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Modelling and Simulation of a River-Crossing Operation via Discrete Event Simulation with Engineering Details

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ABSTRACT

From a military standpoint, a river is an area that should be avoided in a potential engagement because of lack of cover and the necessity of dividing the unit while crossing. Thus, a key point of a river-crossing operation is speed. Many efforts have been made to enable faster river crossing by improvement of tactics, techniques, and procedures (TTP). However, improvements in TTP are evaluated by modelling and simulation much less frequently than are the toe-to-toe engagements between two opposing forces, and to our knowledge, this is the first simulation model of brigade-level river crossing with engineering details. This study presents a simulation model of the river-crossing operation, applies real world parameters, and evaluates which tactics are preferable in a particular operational environments. This analysis has led to new operational methods of river crossing that have been suggested by experienced subject-matter experts. For instance, the current Republic of Korea Army Field Manual dictates to rotate river-crossing rafts in all situations, but our experiment suggests that no rotation is preferable when the width of river is less than 400 m based on the statistical analyses, which includes the regression-based meta-modelling and the ANOVA, of our simulation model that embodies the engineering details of river-crossing equipment.

Keywords: River crossing operation, discrete event simulation, improvement of doctrine, raft

NOMENCLATURE

n_r	Number of rafts operated
n_v	Total number of vehicles to cross the river
n_{vg}	Number of vehicles produced by the generator model
n_{vf}	Number of vehicles that have crossed the river
n_{vw}	Number of vehicles that are waiting to be loaded in the buffer model
v_{river}	Velocity of a running fluid for the river
$t_{crossing}$	Delay time for a raft to return
$d_{crossing}$	Crossing distance
d_{drift}	Drift way which is caused by the velocity of a running river
w_{river}	Width of the river
l_{raft}	Length of a raft
fs_{raft}	Forward speed of a raft
bs_{raft}	Backward speed of a raft
$t_{rotation}$	Delay in time required for a raft to rotate

1. INTRODUCTION

Obstacles are natural or artificial objects that delay, block, or change the movement of opposing forces[1]. A river is a natural obstacle that provides defenders with perfect defensive power and is also one of the most difficult obstacles for attackers to overcome. Moreover, military units are forced to cross a river because in most cases, it is impossible to detour. Thus, a river-crossing operation is one of the most essential military operations, especially for units whose area of operation contains many big and small rivers, such as the Korean peninsula[2,3].

The objective of a river-crossing operation is to transport armed forces from the near-shore of a river to the far-shore[4]. The river-crossing operation has two critical weak points. Firstly, a river is completely open; thus it cannot provide any cover or concealment to a military unit. The units in the river-crossing operation are easily exposed to opposing forces, so are vulnerable to attack[5].

Secondly, the river-crossing forces a unit to split into two parts. In addition, the river-crossing operation takes more time than marching on land, regardless of which river-crossing equipment is used. For these reasons, the river-crossing operation is one of the most risky operations and puts a unit in danger of defeat[6]. Naturally, the key to the success of this operation is speed. Units that need to cross a river must carry out this operation as quickly as possible with their available assets.

After the two World Wars and the Korean War, the United States and the Soviet Union realised the importance of the river-crossing operation. Throughout the Cold War, they developed a great deal of engineering river- crossing equipment that allowed increased speed and improved survivability and capability[7–9].

Thus, most of previous works focus on the engineering and technical layers of river-crossing. According to Lee and Choi[8], recent engineering river-crossing equipment have evolved to (i)

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increase loading capacity, (ii) expand construction length, (iii) minimize construction time, and (iv) enable self-propel[7–9]. On the other hands, Chang[9] suggested the necessity of development of assault river-crossing equipment such as pneumatic assault boat or landing vehicle, tracked (LVT)[9] which comply with speed battle in modern war.

However, there has been little research about the doctrine and operational methods of the river-crossing operation. Arnold[10] asserted the improvement of the doctrine according to the improvement of combat equipment to be transported across rivers in terms of operation concepts and force structure[10]. However, the study did not examine the operational methods of river-crossing equipment, but rather strategies, tactics, and force structures. Repetski[11] analysed the capability of river-crossing using the bridging system according to the existing doctrine, but new methods have not been suggested[11].

To our knowledge, there is no existing study on simulation-based river-crossing using rafts of mechanized brigade-level units. Only field manuals and doctrines explain how to operate the engineering river-crossing equipment according to the size of a unit based on empirical intuition (which will be introduced later in this section[1,4,6]).

This study has assessed the method of river-crossing according to existing doctrine and has allowed to suggest new operational methods to improve tactics, techniques, and procedures (TTP) by modelling and simulation. We have built the model based on the formalism of discrete event systems specification (DEVS) to describe the operation[12].

We used rafts of the Ribbon bridge system (RBS) as the engineering river-crossing equipment for our simulation (see Fig.1)[7–9]. There are two kinds of equipment, pontoon bridges and rafts, but we only consider the rafts since there are no options for a pontoon bridge in terms of operation methods.

Figure 1. Ribbon Bridge System (raft)[7].

RBS rafts are moved by bridge erection boats (BEBs) in a river-crossing operation. There are two methods to attach the BEBs to rafts: conventional and longitudinal methods, as in Fig. 2. we considered the longitudinal method, which suggested various possible changes in operational methods[4]. The BEBs were tied off on both sides of a raft, parallel to the direction in which the raft was heading when a longitudinal method was used[4]. A raft is self-assembling and consists of interior bays and ramp bays. The raft has two ramp bays at its stem and stern for loading and unloading of equipment. It also has at least three interior bays for cargo space and for tying up the BEBs, but more interior bays can be added. Figure 2 also shows two examples of longitudinal rafts, (i) a five-bay raft with two BEBs and (ii) a six-bay raft with four BEBs.

Figure 3 explains two methods of operating rafts in a longitudinal method[4]. The first method is to move a raft forwards by rotating when it returns back to the near-shore. Once the combat equipment is loaded onto a raft on the near-shore, the raft moves forwards to the far-shore. However, when the raft returns back towards the near-shore after unloading the equipment on the far-shore, it rotates 180 degree so that it moves forwards, not backwards. The raft rotates again when it approaches the near-shore so as to meet the near-shore with its stern. Consequently, the raft rotates 360 degree during each crossing mission. The ROK Army Field Manual dictates the use of this method because the reverse thrust of the BEBs iwas 50 per cent weaker than their forwards thrust. The second method is to move the raft backwards when it returns. This method reduces the speed of return, but we can compensate for it by increasing thrust using more BEBs.

The current ROK Army Field Manual dictates the use of five-bay rafts with two BEBs and the use of the first method described in Fig. 3 when conducting a river-crossing operation with rafts[6,13]. However, the method takes additional rotation time. The method described in the Field Manual is appropriate in certain circumstances, but the problem is that the Field Manual dictates the method regardless of variables such as the crossing distance, the number of available rafts, and the amount of equipment to be transported. For example, the slow reverse velocity of the raft is a better choice than rotation when the river is not wide. We can also increase thrust for more speed by attaching more BEBs, e.g., six-bay rafts with four BEBs (see Fig. 2 (c)).

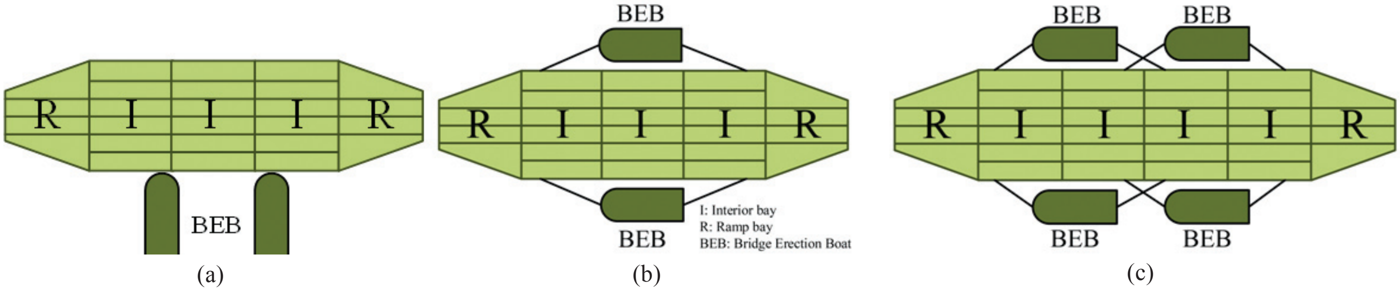
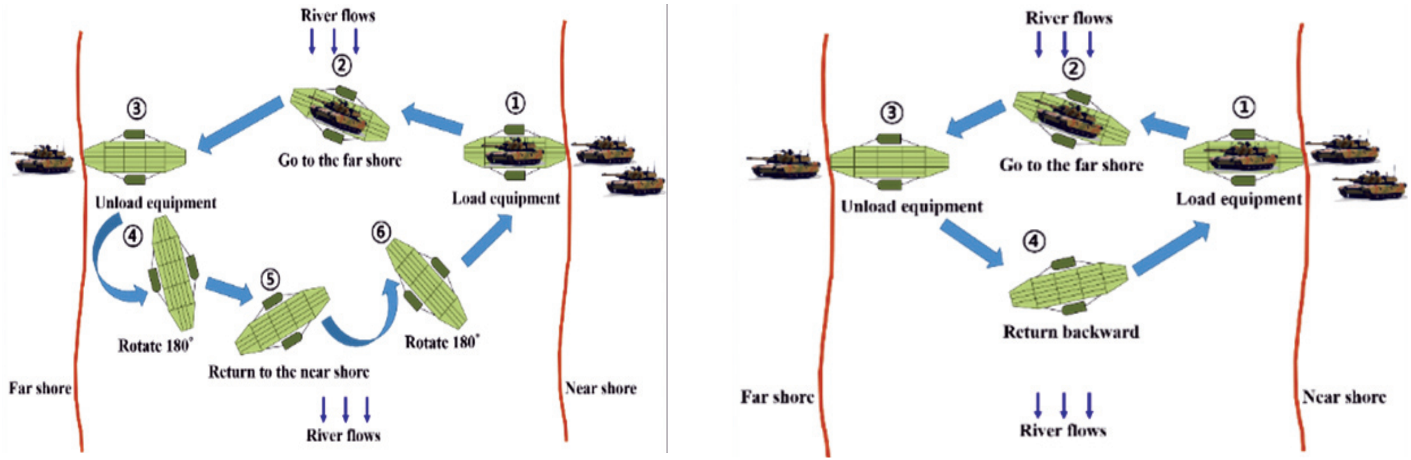


Figure 2. Conventional and longitudinal method to use: (a) Conventional, (b) Longitudinal, (5 bays with 2 BEBs), and (c) Longitudinal (6 bays with 4 BEBs).



(a) (b)

Figure 3. (a) Longitudinal rafting with rotation, and (b) without rotation.

The purpose of this study is to determine the effectiveness of the method given in the existing field manual, test new methods that have been suggested by officers in the field, and compare those methods through experiments[14]. For this purpose, we built a model that represents the river-crossing operation using rafts and performed simulations with the model to see how the operation was affected by (i) the raft type and rotation as operational factors, (ii) the width and velocity of river as environmental factors, and (iii) the number of rafts operated as an equipment factor.

We assume that there is no attack from opposing forces during the operation since the river-crossing operation should be performed when enemy threat of attack is not expected or is removed due to its vulnerability.

We refer to the Republic of Korea (ROK) Army Field Manual to examine the existing systems and tactics in detail. However, the rafts of the RBS that we used in this study are widely used in many countries, including the US Army, and we confirmed that the operational methods for the raft were not different in the US and ROK Armies[1,4,6,13,15].

2. METHODOLOGY

We used the theory of DEVS formalism and used a DEVS diagram to make a model representing the river-crossing operation[12]. DEVS formalism is a module-based formalism that can be easily used to construct hierarchical concepts of the models[16]. It describes state transitions by inputs and the time advance of the internal state via its atomic model. The DEVS coupled model defines coupling relations between models[17].

2.1 Overall Structure of the River-Crossing Operation Model

Figure 4 illustrates the overall structure of our model, the river-crossing operation. The model comprises two coupled models, the experimental frame model (EF) and the river-crossing model (river-crossing). The coupled experimental frame (EF) model consists of two atomic models, the generator (generator) and the data collector (data collector). The river-crossing coupled model consists of one atomic model of a buffer (buffer) and n_r atomic models of rafts (raft).

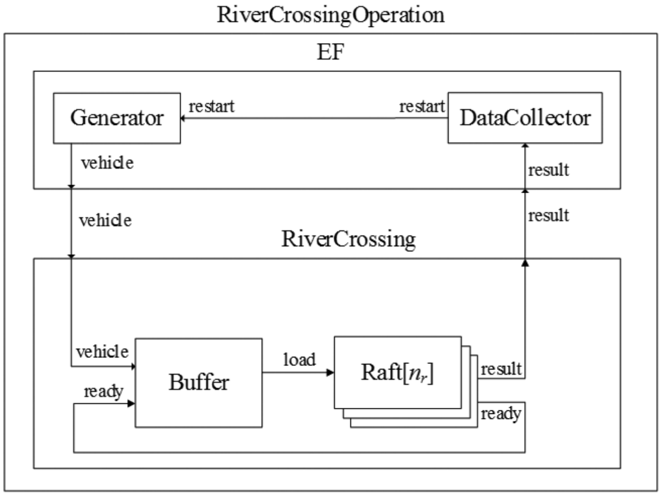


Figure 4. Overall structure of river-crossing operation model.

2.2 The Experimental Frame and River-Crossing Models

Figure 5 shows the generator model and the data collector model. The generator sends vehicles to the buffer model according to the arrival rate obtained from the doctrine[13]. We assumed that the inter-arrival time of a vehicle follows an exponential distribution with a fixed mean because the doctrine only provides the average value. We considered the tactical movement speed of a mechanised infantry brigade with six types of vehicles, (i) tanks, (ii) infantry fighting vehicles (armoured vehicles), (iii) self-artillery vehicles for direct fire support, (iv) 2 1/2–ton combat vehicles, (v) 5/4-ton combat vehicles, and (vi) 1/4-ton tactical vehicles. The role of the data collector is to collect information from vehicles that cross the river, count the number of vehicles, and calculate the operational time. The date collector restarts the simulation to repeat the experiment whenever the designated number of vehicles have crossed. It also stops the simulation when the ending condition is satisfied.

2.3 The Buffer and Rafts Models

Figure 6 shows DEVS atomic models of the buffer and rafts of the river-crossing model. The buffer model has

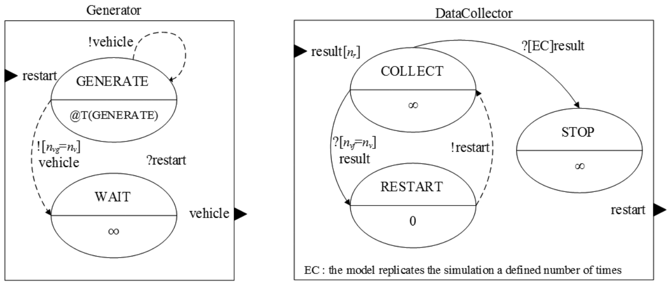


Figure 5. DEVS atomic models for the generator and data collector.

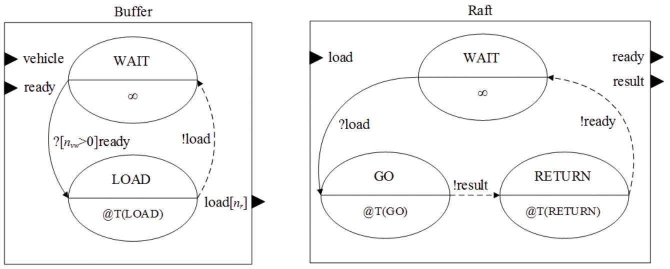


Figure 6. DEVS atomic models for the buffer and rafts.

two states, ‘WAIT’ and ‘LOAD’. The buffer model receives information about vehicles from the generator model and makes the vehicles wait until one of the rafts is available to load. The model knows the available rafts’ information because the rafts send a message when these are ready. If the number of vehicles waiting is more than one and at least one raft is available, the model starts to load vehicle(s) and sends a message to the raft model after T (LOAD) time (the delay time needed to load the vehicles). We obtained an average value for the loading time empirically and assumed that the time followed an exponential distribution with the fixed average.

The raft model has three states: ‘WAIT’, ‘GO’, and ‘RETURN’. The model ships the maximum number of vehicles it can carry and goes to the far-shore. The model unloads the vehicle (s) when these arrive at the far-shore (after T (GO) time) and sends the result message to the data collector model. These then return to the near-shore and send the ready message to the buffer model after T (RETURN) time. This operation is repeated until all of the vehicles have crossed the river.

We also assumed that the values for T (GO) and T (RETURN) follow exponential distributions with fixed means. The means were calculated from the crossing distance, the length of the raft, the forward and backward speeds of the rafts, and the rotation time. Equations (1) through (3) show how to calculate the crossing time of a raft. The crossing time is simply the sum of T (GO) and T (RETURN), as in Eqn. (1). However, the crossing time differs depending on the operation methods. Equation (2) shows the crossing time ($t'_{crossing}$) when the raft rotates twice according to the ROK Army Field Manual. Equation (3) shows the total crossing time ($t''_{crossing}$) when the raft moves backwards when returning to the near shore.

$$t_{crossing} = \mathrm{T(GO)+T(RETURN)} \tag{1}$$

$$t'_{crossing} = 2\frac{\left(d_{crossing} - l_{raft}\right)}{fs_{raft}} + 2t_{rotation} \tag{2}$$

$$t''_{crossing} = \frac{\left(d_{crossing} - l_{raft}\right)}{fs_{raft}} + \frac{\left(d_{crossing} - l_{raft}\right)}{bs_{raft}} \tag{3}$$

where $d_{crossing}$ can be calculated as in Equation (4) and (5).

$$d_{crossing} = \sqrt{d_{drift}{}^2 + w_{river}{}^2} \tag{4}$$

$$d_{drift} = \frac{v_{river}}{fs_{raft}\,(\text{or } bs_{raft} \text{ when moving backward})} \times w_{river} \tag{5}$$

2.4 Simulation Parameters and Performance Measurement

To find points for improvement in terms of operation methods, we considered both qualitative and quantitative elements that affect the total river-crossing operation time[18]. For qualitative elements, we tested three types of rafts by the raft size and the number of BEBs. We took into account whether the raft is rotated when returning and how the rotation time varied with the type of raft.

For quantitative elements, we considered two environmental elements: the width of river ($d_{crossing}$) and the velocity of river (v_{river}). The number of rafts (n_r) that are available to operate is also taken into account. We used information from the Field Manual for equipment parameters such as the forwards (fs_{raft}) and backwards (bs_{raft}) speeds of the rafts[19].

We measured the total delay time of the river-crossing operation to compare three input variables, the operation methods, the crossing time, and the number of rafts. Table 1 shows details of the simulation model.

3. EXPERIMENTAL DESIGN

We conducted experiments to analyse how the operation methods and environmental and equipment factors affected the total operation time. For operation methods, we considered three types of rafts, (i) a five-bay raft with two BEBs, (ii) a six-bay raft with two BEBs, and (iii) a six-bay raft with four BEBs. It is impossible to attach four BEBs to a five-bay raft because of the raft’s length. Whether the raft was to be rotated was also considered (two cases).

For environmental factors, the width of river and the velocity of river varied according to the characteristics of the rivers in the Korean peninsula[20]. We also varied the number of rafts in operation to determine the optimal number of rafts according to the crossing distance and the operation methods.

Table 2 shows the experimental design for our simulation. We established 288 cases for this experiment and the experiment was replicated 20 times for each case.

4. SIMULATION RESULTS

We analysed the performance measure, the total river-crossing time, to test the relationships between the operation time and various factors of the raft type, the raft rotation, the width of river, the velocity of river, and the number of rafts. Figures 7 and 8 show the changes in the total operation time for the raft types and raft rotation, respectively in relation to (i) the width of river, and the number of rafts; (ii) the width of river and the velocity of river[21,22].

Table 1. List of parameters and the performance measurement

Type	Name	Description
Operational Parameters (Input, Decision Point)	Raft type	Types of rafts (raft size × number of BEBs)
	Raft rotation	Rotate the rafts or not (Binary value of rotation: $R = 0$ or 1. Rotation time: 0.67 min for a five-bay raft with two BEBs, 1 min for a six-bay raft with two BEBs, and 1.34 min for a six-bay raft with four BEBs)
Environmental and Equipment Parameters (Input)	w_{river}	Width of river
	n_r	Number of rafts
	v_{river}	Velocity of river
	fs_{raft}	Forwards speed of the raft (two BEBs: 30 km/h; four BEBs: 30 km/h)
	bs_{raft}	Backwards speed of the raft (two BEBs: 15 km/h; four BEBs: 30 km/h)
	T(GENERATE)	Inter-arrival time of vehicles (exponentially distributed with a mean of 1 min)
	T(LOAD)	Loading time of a vehicle (exponentially distributed with a mean of 1.5 min)
Performance Measure (Output)	Total operation time	Total delay time of the river crossing operation

Table 2. Experiment Design of the river-crossing operation model

Variables		Value
Operation Methods	Raft type (Raft size, Number of BEBs)	Type 1 = (5-bays Raft, 2), Type 2 = (6-bays Raft, 2), Type 3 = (6-bays Raft, 4)
	Raft Rotation	Case 1 = Rotation, Case 2 = No Rotation
w_{river} (m)		200, 400, 800, 1600
n_r		3, 4, 5, 6
v_{river} (m/s)		0.5, 1.5, 2.5
Total number of cells		3x2x4x4x3= 288 cases (20 replications for each case)

Figure 7 demonstrates that type 3 rafts (six-bay rafts with four BEBs) always perform better than the other types when crossing a more than 800 meter-wide river. Operating more rafts also makes the operation faster if the width of the river is more than 800 meter. However, no significant influence of the velocity of river is found with this graph.

As for raft rotation in Fig. 8, moving the raft backwards is mostly better than rotating when the width of river is less than 400 m. In addition, under the high velocity of the river, (2.5 m/s in this experiment), rotation was required when crossing a more than 800 meters-wide river for faster operation. These results explain the necessity of changing operational methods according to environmental factors. In short, we need to apply various operational methods depending on the width of the river and the velocity of the river.

Figure 9 confirms the results of Figures 7 and 8 by marginalising the width of river, the velocity of river, and the number of rafts. Overall, type 3 rafts performs well in most cases while raft rotation should be applied based on the width and velocity of the river. In other words, rotation is desirable when the width of the river is more than 800 m and velocity of river is high, e.g., 2.5 m/s, while no rotation is recommended when the width of river is less than 400 meter and velocity of river is low, e.g., 0.5 m/s. The use of many rafts is beneficial when crossing a wide river, but if too many rafts are used when crossing relatively narrow rivers, these can sit idle.

To make our analysis statistically rigorous, we analysed our simulation datasets using meta-modelling and analysis of variance (ANOVA)[23]. The meta-model is a simplified mathematical model for simulation models[24,25]. We used a multiple linear regression model for the meta-model.

Table 3 shows the meta-model of our simulation model. The meta-model reveals that all the independent variables significantly contribute to the total operation time (see the corresponding *p*-values).The standardized coefficient indicates that the use of type 2 and type 1 rafts take longer time than the use of type 3 rafts. The results also show that a greater number of rafts shortens the operation time while a wider and fast runningriver increase the operation time.

The ANOVA results in Table 4 also confirm the meta-modelling results, that is all of the experimental factors significantly influence the performance measure, the operation time. The result also shows interaction effects among the experimental factors. The most significant compounding effects of w_{river} and n_r (F = 3555.626) indicates that the width of river and the number of rafts should be simultaneously considered during the river-crossing operation. In addition,

Table 3. Meta-model analysis on simulation results. Standardised coefficient for sensitivity of factors, and *P*-value for robustness of factors (*: $p<0.01$)

Experiment variable name	Standardized coefficient
Type1	0.1211*
Type2	0.1632*
Case1	0.0245*
Width of river (w_{river})	0.8418*
Number of rafts (n_r)	-0.2614*
Velocity of river (v_{river})	0.1067*
Adj. R-square	0.8102

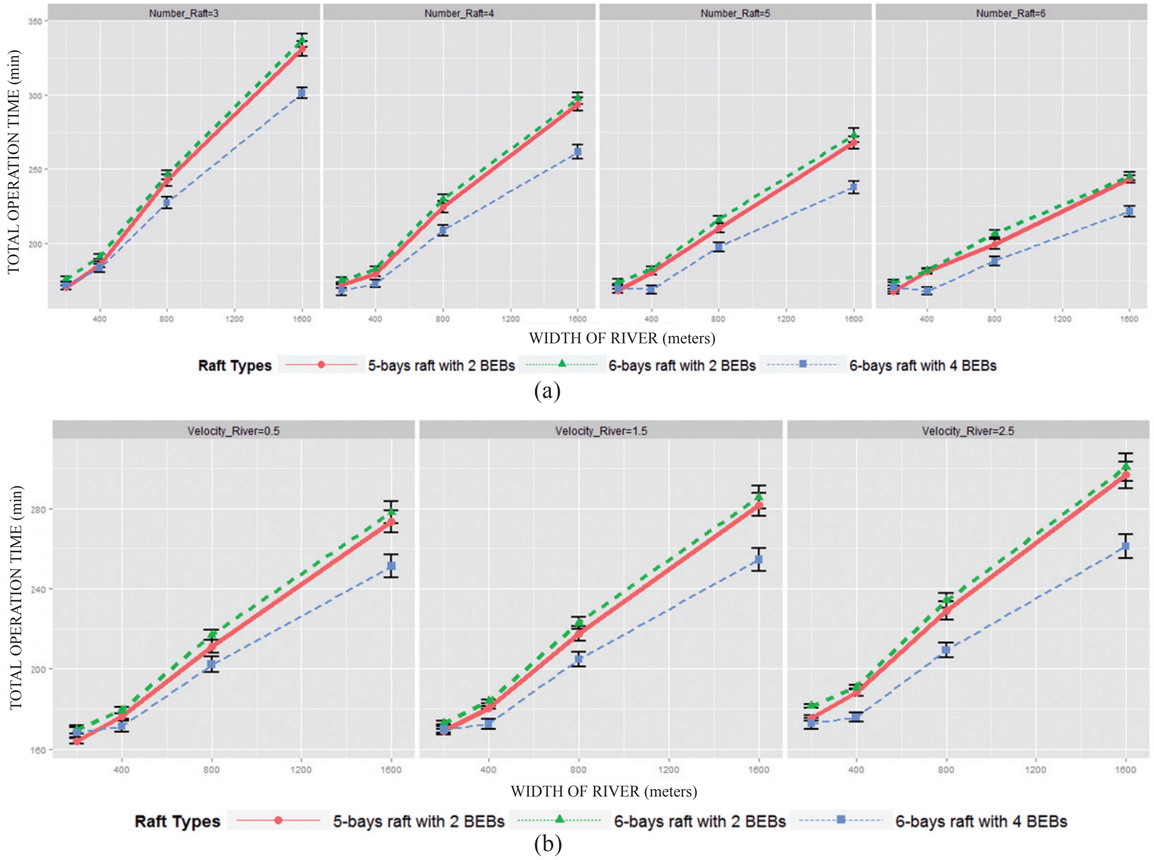


Figure 7. Total operation time by raft types. Error bars of 95 per cent confidence intervals: (a) Total operation time vs width of river and number of rafts, and (b) Total operation time vs width of river and velocity of river.

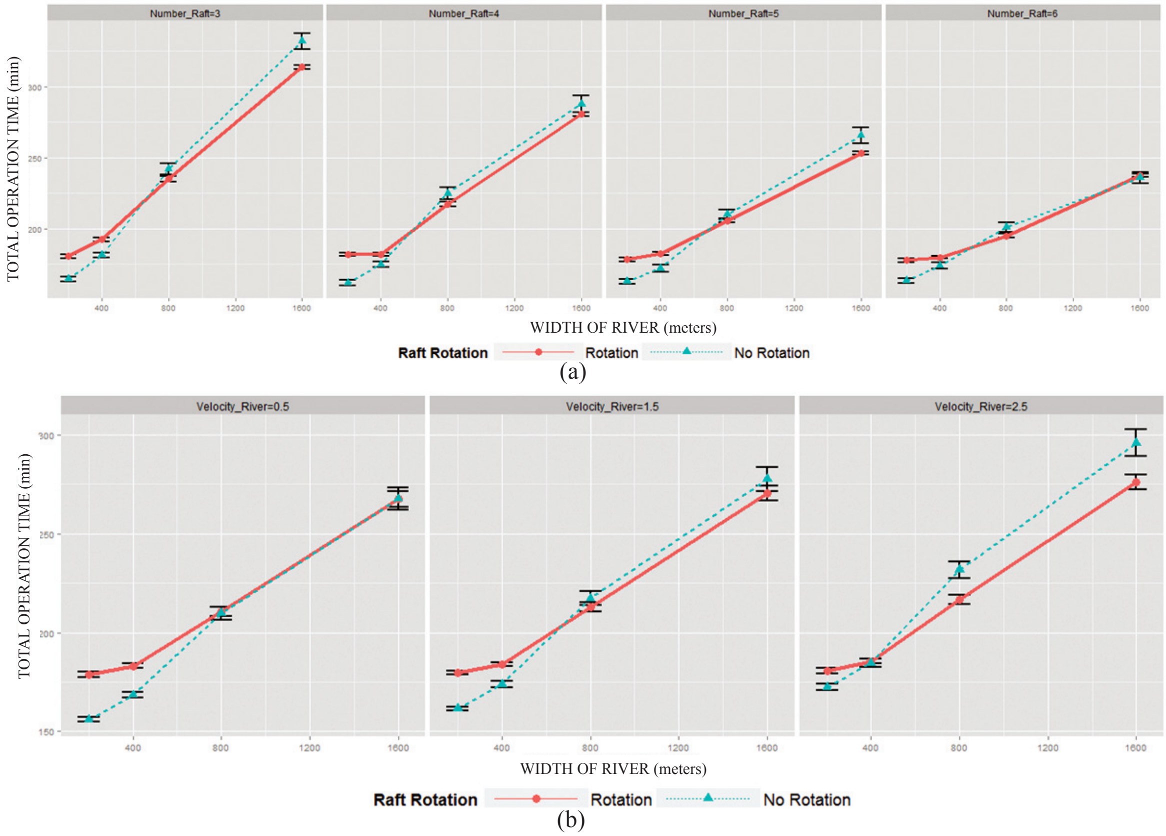
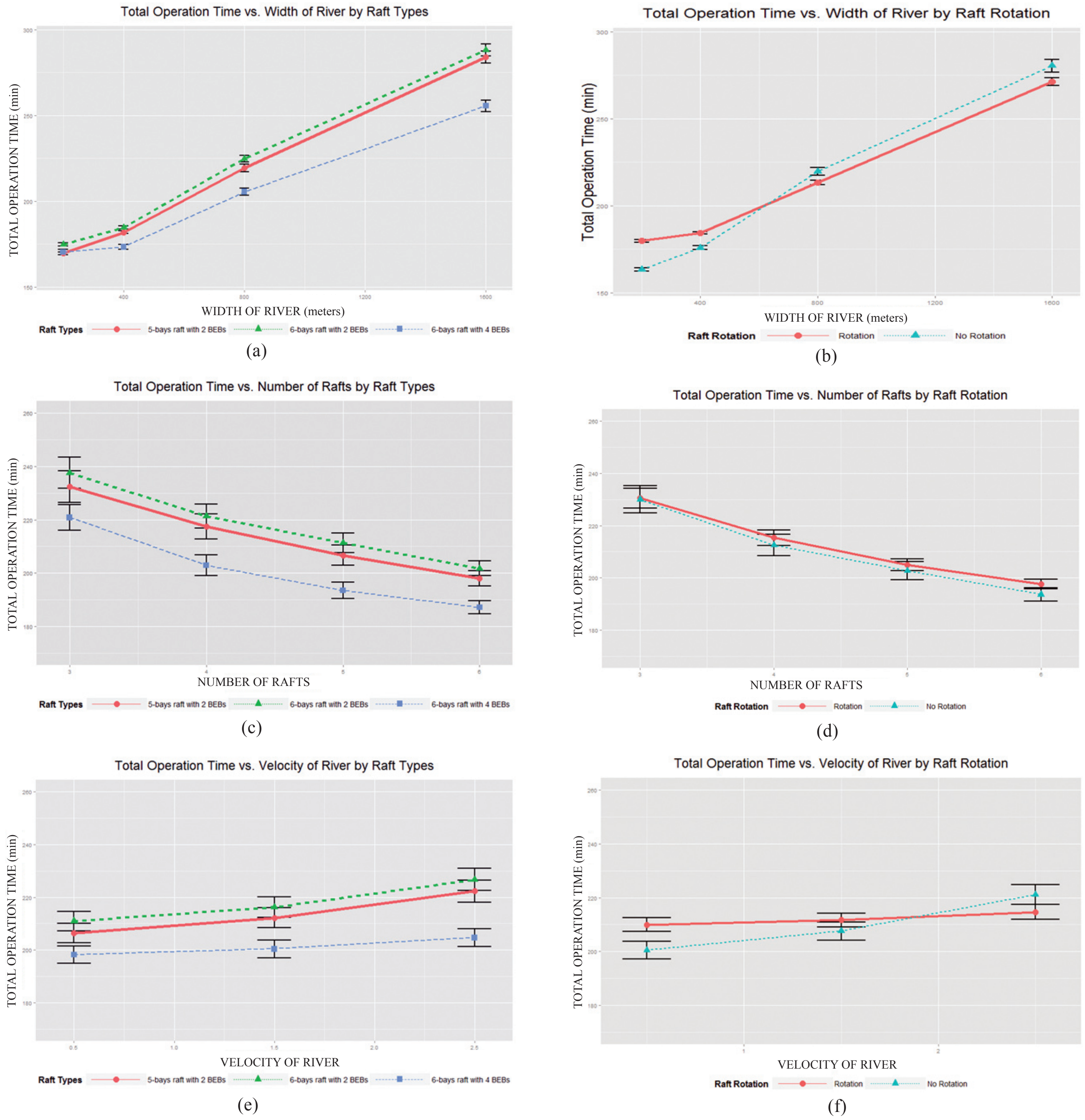


Figure 8. Total operation time by raft rotation. Error bars of 95 per cent confidence intervals: (a) Total operation time vs width of river and number of rafts, and (b) Total operation time vs width of river and velocity of river.



(a) (b) (c) (d) (e) (f)

Figure 9. Changes of total operation time by width of river, number of rafts, and velocity of river. Error bars of 95% confidence intervals.

other interaction effects, such as (i) case1 and w_{river} (F = 525.359); (ii) type2 and w_{river} (F = 428.432); (iii) case1 and v_{river} (F = 257.112); (iv) type 1 and w_{river} (F = 145.223); (v) w_{river} and v_{river} (F = 57.611); (vi) case 1, w_{river} and v_{river} (F = 51.822); (vii) type 1 and v_{river} (F = 21.511); and (viii) type 2, w_{river} and n_r (F = 13.247), show that the operation method should be changed depending on environmental and equipment factors such as the crossing distance and the number of rafts.

5. CONCLUSIONS

The current ROK Army Field Manual for river-crossing operations presents only one operation method for the use of RBS rafts regardless of environmental factors, whereas the equipment is flexible in terms of its operation and assembly. We performed this study to validate the existing field manual and to find any points on which the field manual could be improved.

Table 4. ANOVA for significance analysis of experiment factors and their compounding factors (*: p<0.01)

Source	DF	SS	MS	F	Pr> F
Type1	1	21349	21349	89.380	< 0.001*
Type2	1	273510	273510	1145.064	< 0.001*
Case1	1	8215	8215	34.393	< 0.001*
w_{river}	1	9702388	9702388	40619.550	< 0.001*
n_r	1	935523	935523	3916.617	< 0.001*
v_{river}	1	155963	155963	652.947	< 0.001*
Type1x w_{river}	1	34688	34688	145.223	< 0.001*
Type1 x n_r	1	0	0	0	0.9990
Type1 x v_{river}	1	5138	5138	21.511	< 0.001*
Type2x w_{river}	1	102335	102335	428.432	< 0.001*
Type2 x n_r	1	558	558	2.335	0.1266
Type2 x v_{river}	1	13577	13577	56.839	< 0.001*
Case1x w_{river}	1	125487	125487	525.359	< 0.001*
Case1 x n_r	1	1870	1870	7.830	0.0051*
Case1 x v_{river}	1	61414	61414	257.112	< 0.001*
w_{river} x n_r	1	849297	849297	3555.626	< 0.001*
w_{river} x v_{river}	1	13761	13761	57.612	< 0.001*
n_r x v_{river}	1	211	211	0.884	0.3471
Type1 x w_{river} x n_r	1	559	559	2.342	0.1260
Type1 x w_{river} x v_{river}	1	423	423	1.772	0.1831
Type1 x n_r x v_{river}	1	200	200	0.839	0.3598
Type2 x w_{river} x n_r	1	3164	3164	13.247	< 0.001*
Type2 x w_{river} x v_{river}	1	921	921	3.856	0.0496
Type2 x n_r x v_{river}	1	10	10	0.042	0.8375
Case1 x w_{river} x n_r	1	12378	12378	51.822	< 0.001*
Case1 x w_{river} x v_{river}	1	1195	1195	5.003	0.0253
Case1 x n_r x v_{river}	1	105	105	0.441	0.5067
Error	5732	1369146	239		
Total	5759	13693385			

We developed a model of the river-crossing operation using rafts based on DEVS formalism and simulated the operation via DEVS. With the results from the simulation, we analysed the total operation time by operational, environmental, and equipment factors. The most important insight provided by our results is the necessity of flexible operation methods for various situations.

Overall, the results of our experiment by modelling and simulation demonstrate relationships between the experimental factors of the operation methods, the environmental factors of the width and velocity of river, and the number of rafts. The results show that the use of a fixed method without consideration of various effect elements can cause inefficient operations. Thus, commanders of a river-crossing operation should be trained to make proper and flexible choice from among various options of operation methods based on situation assessment.

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