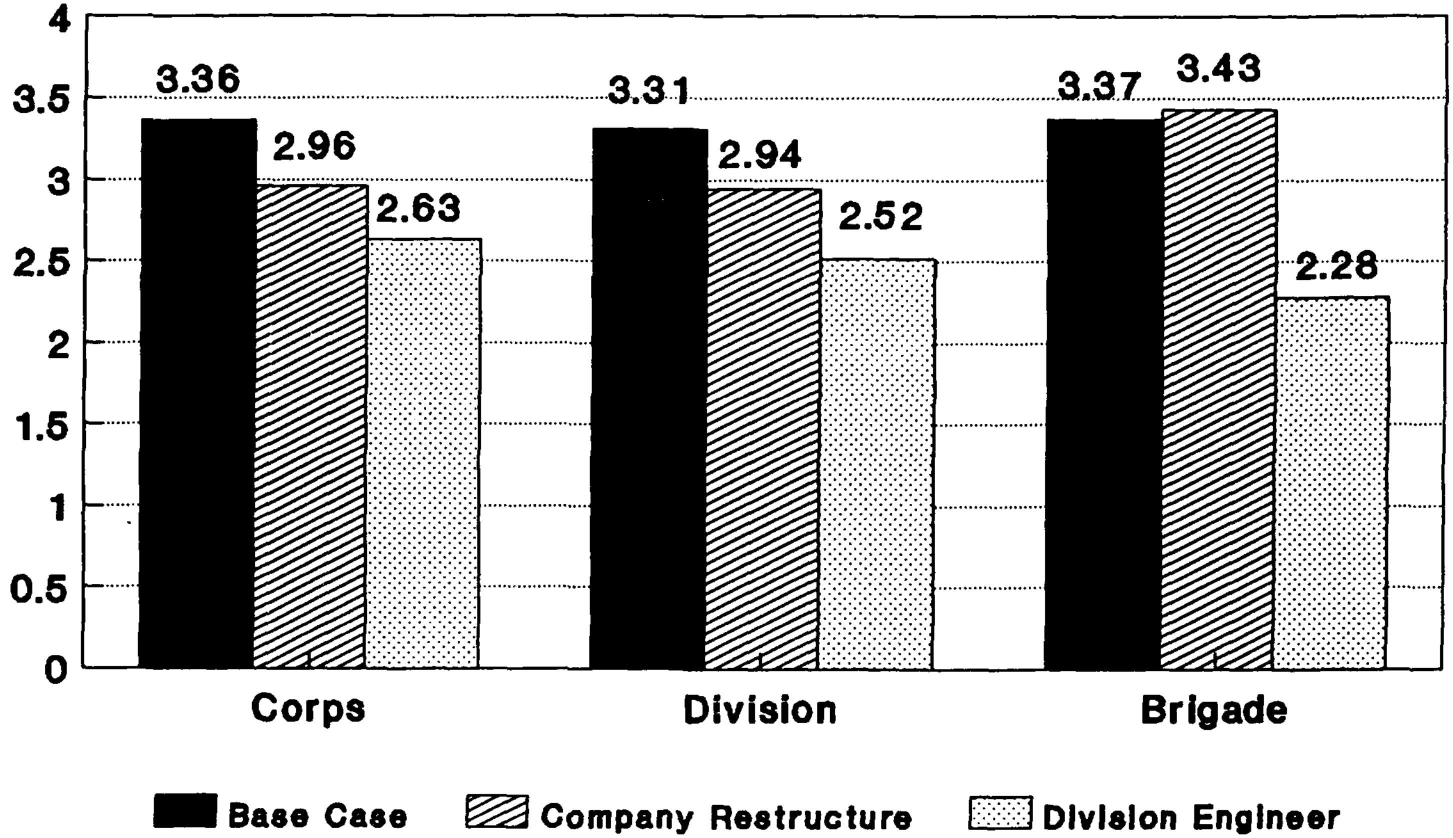


Figure 26

Processing Speed - Transition
Time Delay Average



Smaller is Better

Figure 27

F. OVERALL CONCLUSION

The Division Engineer alternative has emerged as the foremost engineer force structure. If the compounding effects of the MOP'S on each other were taken into account, Division Engineer alternative would become even a stronger performer. The Division Engineer force structure processes more information with higher quality output, and does it faster than the other alternatives at every level of command and for every corps mission.

V. USES OF MODELER

Modeler is a simulation tool developed for the Air Force to analyze foreign Command and Control systems. Modeler allows for an automated means for constructing Stochastic, Timed, Attributed Petri Nets (STAPNs), simulating the underlying operations of such systems.

The version of the software we are interested in is Modeler 1. It runs on a SUN work station utilizing the SUN OS operating system. Its graphics capabilities are provided by X-windows 11.0. The software developer ALPHATECH believes that with a small number of modifications the product should run on any system with 4-8 Megabytes of random-access memory, 100 Megabytes of on-line disk-based storage, and able to run a C compiler and X windows. [Ref. 6]

A. HISTORICAL USES OF MODELER

In addition to the ESS, Modeler has been used on two other studies. Both of these studies were conducted by the Navy. The purpose of both of these studies were to demonstrate Modeler's ability to model Navy Command and Control systems.

B. FURTHER USES OF MODELER

The world has witnessed unprecedented events over the last few years. These events, along with the development of Airland Battle Future, will require the Army to consider changes in it's force structure and introductions of new technologies onto the battlefield. These changes will require the Army to evaluate it's Command and Control structure at all levels and in all theaters.

Modeler provides the military analyst with a powerful tool to assist in the design of and improvement of existing command and control systems.

Modeler has a wide range of uses. It can model a staff in detail or an aggregated system. Analysis at every level of the Army hierarchy can develop uses for Modeler.

Some suggested areas for further analysis are:

- Distribution of supplies in the corps.
- Command and Control in Post Warsaw Pact Europe.
- Command and Control of Air Defense in the corps.
- Medical evacuations in the corps.
- Command and Control of counter-drug enforcement.
- Command and Control of deployment operations.

This list is by no means exhaustive, but analyzing these areas will further develop the methodology for command and control and systems analysis.

VI. CONCLUSION

A. RESULTS

The Division Engineer alternative is the best engineer force structure to support the heavy corps. It consistently outperformed the other alternatives in every measure of performance and in every case.

The performance measures obtained at the corps in each of the three cases are summarized in Tables (13) through (15).

TABLE 13

	OFFENSE CASE		
ALT ALT A / MOP	BASE CASE	COMPANY RESTRUCT	DIVISION
PROCESSING CAPACITY	67.00%	65.00%	* 89.00%
MESSAGE QUALITY	0.55	0.57	* 0.65
PROCESSING SPEED	2.73	2.79	* 2.13
* INDICATES BEST PERFORMANCE			

TABLE 14

	DEFENSE CASE			
ALT ALT A / MOP	BC OPCON	BC DS	COMPANY RESTRUCT	DIVISION ENGINEER
PROCESSING CAPACITY	63.00%	56.00%	62.00%	* 85.00%
MESSAGE QUALITY	0.60	0.60	0.61	* 0.66
PROCESSING SPEED	2.39	2.84	2.74	* 2.15
* INDICATES BEST PERFORMANCE				

TABLE 15

	TRANSITION CASE		
ALT ALT A / MOP	BASE CASE	COMPANY RESTRUCT	DIVISION ENGINEER
PROCESSING CAPACITY	48.00%	59.00%	* 78.00%
MESSAGE QUALITY	0.57	0.55	* 0.67
PROCESSING SPEED	3.36	2.96	* 2.63
* INDICATES BEST PERFORMANCE			

The Division Engineer force structure processes more information with higher quality output, and does it faster than the other alternatives at every level of command and for every corps mission.

B. RECOMMENDATIONS

Implement the engineer force structure described by the Division Engineer alternative in the armored and mechanized corps immediately. Continue research to determine if a Division Engineer type alternative is appropriate for Army wide implementation.

Modeler proved to be a useful tool in the analysis of engineer force structures. We should exploit the features of Modeler in future Army analysis of systems and command and control structure.

LIST OF REFERENCES

1. Kem, MG Richard S.; Capka, MAJ J. Richard; Soo, MAJ Houng Y., E-Force, *Engineer Magazine*, Spring 1986.
2. *FM 100-5, OPERATIONS*, Department of the Army, 5 May 1986.
3. Peterson, James L., *Petri Net Theory and the Modeling of Systems*, Prentice - Hall Inc., 1981.
4. Blitz, Alan, *MODELER 1 USERS' MANUAL*, ALPHATECH Inc., July 1989.
5. Powell, William S., *Analysis of Engineer Command and Control Using Modeler I*, ALPHATECH, Inc.
6. Vail, P.A., *Functional Description Document Modeler 1, C3 Systems Dynamics Project*, ALPHATECH Inc., August 1990.
7. Moore, Kendra E., *Stochastic, Timed, Attributed Petri Net Modeling of C3 Networks*, ALPHTECH Inc., March 1990.
8. *An Iterative Modeling Methodology*, ALPHATECH Inc., March 1990.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center Cameron Station Alexandria, VA 22304-6145	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, CA 93943-5002	2
3.	Director TRADOC Analysis Command - Fort Leavenworth ATTN: C3I (CPT Tabacchi) Fort Leavenworth, KS 66027-5200	2
4.	Engineer Studies Center ATTN: Mr. Bruce Springfield Casey Building 2594 Fort Belvoir, VA 22060	1
5.	Chief of Naval Operations (OP-81) Navy Department Washington, DC 20350	1
6.	CPT Peter J. Tabacchi 349 E. 2nd Street Beaver, PA 15009	3
7.	LTC William J. Caldwell, Code OR/Cw Department of Operations Research Naval Postgraduate School Monterey, CA 93943-5000	2
8.	Professor Robert R. Read, Code OR/Re Department of Operations Research Naval Postgraduate School Monterey, CA 93943-5000	2